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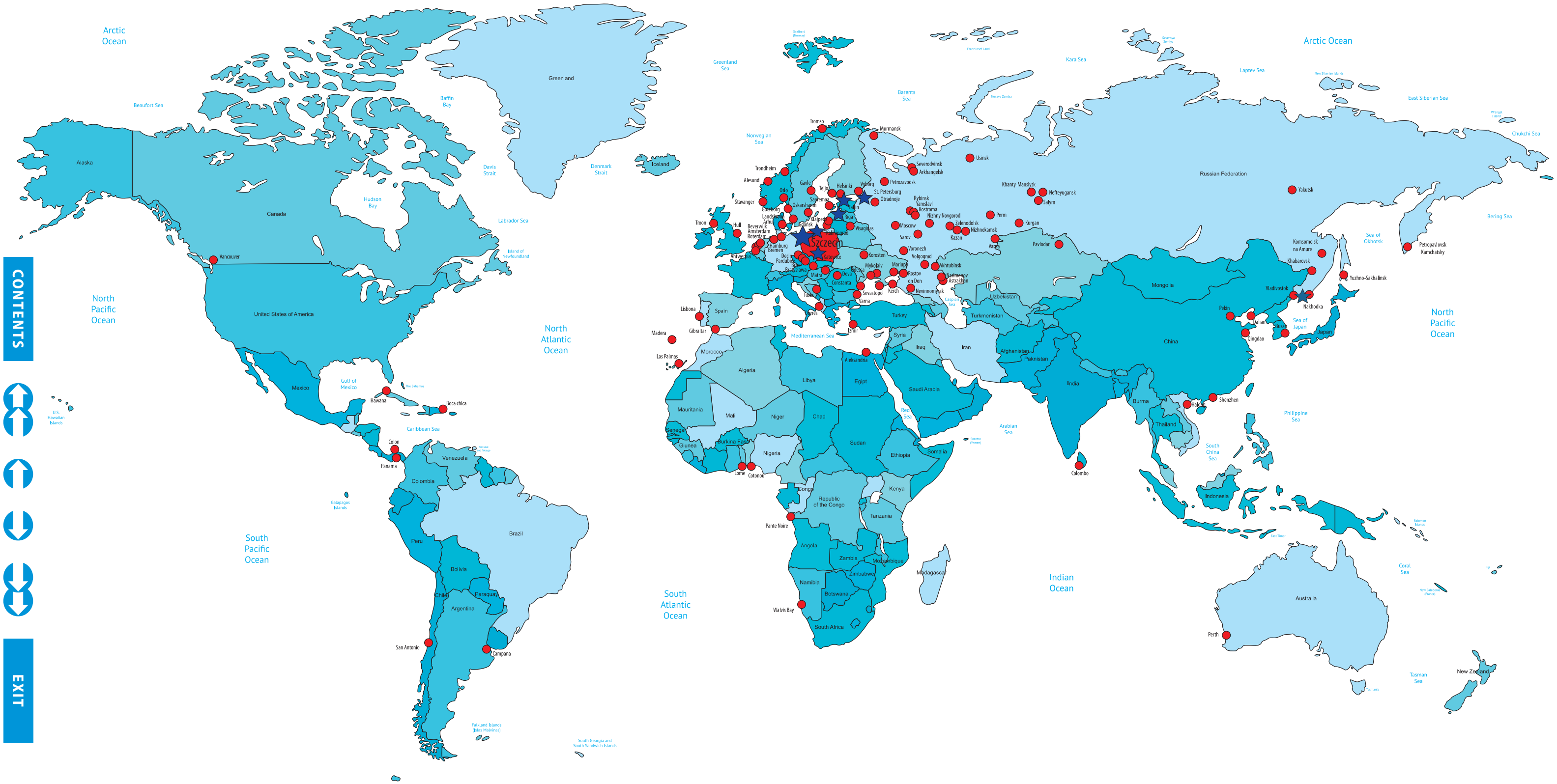

Marine Service Jaroszewicz
certified servicing and delivering
of the resin compounds:
EPY, Chockfast and Epocast

Notation for MSJ activity locations:

- ★ Head quarter
- ★ authorized servicing agents
- ● places where seating services were rendered (1974÷2014)

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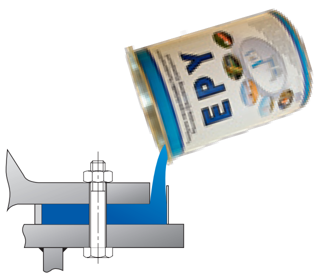

Szczecin 2015

Karol Grudziński, Wiesław Jaroszewicz, Jędrzej Ratajczak, Magdalena Urbaniak, Paweł Grudziński
MOUNTING OF MACHINES AND DEVICES BY USING EPY RESIN COMPOUND

The book presents a modern method for the seating of marine and land-based machines and devices by using chocks cast of EPY resin compound specially developed for this purpose. General requirements referring to the seating of machinery on foundations (especially those used in shipbuilding) are included together with relevant evaluation criteria. The properties of resin compounds used for foundation chocks, the background of chocking arrangement design and the techniques used for casting the chocks, are also outlined. Many examples of so installed machines and devices are described, illustrating various possible applications of EPY compound to the seating of new machinery and the repair of existing ones. The results and descriptions of research aimed at finding solutions for many practical problems in this field, constituting a scientific basis of the methods developed for the assembling machines and other objects by using EPY resin compound, are also given. The book shows in a scientific and practical manner that the application of foundation chocks cast of the thermo-curing compound EPY instead of traditional chocks made of steel not only simplifies assembly but also ensures better anchoring of machines. This guaranties better resistance to wear and tear, better operational reliability and longer service life. Ultimately, it provides significant reduction of cost, and practically noticeable reduction of vibration and noise.

This book is addressed to designers and shipbuilding technology specialists as well as engineers and technicians dealing with design, modernization and execution of various heavy machinery installation on land. It may be also of use for the scientific workers and students at higher technical schools in the faculties engaged in the fields of shipbuilding and offshore technology, machinery design and maintenance, industrial constructions and the building of roads and bridges.

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Contents

Introduction

This book presents a modern method for the seating of shipboard machines and devices as well as various land-based machinery and facilities, on foundations with the use of chemically curing polymer resins specially developed for this purpose. It also presents the way of development of such compounds in Poland and the modern machinery seating technology based on these compounds. The results of 40-year research and practical applications of the compounds to assembling machines and devices are also contained in this book.

The book is an up-to- dated and significantly extended version of the previously edited book (in 2002 and 2005) titled: "*Seating of machines and devices on foundation chocks cast of EPY compound*". Since then were performed many new research and development studies covering much greater range of practical applications of the compound both in shipbuilding and for assembling many various land-based objects. In particular, to the book was added a new chapter containing description and test results of complex physical and chemical features of EPY compound and its behaviour depending on its curing, temperature and loading rate conditions. In the new book changes which had place in some rules dealing with application of resin compounds to assembling shipboard machines and devices, were taken into account. Also, the granted certificates necessary for application of EPY compound to assembling crucial machines and devices, especially in shipbuilding and ocean engineering, have been renewed.

Young scientific workers greatly contributed in conducting research work, novel practical applications as well as preparation of new material for this book. Within this scope they prepared a. o. their doctorate dissertations, introduced significant creative ideas, becoming this way co-authors of this book which is a significantly extended edition of its earlier version. This book results from multi-year close cooperation between the Chair of Mechanics and Machine Elements, Polytechnic of Szczecin (transformed into The West-Pomeranian University of Technology in 2009) with the Marine Service Jaroszewicz Co in Szczecin. The need of writing this book has arisen from that the authors considered their duty to gather and put in order the results of 40-year research work and the resulting scientific and utilitarian effects. The detailed, chronologically ordered list of scientific research projects (both published and unpublished) dealing with the resin compound in question and its application to engineering practice, carried out first in Polytechnic of Szczecin, and later in The West-Pomeranian University of Technology, is included at the end of the book.

In practical activity since 1974 till the end of 2014, in total, 11,490 different objects were seated with the use of the compound, including 10,101 shipboard machines and devices (2236 main propulsion engines) as well as 1389 other machines and land-based facilities such as turbines, large reciprocating compressors, mining hoisting machines, fans, large dimension bearings and toothed rings of brown coal excavators, bridge span bearings etc. Owing to the results of the specialty research, many original, innovative first-in-the-world solutions have been obtained in this field and successfully tested in practice, winning broad recognition. The EPY compound developed in Poland and machine seating technology based on it is granted all the necessary certificates and belong today to the worldwide leading achievements in this field.

The ever-increasing needs of designers, constructors and technology specialists in shipbuilding and ocean engineering where the seating of ship main propulsion systems and many other auxiliary devices has become today a standard practice, were another motivation for the writing of this book. The motivation was also supported by the fact that the novel machinery chocking technology with the use of resin compound and possibility of its practical application in various particular cases and situations has been drawing increasing interest from the side of engineers of other engineering branches. Therefore the book is addressed not only to designers and technology specialists engaged in the shipbuilding and ocean engineering but also to a wide group of other prospective readers dealing with designing, assembling and operation of various land-based machines and facilities. This is due to the fact that the way of assembling machines and facilities (especially heavy ones and generating large dynamic loads) has a significant effect not only on the time and cost of this operation but also very often on final quality, reliability and life of installed and mutually cooperating machinery units.

In the book it was demonstrated in a scientific and practical way that an appropriate application of the resin compound to the assembling of machines and devices can consequently lead to significant technical, economic and operational advantages, especially to lower noise and vibration levels and improved reliability and service life of the machines and devices.

Taking into account the broad range of readers (including scientific workers and students of technical universities) the layout of the book has been arranged in a way which facilitates the finding of a searched topic or its solution where the resin compound is applied.

The book also contains the general requirements for the seating of machines and devices and its evaluation criteria. Kinds and characteristics of traditional seating methods with the use of steel chocks are also discussed, as well as comparative analyses are presented, confronting the traditional technology and the modern one based on chocks made of resin compound cast directly *in situ*.

The properties of resin compounds used for machinery seating are also discussed together with the requirements for them. The background of resin chocking system design and the methods for casting (ready to use) chocks *in situ* are highlighted as well.

Many examples included in the book illustrate various possible applications of the resin compound to the seating of new machines and devices as well as repair and modernization of existing objects.

The presented descriptions and results of numerical calculations and experimental research (aimed at solving practical problems) make it possible to better understand various current problems concerning the seating of machines and devices as well as possible applications of the resin compound for solving the problems in various fields of engineering.

They also constitute an important scientific basis and a source of data for new applications and further research on the improvement of properties of the resin compound as well as the methods of its use for the seating of machinery.

The authors of this book would like to thank all the employees of the Chair of Mechanics and Machine Elements, Polytechnic of Szczecin, and the Marine Service Jaroszewicz Co, Szczecin, who participated in the research and development work as well as in the elaboration of the materials included in this book. Deep thanks are also directed to many employees of Polish shipyards and other industries and R&D centres and installation teams, associated with them, for their inspiration and effective help in the process of implementation of new solutions as well as for many fruitful discussions stimulating further development of the new method of the seating of machines and devices with the use of the polymer resin compound in question.

The authors of the book are aware of its imperfections and various glitches may be found in it. They will be certainly gracious to the readers who convey their remarks concerning its content and layout. They are also ready to discuss, advise and help in any matters related to the subject of the book.


ODFJELL SEACHEM

1 Characteristics and types of chocking arrangements used for ship machinery

1.1. Basic tasks and requirements related to chocking of ship machinery

The seating of a machine consists in obtaining its precise alignment in a specified position and then fixing it securely to foundation in such a way that it is able to fulfil its functions within the assumed service period. This operation is to be performed in accordance with the rules of classification institutions and the requirements of machine manufacturers [1].

Ship machines and devices are not seated directly on the supporting surfaces of foundations, but on appropriate intermediate elements, i.e. foundation chocks (Fig. 1.1). This is due to the fact that large supporting surfaces of foundations and bodies of seated machines are difficult to match in contact exactly, but also to the often arising need to have the mutually cooperating machines and devices aligned coaxially with high precision. Introduction of foundation chocks makes it possible to replace a continuous support surface with a discrete support at a finite number

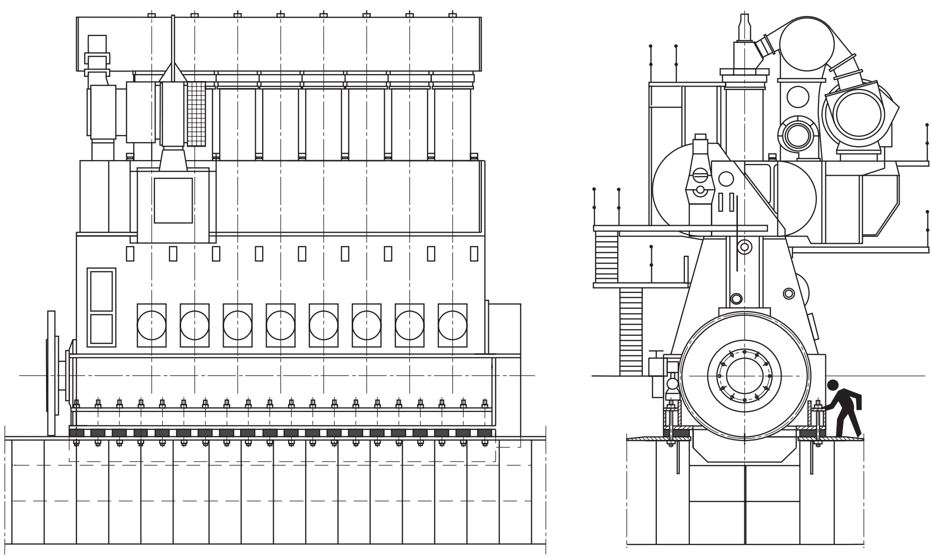


Fig. 1.1. The layout of a main engine seating arrangement

of supporting points (areas). In case the number of points is larger than three the whole arrangement becomes statically indeterminate. Then it is difficult to determine the interaction forces between the machine and its foundation in the supporting points. For shipboard machines and devices the minimum number of foundation chocks is usually four, but it often may be over a dozen, with main engines having as many as a few dozens of foundation chocks.

Comprehensive evaluation of a seating technology for ship machines and devices requires that both technical, economic and service factors are taken into account. The main technical task is to correctly arrange the machines and devices in space and in relation to cooperating objects, while providing reliable fixing which should guarantee their correct and safe operation. It is assumed that the unreliability of the seating cannot lead to additional overhauls of any machine throughout its service life onboard.

The evaluation of technical and economic aspects of a seating arrangement should include:

- Difficulty level of assembly and disassembly procedures;
- Labour and material costs;
- Time of execution of chock fitting and its quality;
- Stress state after the installation.

The following factors are important in service:

- reliability and durability of a seating arrangement;
- number and kind of required maintenance operations;
- good insulation against mechanical vibration and structural sound.

1.2. Seating the machines and devices on metal chocks

Metal chocks made of steel or cast iron, with their characteristic high rigidity, have been traditionally used in shipbuilding (Fig. 1.2a), hence the seating arrangements using them are called rigid. The load should be evenly distributed among all chocks (Fig. 1.1). To this end their suitable arrangement and fitting has been applied.

Resulting from high rigidity of metal chocks, little inaccuracies in their fitting may lead to a highly uneven loading of foundations, holding down bolts and the bodies of machines and devices. As this phenomenon is highly detrimental, demanding requirements have been introduced with regard to precision of fitting the chocks during the assembling of ship machines and devices [2]. It specially concerns main propulsion engines, gears and shaft line bearings. Fitting the metal foundation chocks in a way fulfilling the requirements has been a difficult, labour consuming and expensive task which includes the need of machining the supporting surfaces of the foundation on board, machining the chocks themselves and laborious, individual hand-fitting during assembling. Moreover, the seating on metal chocks is conductive to transmitting vibration and structural sound.

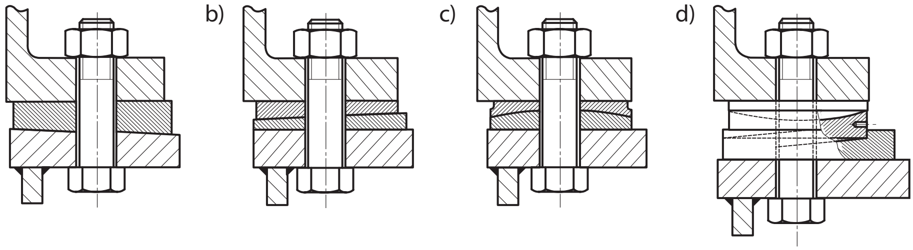


Fig. 1.2. Examples of ship machinery rigid seating arrangements: a) with a uniform metal chock; b÷d) with adjustable metal chocks

In order to simplify and shorten cycle of assembling and improve its accuracy, new, more effective solutions have been searched for. Special design solutions of compensation foundation pads have been developed [3] (Fig. 1.2b, c, d). Their application shortens the time of assembling machines and devices on board but only at the cost of a longer time of manufacturing the pads of a complicated form. Some of them (Fig. 1.2b, d) provide an easy adjustment of height of seated objects, other, with separating spherical surface (Fig. 1.2c, d) ensure a uniform distribution of pressure on the supporting surfaces of chocks owing to their ability of appropriate self-alignment in the direction of load action. All the adjustable metal chocks yield finally a rigid fixing of machines and do not introduce any significant changes into the static and dynamic system of machine-chock-foundation in comparison to the traditional seating arrangement based on uniform metal chocks. Another disadvantage of the adjustable foundation chocks is also greater number of their contact surfaces. The problem is going to be discussed in more detail below.

1.3. Seating the machines and devices on flexible chocks

The problem of noise and vibration has been steadily growing in importance since the beginning of mechanical propulsion of ships, and in the 1930s [4] it resulted in developing a new field of ship machinery foundation engineering when it was discovered that a way of joining the machines and their foundations plays an important role in the generation and propagation of vibration and noise through the ship. [5÷6]. As a consequence the so called flexible seating of machines and devices have been introduced. It consists in applying rubber chocks (pads) instead of traditional steel or elastic ones of special design solutions (Fig. 1.3) [7].

The flexible seating of ship machines and devices on board yields:

— more uniform distribution of loads exerted to chocks;

— a high degree of insulation of foundation against mechanical vibration and structural sound generated by the machines (up to abt. 90%), [5, 8];

— a high degree of insulation of machines and devices against kinematic excitations and deformations of foundations;

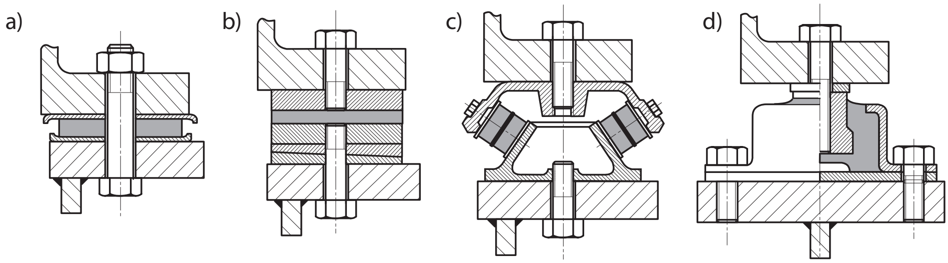


Fig. 1.3. Examples of flexible seating arrangements of shipboard machinery

— freedom for thermal deformations of the machinery bodies;
— possible application of lighter foundations.

The problem of the flexible seating of ship machines and devices is complex in its theoretical, technological and operational aspects [9÷15]. Solutions can be found by searching for such chocks and seating arrangement design which, in dynamic load conditions, would fulfil the assumptions for vibration and noise insulation, and ensure reliable and firm fixing for the seated objects. The problems posed by flexible seating concept have not been fully solved up so far. Practical implementation of flexible chocks requires to use both computational and experimental methods which generally do not guarantee that an optimum solution is achieved [16÷18].

The development of flexible seating arrangements for machines and devices strives for better calculation methods, manufacturing of materials with precisely defined elastic and damping properties as well as designing such chocks and their arrangements which would properly fulfil the task of insulating and damping mechanical vibration and structural sound [19÷24].

Application of special flexible chocks of complicated design raises the costs of seating considerably. There is an obvious tendency to maximizing quality indices of performance of machines and devices at the simultaneous lowering the costs and ensuring the comfort to the crew and passengers on board. Due to serious technical difficulties and high costs the flexible chocks are rather rarely applied to the seating of heavy shipboard machines and devices. An example of such seating applied to main engine is presented in Chapter 6, where the EPY resin compound was used for appropriate placing vibroisolators on engine foundation.

1.4. Seating the machines and devices on chocks cast of resin compounds

The progress of chemistry and material engineering which took place in the second half of 20th century provided many opportunities for developing special structural materials and technologies whose practical application resulted simultaneously in large technical, economic and operational benefits. An example of such materials are special chemically curing composites based on epoxy resins, which were developed for foundation chocks of ship machines and devices and many land based objects as well, requiring exact alignment and firm fixing.

Chemically curing compound of precisely defined properties continually improved in time proved to be almost ideal material for machinery foundation chocks. Their introduction to practical applications was decided first of all by the following factors:

— easy on-site casting of ready-made foundation chocks of any dimensions and shapes;

— good strength and operational characteristics of the hardened compound;

— significant reduction of time and cost of seating a machine or device on foundation.

Foundation chocks made of resin compounds, ready-cast directly under correctly positioned and aligned machine (Fig. 1.4), fill the entire space delimited for them between the foundation top and machine bedplate and ensure excellent fit with both contact surfaces.

Significant technical, economic and operational benefits resulting from application of new materials and modern assembling technology have been proved in practice and established a new standard for the seating of shipboard machines and devices [25÷30]. Its use is now worldwide, including Polish shipbuilding and repair yards. Owing to its numerous advantages this technology has been also wider and wider applied to the seating of many crucial land-based objects [31÷33].

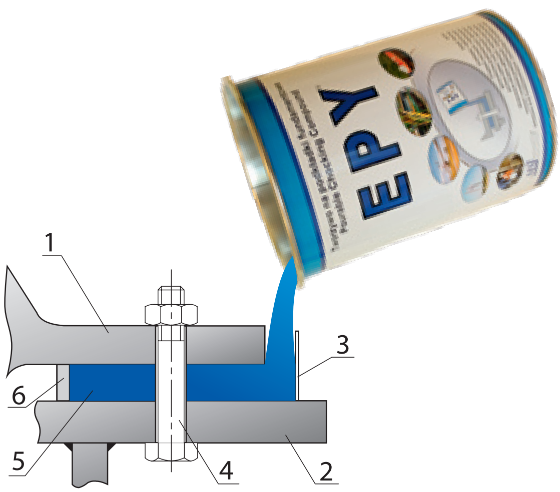


Fig. 1.4. Casting of a resin compound foundation chock: 1 — machine bed plate, 2 — foundation, 3 — face plate (sheet), 4 — holding down bolt, 5 — compound chock, 6 — mould barrier (foam)

1.5. Characteristics of seating arrangements based on metal chocks and cast resin compound chocks

In order to highlight the problems of the seating process and the progress in this field as far as used materials and methods are concerned, basic features of the traditional seating technology based on metal chocks will be discussed below in comparison to the modern one based on cast resin compound chocks.

The traditional way of seating heavy machines and devices on their foundations with the use of compensation metal chocks has a few important disadvantages, including:

— the necessity for exact machining of load-carrying surfaces of foundation plate and machine bedplate;

— the necessity of pre-machining metal chocks and difficult, laborious and time-consuming, individual fitting of chocks to the bearing surfaces of foundation and machine bedplate;

— high rigidity of metal chocks;

— small effective contact area between the chocks and foundation top and machine bedplate;

— low isolation against mechanical and acoustic vibration.

As a result of high rigidity (large value of the elasticity modulus E) small inaccuracies in fitting of metal chocks may result in occurrence of high assembling stresses and deformations in machine bodies and foundations. The stresses and deformations have a detrimental effect on the performance and life of machines and devices. Apart from the difficulty in obtaining adequate fitting, and the aforesaid high rigidity, another important disadvantage of metal chocks is their very small effective area of contact with bearing surfaces of machine bedplate and foundation top. Even with exact fitting of foundation chocks according to the relevant criteria [2], any unevenness of surfaces (roughness, wavy finish, shape errors) appearing after machining makes that the chocks get contact in separate, randomly distributed „points" (Fig. 1.5a), and the total effective contact area is only a small percentage of that nominal [34]. As a result of action of dynamic loads when the machine is running, micro-zones of effective contact suffer substantial plastic deformations which consequently result in the so called sagging of connected elements [35], loosening of holding bolts and "peening" of all the bearing surfaces of foundation, chocks and machine bedplate. Final consequences may be cracks in the foundation and the machine body, breaks of foundation bolts, unstable running of the machine, and failures [29].

Application of chocks of chemically curing resin compound, ready-cast in moulds which are made on metal or concrete foundation under the machine (Fig. 1.4) placed in its service position, eliminates many operations, simplifies the assembling process and shortens it considerably. Apart from a rough cleaning and degreasing of foundation plate surface no other special preparation is required for it. Existence

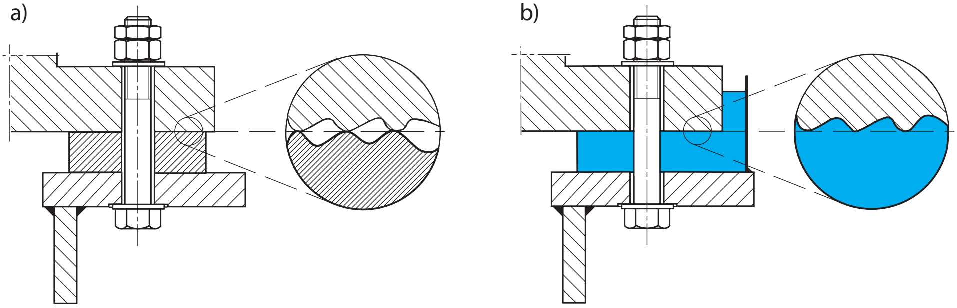


Fig. 1.5. Schematic drawings of a foundation bolt joint: a) with metal chock; b) with cast resin compound chock

of unevenness, corrosion pits and not exactly parallel position of surfaces, which make the application of traditional metal chocks difficult or impossible, is of no importance in case of cast resin compound chocks are used.

The chocks ready-cast under the machine according to an appropriate technology, tightly adhere to the load — carrying surfaces of the machine and its foundation [25, 26, 36]. They fill all uneven areas on the contact surfaces (Fig. 1.5b). It is a specific case of a joint in which the effective contact area is larger than nominal. This ensures a favourable distribution of normal pressure over the contact surfaces of joined elements and a high value of effective friction factor (close to 1 or even greater), which have a favourable effect on the transferring of forces tangential to supporting surfaces.

Resin compound chocks dampen vibration better and form a substantial barrier against transferring the so called structural sound [37÷40]. On the chock contact surfaces neither fretting corrosion nor peeling and other wear phenomena occur.

2 Resin compounds used for ship machinery foundation chocks

2.1. General requirements concerning resin compounds used for foundation chocks

Attempts to rationalise the assembly work, improve the quality and shorten installation time of ship machinery by using various adjustable or flexible chocks (described in Ch. 1) did not enter the shipyard practice on a larger scale, especially with regard to main engines. The traditional seating method with the use of metal chocks (made of steel or cast iron) began to fade away only when special chemically-curing resin compounds were developed (in the early 1960s) together with the cast-in-place technology which allowed foundation chocks to be made directly under already aligned machines. The first resin compound called Chockfast was developed by the Philadelphia Resins Corp. (USA) and its name directly implies a "fast foundation chock". The first main ship propulsion engine was seated on "Chockfast" foundation chocks during repair work in 1963 (USA). The new method of seating the machines and devices on the cast resin compound chocks quickly gained recognition due to its numerous advantages and began entering shipyard practice not only in ship repair but also building new ships. The Chockfast compound is now manufactured in a number of kinds, and the one, named Chockfast Orange became especially popular for the seating shipboard machines and devices.

The requirements for the resin compounds used for foundation chocks of ship machines and devices are numerous, varied and difficult to satisfy, especially in case of main engines, gears, shaftline bearings and other machinery requiring accurate alignment. The fact that currently only three such compounds obtained widespread recognition of worldwide classification societies and ship engine manufacturers and entered practical use in shipbuilding is the best confirmation of the above. Apart from the American compound Chockfast Orange and the German compound Epocast 36, only Polish compound named EPY produced by Marine Service Jaroszewicz Co (MSJ) with the use of only domestic raw materials, has found widespread application. In the last decade of 20th century a new resin compound named "Loctite 7202 Marine Chocking", produced by Henkel, intended for foundation chocks of machines and devices, appeared on the market. The compound has been approved by American Bureau of Shipping, Bureau Veritas, Det Norske

Veritas, Lloyd's Register and Germanischer Lloyd for the seating of main engines and auxiliary devices on sea-going ships.

Marine Service Jaroszewicz Co has been cooperating for many years with the manufacturers of the Chockfast compound (ITW Philadelphia Resins, USA) and the Epocast compound (H.A. Springer marine + industrie service GmbH, RFN, belonging presently to ITW Philadelphia Resins, USA) and is authorized to carry out seating work by using the compounds of their production. Since 2012 the MSJ is also authorized to carry out the seating of machines and devices with the use of the Loctite 7202 compound (of Henckel).

Development of a resin compound for foundation chocks required finding solution to many complex problems concerning its composition, design and casting technology of chocks, assembling and operation of machines. Moreover, many psychological and formal barriers put up by classification societies, engine manufacturers, ship owners, ship designers and shipyards had to be overcome, as it was a common view that the material of higher strength is a better structural material. Such reasoning may be correct but not always, and there are cases when it is downright mistaken. In case of foundation chocks, resin compounds, despite their much lower compression strength, proved to be a much better structural material than steel or iron. Basic requirements concerning the compounds for foundation chocks are determined in the relevant rules of classification societies [41÷43]. In liquid state the compounds should have no air content and good castability, and low shrinkability during curing. When cured, they should have low creep and high static and fatigue strength under compression.

A characteristic feature of chock compounds, very important for practice, is their reactivity [42], which influences the run of the chock curing process and its peak temperature value. It depends on temperature of the compound when cast into the mould, ambient temperature, mass and shape of the chock and local heat transfer conditions. Higher curing temperature yields a higher degree of cross-linking of compound and the resulting chocks have better mechanical properties: higher strength, hardness and better resistance to creep. Compounds of higher reactivity can have lower minimum temperature during casting the chocks.

Compounds of low reactivity cannot ensure good cross-linking in chocks at lower ambient temperatures even in circumstances of high thermal capacity and good thermal conductivity of foundation and machine bedplate. On the other hand, too high reactivity may result in appearance of high casting stresses in the chock and large shrinkage during the process of curing. Total shrinkage is an effect of changes in volume, resulting from the chemical curing reaction and a thermal contraction induced by a drop of the chock temperature from the peak value of the exothermal curve to the ambient temperature. Knowledge of exothermal properties of a given compound is thus necessary to determine important details of seating technology such as, e.g., minimum and maximum ambient temperatures during casting, desired temperature of compound when cast into the mould, minimum and maximum thickness of chocks, and curing time in function of ambient temperature.

Foundation chocks are in constant contact with wet air, grease, fuel and water, so they must be resistant to ageing in such conditions and elevated temperature. How the foundation chock behaves during service is first and foremost dependent on the operational temperature and pressure exerted on it.

Temperature of the chocks under ship main engines may in some circumstances reach 80°C, so the chock must have adequate resistance to creep, which is in turn a limiting factor for maximum admissible pressure. The unavoidable process of compound creeping should cause a possibly low drop in chock height, which should almost stop after a relatively short time. This is the reason why admissible pressure on foundation chocks under main engines is limited to only 5 MPa, while the ultimate compressive strength of compounds may reach even 150 MPa. Application of compounds to foundation chocks for the seating of ship machines and devices requires approval from the side of ship owner, machinery manufacturers and the classification societies supervising construction of the ship.

Obtaining the approval certificates from the side of the classification societies is based on the results of appropriate laboratory and service tests. It is further required due to specific features of such tests that they are carried out in a recognised laboratory under the supervision of their surveyors or in the own laboratory of a given classification society.

The requirements of various classification societies differ with regard to the kinds of tests and the way they should be carried out, as well as to approval criteria. They are numerous and varied [41÷43]. For instance Germanischer Lloyd [43] requires that the following parameters of a compound under investigation are to be determined:

— longitudinal modulus of elasticity (in compression) acc. ISO R 604;
— surface hardness in Barcol degrees (°B) acc. EN 59;
— tensile strength acc. ISO 527;
— compressive strength acc. ISO 604;
— shear strength acc. ASTM D732;
— bending strength acc. ISO 178;
— impact strength (Izod method) acc. ISO 180;
— shrinkage acc. ASTM D2566 or DIN 53464;
— flame propagation velocity acc. ASTM D635 and ISO R 1210;
— settling under load acc. ASTM D621; for foundation chocks: sample loading time (h): 24; test temperature (°C): –30/+23/+50/+70/+100; pressure to be exerted (N/mm^2): 3.5/7/14/28;
— longitudinal thermal expansion coefficient (1/K) acc. DIN 53752;
— friction coefficient against steel: for a cast and machined sample with the use of an anti-adhesive agent and without it;
— curing time in various temperatures;

— thermal resistance acc. ISO 75;
— resistance to oils, petrol and other agents acc. ISO 175;
— As well as other parameters on request of the society.

Moreover in the referred to GL rules [43] there are many different additional conditions to be satisfied in order to obtain a relevant certificate for the application of a given compound in shipbuilding industry.

The classification societies, for issuing or extending the certificate, often require to perform many repeated or additional tests carried out in strictly defined conditions. For instance, Lloyd's Register of Shipping (LR) has required to perform vast and expensive tests on EPY compound in order to extend the certificate. The tests were done in the laboratory of the Chair of Mechanics and Machine Elements, West-Pomeranian University of Technology, Szczecin in 2012, under the strict supervision of LR surveyor. The run and results of the tests were presented in the relevant report [44] submitted to LR classification society.

In 2009 EU Parliament and Council replaced the former Directive 94/57 by the new decree (EC) No 391/2009, concerning harmonization of common principles and standards used by supervision organizations carrying out inspection and testing the ships [45]. The decree, in its Article 10, puts the duty of carrying out regularly mutual consultations, on the supervision organizations recognized by the EU (Recognised Organisations, shortly called RO's) in order to maintain equivalence of their requirements while tending to uniform the used principles and procedures and ways of their implementation.

The decree entered in force on 1st January 2013. According to it, any products (i.e. materials, equipment elements or device components on board a ship) which have passed certification procedures and obtained the approval certificate for a given product (called: EU RO Mutual Recognised Type Approval Certificate, shortly: EU RO MR TAC), can be installed on all ships without offending rights of a state whose flag a ship flies. It practically means that the approval certificates for a given product, formally obtained from one of the EU recognized organizations, should be obviously respected by any other organization recognized by EU. Any refusal to respect such certificate should be justified.

The recognized organizations are obliged to harmonize technical and procedural conditions for mutual recognition of certificates for selected products. The conditions should take into account the equivalent requirements based on the most stringent and rigorous ones.

As the certification procedures are new for all EU recognized organizations, all the products for which a new certification procedure has to be performed, have been divided into certain groups. The term of certification to be performed has to be dependent on that to which group a given product belongs. 11 products including resin compound for machine foundation chocks (Resin chocks code 13350000) were classified to the first group (marked TR1), for which the new certification entered in force by 1st January 2013. For the 11 products, the comprehensive procedural and technical requirements which are to be satisfied to obtain the certificate for a given product, respected by all EU recognized organizations, are formulated in the document "EU Mutual Recognition Technical Requirements" (p. 12.8), [46]. There are today 12 organizations which concluded a relevant mutual agreement and have been recognized by EU, namely:

— American Bureau of Shipping ("ABS"), 16855 Northchase Drive, Houston, TX 77060, USA;
— Bureau Veritas ("BV"), 67-71, boulevard du Château, 92200 Neuilly-sur-Seine, France;
— China Classification Society ("CCS"), 9 Dongzhimen Nan Da Jie, Beijing, 100007 China;
— Det Norske Veritas ("DNV"), Veritasveien 1, 1363 Hovik, Oslo, Norway;
— Germanischer Lloyd ("GL"), Brooktorkai 18, 20457 Hamburg, Germany;
— Korean Register of Shipping ("KR"), 36, Myeongji ocean city 9-ro, Ganseo-gu, Busan, Seoul 618-814, Rep. of Korea;
— Lloyd's Register Group Ltd ("LR"), 71 Fenchurch Street, London EC3M 4BS; UK;
— Nippon Kaiji Kyokai ("NK"), 4-7 Kioi-cho, Chiyoda-ku, Tokyo 102-8567, Japan;
— Polski Rejestr Statków S.A. ("PRS"), Al. gen. Józefa Hallera 126 80-416 Gdańsk, Poland;
— RINAVE – Registro Internacional Naval SA ("Rinave"), X1Pólo Tecnológico de Lisboa, Lote 21, 1600-485 Lisboa, Portugal;
— RINA, Via Corsica 12, Genova, Italy;
— Russian Maritime Register of Shipping ("RS"), 191186 St. Petersburg, 8, Dvortsovaya Nab., Russian Federation.

In order to obtain, for a given compound intended for machine foundation chocks, a common certificate (EU MR TRC) issued by the above mentioned organizations it is necessary to submit relevant documentation to one of them. In the submitted documentation many various data concerning a given compound, strictly defined in p. 12.8 (under heading: Resin chocks) of the above mentioned document [46], are to be included. In particular in the technical data concerning the resin compound in question the results of material tests performed in compliance with the below given standards and recommendations, are to be included:

— ASTM D 696-ISO 604 (compressive strength, modulus of elasticity);
— ASTM D 638-ISO 527 1,2,4,5 (all – in relevant cases) (tensile strength, modulus of elasticity),
— ASTM D 621-ISO 75-2 (deflection under load),
— ASTM D 256-ISO 180 (impact strength acc. Izod),
— EN 59, wcześniej ASTM D 2538 (hardness acc. Barcol),
— ASTM D4065, former ASTM D 2236 – DIN53445 0-ISO 6721-1 (shear modulus, logarithmic decrement);

— ASTM D 790-ISO 178-ISO 14125 in relevant cases (bending strength, maximum deflection);
— ASTM D 2566 (WITHDRAWN) – ISO 3521 (linear shrink during curing);
— ASTM D 635 – FTP Code, Annex 1, Part V (compound flammability, propagation of flame);
— DIN 50100 (compression fatigue test);
— DIN 53481 (dielectric resistance);
— DIN 53428 (insulating resistance);
— ISO 3521 or equivalent one (volumetric shrink);
— ISO 11357, ISO 11359 or equivalent one (vitrification temperature);
— ISO 1675 or equivalent one (density);
— EN 1465 (shear strength of lap joint under tensile load);
— ASTM D 732 (shear strength);
— DIN 53752 (thermal expansion coefficient);
— ISO 175 (resistance to action of various agents, oil and water);
— coefficient of friction against steel for machined sample cast with and without an anti-adhesive agent (its kind is to be determined);
— resistance to creeping;
— determination of exothermic curve.

Notion:
Use of other standards may be also approved provided they are not less effective (stringent). The tests must be carried out in laboratories recognized by a given society or in presence of its surveyor. Samples should be taken from production line or resources of a resin compound provider. Test conditions are to be given by the provider.

Foundation chocks can be cast only by firms authorized by the manufacturer of a given resin compound with maintaining the limiting conditions required for a given process. Such authorization which confirms that the personnel conducting chock casting process has been appropriately trained by the compound manufacturer, is to be submitted to a local surveyor on her/his request.

2.2. Development of Polish resin compounds for foundation chocks and relevant technology of seating machines and devices

Polish shipbuilding industry striving for freeing itself from the costly import of compounds and seating services from Western countries approached the Technical University of Szczecin in 1969 with the initiative to commence research on development of own (domestically made) chemically curing compounds for foundation chocks, and the relevant, based on the compounds, technology of seating ship machines and devices. As a result, the resin compounds marked EP-551, EP-571 and EP-578 were developed and tested by the Technical Mechanics Division of Technical University of Szczecin. Soon after that they obtained the approval of the Polish Register of Shipping and were introduced as a practical seating method in Polish shipbuilding industry. The authors of these developments were: J. Lorkiewicz (DEng), K. Grudziński (DEng) and W. Jaroszewicz (MScEng). The first shipboard seating operations were performed by the Technical University of Szczecin in 1974, on board the training-cargo motor ship “Kapitan Ledóchowski” (Fig. 2.1). The scope of the work comprised the seating of an electric generating set and three pumps in the ship’s engine room on foundation chocks made of EP-551 compound.

The developed compound and seating technology based on it passed successfully practical exam and began to be introduced step by step to machine seating practice in Polish shipbuilding and ship repair yards. The first operation of the seating of a main propulsion engine (HCP-Sulzer 6AL25/30) on foundation chocks made of EP-551 compound was performed by Szczecin Shipyard on the ferry ship “Karsibor I” (Fig. 2.2a) in November 1976. The engine together with the electric generator driven by it was assembled on a common frame and next the whole unit was seated on its foundation with the use of chocks cast of the resin compound (Fig. 2.2b, c).

More detailed information on conducted research, properties of developed compounds and the machinery seating technology based on these compounds as well as kinds and number of seating operations until 1984 are given in the publications [25÷26].

Since 1978 seating operations have been carried out by specialized teams authorized by the Technical University of Szczecin, which operated within:

Fig. 2.1. The training/cargo motor ship „Kapitan Ledóchowski” on which the first auxiliary machine was seated on the foundation chocks made of the resin compound developed by the Technical University of Szczecin

a)

b)

c)

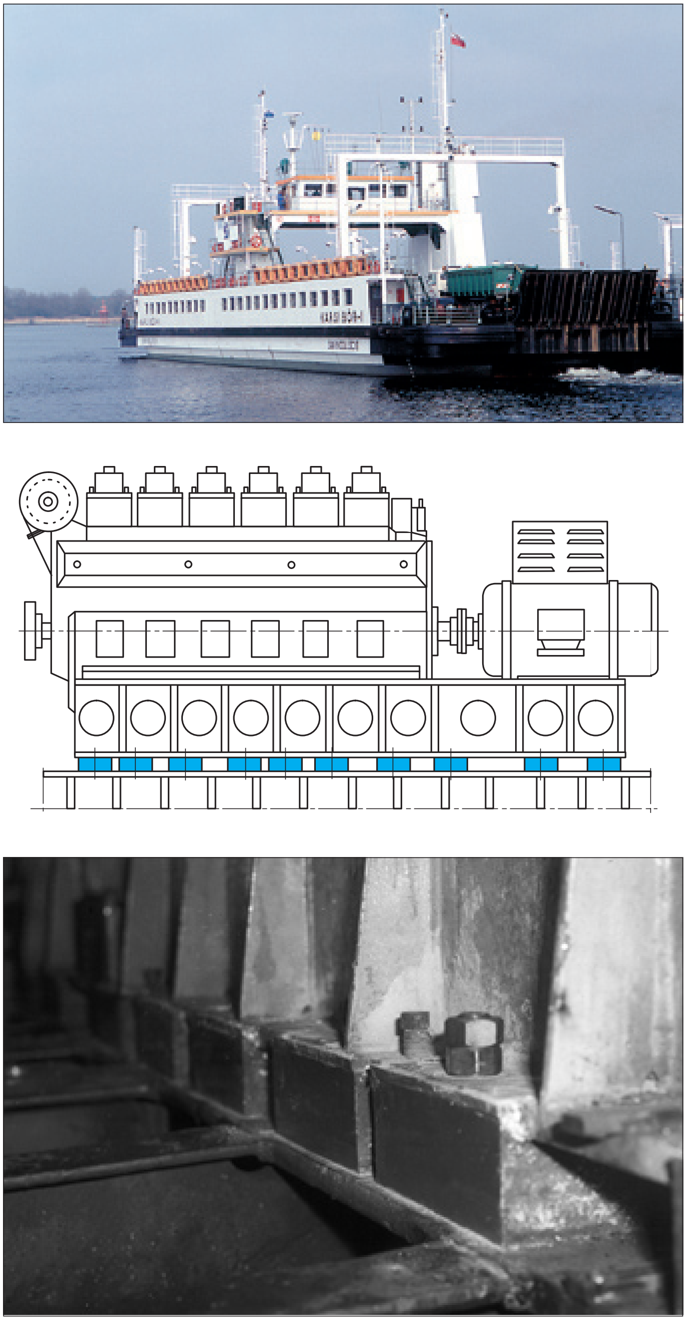


Fig. 2.2. The first main propulsion engine installed on foundation chocks made of Polish resin compound, aboard the ferry ship „Karsibór I": a) overall view of the ferry; b) layout of the seated machine; c) view of the foundation chocks cast of resin compound

— Morska Stocznia Remontowa (Maritime Ship Repair Yard) in Świnoujście (its director was then Mr P. Soyka (MScEng) and the head of installation team — Mr S. Kownacki (MScEng));

— Przedsiębiorstwo Robót Malarskich i Izolacyjnych (Painting and Insulation Works) "Malmor" in Gdańsk (its director was then Mr W. Symoni (Eng) and the head of installation team was A. Adamkiewicz (MScEng));

— Przedsiębiorstwo Zagraniczne(Foreign Company) "KITI" in Poland, sited in Warsaw (its director was then Mr A. Łuba (MScEng), and the head of installation team — W. Jaroszewicz MScEng)).

In parallel with the implementation work, research and development projects on the improvement of the properties of compounds and the machinery seating technology as well as design, modeling and calculation of foundation joints based on holding down bolts, were carried out by the Technical University of Szczecin. The projects were carried out within the framework of the so called "crucial problems" in close cooperation with Szczecin Shipyard, Centrum Techniki Okrętowej (Ship Design and Research Centre — CTO) and Centrum Techniki Wytwarzania (Production Engineering Centre — CTW) "Promor" in Gdańsk, Instytut Podstawowych Problemów Techniki Polskiej Akademii Nauk (Institute of Fundamental Engineering Problems, Polish Academy of Sciences — IPPT PAN) in Warsaw as well as the above mentioned companies conducting seating operations.

An especially important role in the initiation and execution of many research projects was played by Serwis Posadawiania Maszyn (Machinery Installation Service Team) operating within PZ "KITI". The team was managed by Mr W. Jaroszewicz (DEng), a former scientific worker of the Technical University of Szczecin (since 1972), who was involved in this field from the beginning of his scientific research activity. His work was awarded in 1980 with the degree of Doctor in Engineering Sciences on the basis of the thesis titled "Foundation chocks made of chemically curing compounds for the seating of ship main engines and auxiliary devices". The promoter of this work was Mr K. Grudziński (DEng), Ass. Prof., and the reviewers were E. Skrzymowski (DEng), Ass. Prof., and Mr T. Gerlach, Prof.

Having been in chargé of the Machinery Installation Team within PZ "KITI" since 1982, Mr W. Jaroszewicz has not only conducted broad range of services for the shipbuilding industry but also actively participated in research and development projects carried out by the Chair of Mechanics and Machine Elements of the Technical University of Szczecin. The research projects in this area have been carried out by a team including: Mr J. Lorkiewicz (DEng), Mr W. Jaroszewicz (DEng), Mr L. Łabuć (DEng), Mr R. Kawiak (DEng), Mr L. Tuczyński (Eng), and Mr J. Markiewicz, under supervision of Mr K. Grudziński (DEng), Ass. Prof. The doctorate thesis of Mr R. Kawiak [47] (concerning problems of modeling and calculation of foundation bolt joints), the patents [48÷50] as well as a new, improved type of Polish chocking compound (EPAX) were among the results of these projects. This new compound as well as the technology for seating ship machines and devices, based on it have been granted approval certificates from classification societies and ship engine manufacturers. Seating operations with the use of this compound have been performed on many ships built or repaired in Polish shipyards for many overseas ship owners under the supervision of various classification societies such as: Polish Register of Shipping (PRS), Lloyd's Register (LR), Germanischer Lloyd (GL), Bureau Veritas (BV), Det Norske Veritas (DNV), Maritime Register of Shipping (MRS).

In July 1986 in Gdynia Shipyard four 16ZV40/48 Zgoda Sulzer engines, each rated at 10 000 HP were installed aboard the m/f "Stena Germanica" (Fig. 2.3) by using foundation chocks of EPAX resin compound. In Gdańsk Shipyard the first main propulsion engine (6L40/48 Zgoda-Sulzer engine of 4500 HP rated power) was seated on EPAX compound chocks aboard the m/t "Dalmor" in October 1986. As far as Szczecin Shipyard is concerned, the first large main engine (6L50MCE HCP-MAN/B&W engine of 5181HP rated power) was seated on EPAX compound chocks aboard the m/s "Kopalnia Halemba" in June 1990.

In 1989 Mr W. Jaroszewicz took over the Machinery Installation Service Team from PZ "KITI" and started his own commercial company rendering seating services from its site in Szczecin. A new resin compound, version named EPY, was then introduced to seating work. Its chemical content ensures fast and effective curing at a very low shrinkage without emission of by-products.

The properties of the compound stand equal in any respect to those of other modern resin compounds offered by the specialized companies from Western countries. This applies in particular to the American compound Chockfast Orange and the German compound Epocast 36. On the basis of contracts signed with the H.A. Springer

Fig. 2.3. The passenger / car ferry ship "Stena Germanica" with main propulsion engines seated on EPAX compound chocks

marine + industrie service GmbH (in August 1995) and the ITW Philadelphia Resins (in July 2001), MSJ Company is now an exclusive provider of Epocast and Chockfast compounds and authorized executor of machinery seating operations in Poland, Estonia, Russia, Czech Republic, Lithuania, Latvia, Slovakia and Ukraine.

Some more important properties of Polish compound EPY against the comparative values of the above mentioned foreign compounds, are presented in Tab. 2.1. The EPY compound has been approved by the worldwide recognized ship engine manufacturers and classification societies as equivalent to the Chockfast Orange and Epocast 36, offered by Western companies (currently incorporated in Illinois Tools Works, ITW). The EPY compound has also the approval certificates of relevant domestic institutions which allow for its use in building of roads and bridges as well as the seating of mining machines and facilities. The list of institutions and engine manufacturers which issued their approval certificates for EPY compound is given in Tab. 2.2. Copies of the certificates are presented on pp. 34÷42.

A vast number of separate certificates for the compounds intended for machinery foundation required by various organizations supervising shipbuilding and ship repair operations, ship machinery manufacturers as well as other institutions is a serious technical, organizational and financial problem, for the reason of non-equivalent requirements. Therefore, EU Parliament has undertaken an appropriate action aimed

Table 2.1. Basic properties of compounds used for machinery foundation chocks

Parameter	Testing method according to	Compound			
		EPY[1]	Chockfast Orange[2]	Epocast 36[3]	Loctite 7202[4]
Compressive strength, MPa	ASTM D-695	150	131	164	152
Modulus of elasticity, MPa	ASTM D-695	4255	3677	5610	—
Tensile strength, MPa	ASTM D-638	54.9	34.2	49.4	37.9
Shear strength, MPa	FED-STD-406 (Method 1041)	59.1	37.3	—	—
Hardness, °B	ASTM D-2583	49.8	40 (min. 35)	55	—
Density, kg/m^3	EN ISO 1183-1	1570	1580	1640	—
Curing time in relation to temperature, h	—	24 h at 20°C 48 h at 15°C	24 h at 21°C 48 h at 15°C	24 h at 21°C 48 h at 16°C	24 h at 21°C 35 h at 15°C

[1] http://www.epyresin.eu/2/produkty/pokaz_prace.php?id=145, access 10.02.2013.
[2] http://www.chockfast.com/2011pdf/659H_Chockfast-Orange.pdf, access 10.02.2013.
[3] http://www.epocast.com/tech-bull/ep36.pdf, dostęp 10.02.2013.
[4] http://www.loctite-glue.com/sg_obrazki_/00030230_zalac_001.pdf, access 10.02.2013.

Table 2.2. List of institutions and ship engine manufacturers who issued their approval certificates for EPY compound

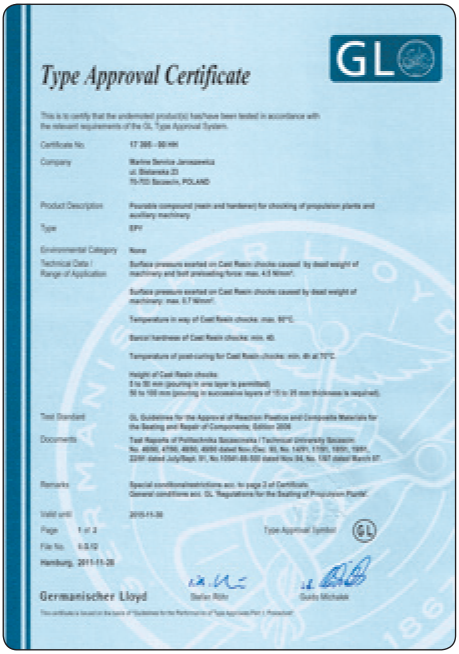
№	Certificate	Certificate no.	Date of issue	Remarks
1	American Bureau of Shipping	02-LD293860-2-PDA	18.03.1997	p_{max} = 15 MPa, T_{max} = 80°C
2	Bureau Veritas	03626/E0 BV	16.11.1989	p_{max} = 5 MPa, T_{max} = 80°C
3	Bureau Veritas	SMS.W.II/1193/C.0	14.02.1995	Company certificate
4	Det Norske Veritas	M-11625	23.10.2006	p_{max} = 5 MPa, T_{max} = 80°C
5	Germanischer Lloyd	17 395-00 HH	20.12.1991	p_{max} = 5 MPa, T_{max} = 80°C
6	Germanischer Lloyd	50 652-03 HH	18.12.2003	Annexe 31GL
7	Germanischer Lloyd	QS-244 HH	20.07.1994	ISO 9001:2008
8	H.A. Springer marine + industrie service	EB/Ba	02.10.2001	Contract of 28.09.2001
9	Polish Road & Bridge Research Institute	AT/2006-03-0018	21.12.1994	Permissible calculated load
10	Polish Institute of Maritime and Tropical Medicine	PB/251/348/99	08.10.1999	Health certificate
11	Polish Building Research Institute	AT-15-4824/2007	28.02.2001	Permissible calculated load
12	IQNet The International Certification Network	RU-11.0823.026	01.09.2005	ISO 9001:2008
13	ITW Philadelphia Resins	7/09/01	07.09.2001	Contract of 25.06.2001
14	Lloyd's Register	MATS/526/3	12.03.1990	p_{max} = 5 MPa, T_{max} = 80°C
15	MAN-B&W Diesel AG	0343/95	12.06.1995	p_{max} = 5 MPa, T_{max} = 80°C
16	MAN-B&W Diesel AG	0604/95	06.11.1995	p_{max} = 5 MPa, T_{max} = 80°C
17	MAN Diesel & Turbo	1300/BHN/INR/253	25.03.1996	p_{max} = 5 MPa, T_{max} = 80°C
18	New Sulzer Diesel Ltd	7056 M. Lüthi/bg	08.07.1996	p_{max} = 5 MPa, T_{max} = 80°C
19	Polish Register of Shipping	TM/1124/800002/10	06.04.1990	p_{max} = 5 MPa, T_{max} = 80°C
20	Polish Register of Shipping	TM/1125/842502/10	31.05.2004	Company certificate
21	Registro Italiano Navale	MAC136612XG	15.07.1999	p_{max} = 5 MPa, T_{max} = 80°C
22	Registro Italiano Navale	2010 XP 74	01.04.2010	Company certificate
23	Russian Maritime Register of Shipping	11.00477.258	20.07.2006	p_{max} = 5 MPa, T_{max} = 80°C
24	Russian Register Certification System	11.0823.026	15.12.2000	ISO 9001:2008
25	Russian Maritime Register of Shipping	10.00271.258	18.08.2005	Company certificate
26	State Transport Control Authority	7 2229 207 2011 Q	14.01.2008	PN-EN ISO 9001:2009
27	Wärtsilä NSD Co.	465.942	04.05.2000	p_{max} = 5 MPa, T_{max} = 80°C
28	State Mining Authority	GM-127/95	10.04.1996	Permissible calculated load
29	Principal Mining Research Institute	B/2347/2012	10.04.1996	Permissible calculated load
30	Russian River Register	13716	03.09.2010	Company certificate
31	Russian River Register	SZF K 12-10	12.08.2010	Permissible calculated load
32	Internal Market Harmonization Office	009213117	18.03.2011	Registration Certificate for EPY
33	Russian Federation Defence Ministry	236/331/1862	26.06.2013	WMF FR Approval for EPY
34	Russian Maritime Register of Shipping	14.09099.381	04.02.2014	EU RO MR DEC
35	Russian Maritime Register of Shipping	14.09101.381	25.02.2014	EU RO MR TAC


ABS
CERTIFICATE OF
DESIGN ASSESSMENT
This is to Certify that a representative of this Bureau did, at the request of
Marine Service Jaroszewicz - Szczecin
PRODUCT Epoxy Resin
MODEL EPY
AMERICAN BUREAU OF SHIPPING


TYPE APPROVAL CERTIFICATE
MARINE SERVICE JAROSZEWICZ S.C.
POURABLE COMPOUNDS FOR ENGINE CHOCKING


RECOGNITION FOR
BV MODE II SCHEME
MARINE SERVICE JAROSZEWICZ S.C.
Szczecin - POLAND


DNV
DET NORSKE VERITAS
TYPE APPROVAL CERTIFICATE
Marine Service Jaroszewicz S.C.



Type Approval Certificate

GL

This is to certify that the undernoted product(s) has/have been tested in accordance with the relevant requirements of the GL Type Approval System.

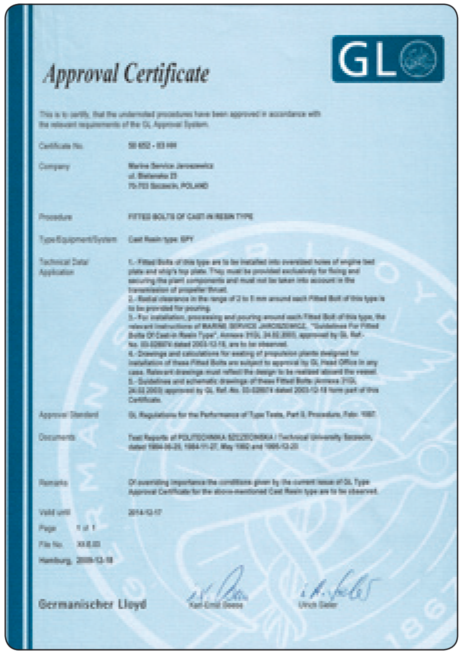
Certificate No. 17 395 - 00 HH

Company: Marine Service Jaroszewicz, ul. Bielańska 23, 70-703 Szczecin, POLAND

Product Description: Pourable compound (resin and hardener) for chocking of propulsion plants and auxiliary machinery

Type: EPY

Germanischer Lloyd



Approval Certificate

GL

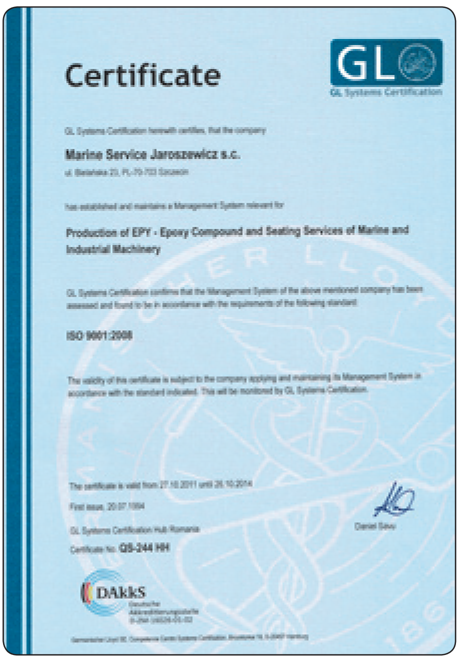
This is to certify, that the undernoted procedures have been approved in accordance with the relevant requirements of the GL Approval System.

Company: Marine Service Jaroszewicz, ul. Bielańska 23, 70-703 Szczecin, POLAND

Procedure: FITTED BOLTS OF CAST-IN RESIN TYPE

Type/Equipment/System: Cast Resin type: EPY

Germanischer Lloyd



Certificate

GL
GL Systems Certification

GL Systems Certification herewith certifies, that the company

Marine Service Jaroszewicz s.c.

has established and maintains a Management System relevant for

Production of EPY - Epoxy Compound and Seating Services of Marine and Industrial Machinery

GL Systems Certification confirms that the Management System of the above mentioned company has been assessed and found to be in accordance with the requirements of the following standard

ISO 9001:2008

Certificate No. QS-244 HH

DAkkS

H. A. SPRINGER marine + industrie service GmbH

MARINE SERVICE JAROSZEWICZ
Attn. Dr. Ing. W. Jaroszewicz
ul. Bielańska 23
70-703 Szczecin
POLEN

EPOCAST 36®
EPOCAST 36-P
CELLOFLEX

CERTIFICATE

We herewith certify that the contact person listed below and the persons named on the enclosed identity card list are employed by

MARINE SERVICE JAROSZEWICZ

They have received training in the application of EPOCAST 36 and are authorized by us to carry out and to supervise the installation of EPOCAST 36 and EPOCAST D on board of ships.

Contact person : Dr. Ing. W. Jaroszewicz

H.A. Springer
marine + industrie
service GmbH

INSTYTUT BADAWCZY DRÓG I MOSTÓW
03-302 Warszawa, ul. Instytutowa 1
tel. sekretariat: 22 814 50 25, fax: 22 814 50 28

Warszawa, 10 października 2012 r.

APROBATA TECHNICZNA IBDiM
Nr AT/2006-03-0018/1

Na podstawie § 16 pkt 2 rozporządzenia Ministra Infrastruktury z dnia 8 listopada 2004 r. w sprawie aprobat technicznych oraz jednostek organizacyjnych upoważnionych do ich wydawania (Dz. U. Nr 249, poz. 2497 ze zm.), po przeprowadzeniu postępowania aprobacyjnego, którego wnioskodawcą jest producent o nazwie:

Marine Service Jaroszewicz s. c.

z siedzibą: ul. Bielańska 23, 70-703 Szczecin

Instytut Badawczy Dróg i Mostów
stwierdza pozytywną ocenę techniczną i przydatność wyrobu budowlanego:

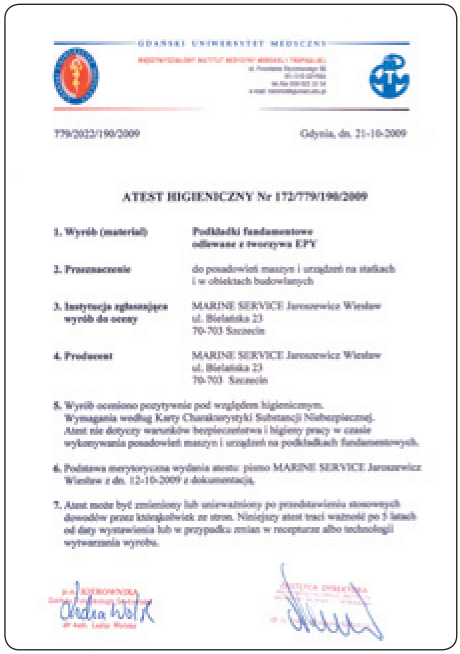
Zaprawa epoksydowa do podlewek i zakotwień

o nazwie handlowej: EPY

do stosowania w budownictwie - w inżynierii komunikacyjnej - w zakresie stosowania i przeznaczenia oraz przy spełnieniu warunków podanych w niniejszej Aprobacie Technicznej IBDiM.
Instytut Badawczy Dróg i Mostów dla wyżej wymienionego wyrobu budowlanego wskazuje obowiązujący system 2+ oceny zgodności.

DYREKTOR
prof. dr hab. inż. Leszek Rafalski

Data wydania Aprobaty Technicznej: 02 lipca 2011 r.
Data utraty ważności Aprobaty Technicznej: 02 lipca 2016 r.



GDAŃSKI UNIWERSYTET MEDYCZNY

779/2022/190/2009 Gdynia, dn. 21-10-2009

ATEST HIGIENICZNY Nr 172/779/190/2009

1. Wyrób (materiał): Podkładki fundamentowe odlewane z tworzywa EPY
2. Przeznaczenie: do posadowień maszyn i urządzeń na statkach i w obiektach budowlanych
3. Instytucja zgłaszająca wyrób do oceny: MARINE SERVICE Jaroszewicz Wiesław, ul. Bielańska 23, 70-703 Szczecin
4. Producent: MARINE SERVICE Jaroszewicz Wiesław, ul. Bielańska 23, 70-703 Szczecin
5. Wyrób oceniono pozytywnie pod względem higienicznym. Wymagania według Karty Charakterystyki Substancji Niebezpiecznej. Atest nie dotyczy warunków bezpieczeństwa i higieny pracy w czasie wykonywania posadowień maszyn i urządzeń na podkładkach fundamentowych.
6. Podstawa merytoryczna wydania atestu: pismo MARINE SERVICE Jaroszewicz Wiesław z dn. 12-10-2009 z dokumentacją.
7. Atest może być zmieniony lub unieważniony po przedstawieniu stosownych dowodów przez którąkolwiek ze stron. Niniejszy atest traci ważność po 5 latach od daty wystawienia lub w przypadku zmian w recepturze albo technologii wytwarzania wyrobu.

INSTYTUT TECHNIKI BUDOWLANEJ
PL 00-950 WARSZAWA, ul. FILTROWA 1

Seria: APROBATY TECHNICZNE

APROBATA TECHNICZNA ITB
AT-15-4824/2007

Na podstawie rozporządzenia Ministra Infrastruktury z dnia 8 listopada 2004 r. w sprawie aprobat technicznych oraz jednostek organizacyjnych upoważnionych do ich wydawania (Dz. U. Nr 249 z 2004 r., poz. 2497), w wyniku postępowania aprobacyjnego dokonanego w Instytucie Techniki Budowlanej w Warszawie na wniosek firmy

MARINE SERVICE JAROSZEWICZ
70-703 Szczecin, ul. Bielańska 23

stwierdza się przydatność do stosowania w budownictwie wyrobu pod nazwą

TWORZYWO CHEMOUTWARDZALNE
EPY

w zakresie i na zasadach określonych w Załączniku, który jest integralną częścią niniejszej Aprobaty Technicznej ITB.

Termin ważności:
29 marca 2012 r.

Załącznik:
Postanowienia ogólne i techniczne

DYREKTOR
Instytutu Techniki Budowlanej
doc. dr inż. Stanisław M. Wierzbicki

Warszawa, 29 marca 2007 r.

IQNet
THE INTERNATIONAL CERTIFICATION NETWORK

CERTIFICATE

IQNet and
Certification Association "Russian Register"
hereby certify that the organization

Marine Service Jaroszewicz s.c.
Poland, 70-703 Szczecin, ul. Bielanska, 23

for the following field of activities

production of EPY-Epoxy Compound and seating services of marine and industrial machinery on "EPY", "Chockfast" and "Epocast" resin chocks

has implemented and maintains a

Management System

which fulfils the requirements of the following standard

ISO 9001:2008

Issued on: 29th August, 2011
Validity date: 29th August, 2014

Registration Number: RU-11.0823.026

Michael Drechsel
President of IQNet

General director of Russian Register

ITW Polymer Technologies

March 4, 2010

Dr. Inz. Wieslaw Jaroszewicz
Marine Service Jaroszewicz
Ul. Bielanska 23
70-703 Szczecin, Poland

CERTIFICATE

We hereby certify that the person listed below and personnel named on Chockfast technician cards are employed by

MARINE SERVICE JAROSZEWICZ

They have received training in the application of epoxy chocking compounds and are authorized by ITW Polymer Technologies to carry out and supervise Chockfast installations.

Contact : Dr. Inz. Wieslaw Jaroszewicz

Robert Scibio
Business Manager
Marine Products

Lloyd's Register

STATEMENT OF ACCEPTANCE OF CHOCKING RESIN

Certificate No. MATS/5069

This certificate is issued to the company named below. Based on the examination of the data submitted the product described is considered acceptable for use in constructions built under Lloyd's Register's survey. This acceptance is subject to Lloyd's Register being informed of any changes in or modifications to the product and the product being used in accordance with the manufacturer's instructions and with the relevant requirements of Lloyd's Register's Rules and Regulations.

Company: MARINE SERVICE JAROSZEWICZ, SZCZECIN, POLAND

Trade name: EPY Chocking Compound

Maximum loading of 5.0 MPa for a maximum service temperature of 80°C where the chocking compound is post cured to a minimum temperature of 70°C for 16 hours.

INDIVIDUAL MEASURED MINIMUM BARCOL HARDNESS SHALL BE 40 OR GREATER

Valid until: 1 June 2017

Date: 10 June 2012

MAN B&W Diesel AG

MARINE SERVICE JAROSZEWICZ
Ul.Bielanska 23
PL 70-703 Szczecin

Augsburg, 12.06.95
TMF Dr.Bergbauer
(0343/95)
call: 3514

Chocking of MAN B&W four-stroke engines with EPY-resin

Dear Mr. Jaroszewicz,

following the discussions we had with you and Prof. Grudzinski and based on the documentation that has been handed over to us we can state that we have no objections to use EPY supporting chocks for our four-stroke engines in case of the following standard applications:

- rigidly mounted engines.
- chocking of mounts for MAN B&W direct resilient mounting system.

Chocking of steel spring plates for MAN B&W semi-resilient mounting system will only be allowed as soon as fatigue test results of the EPY material are available and have been checked by us.

Our approval of the EPY material depends on the approval of some of the most important classification societies. No investigations have been carried out by MAN B&W itself. The following conditions have to be observed:

- Mixing and processing of the cast resin has to be carried out by the manufacturer or its authorised representative.
- Pressure on chocks effected by engine weight is max. 0.7 N/mm²;
- Pressure by holding-down-bolts and engine weight together does not exceed 5.0 N/mm².
- Maximum temperature permissible at the chocks during operation is 80 deg C.
- The arrangement of the epoxy resin chocks and the tension of the foundation bolts must comply with the requirements of MAN B&W.

MAN B&W Diesel AG

MARINE SERVICE JAROSZEWICZ
ul. Bielanska 23
PL 70-703 Szczecin

Augsburg, 06.11.95
TMF Dr.Bergbauer
(0604/95)
call: 35 14

EPY chocks

Dear Mr. Jaroszewicz,

we are pleased to inform you that based on the results of pulsating compressive test of EPY-plastic carried out by Prof. Grudzinski at Politechnika Szczecinska (test report dated Sept. 1995, approved by GL) we have no further objections to use EPY material for chocking of MAN B&W semi-resilient mounting system in case the following conditions are met:

- Conditions set in our letter TMF 0343/95 (dated 12.06.95).
- It is insured by proper manufacturing of the chocks that real chocks have the same fatigue strength as the test specimens.

We again have to point out, that MAN B&W, being not the designer of the engine foundation, are unable to accept any responsibility for the chocking of engines with synthetic resin. Processing, utilisation, special design and warranty remain the responsibility of MSJ and its authorized representatives. MAN B&W will not be responsible for any damage on the engines or the steel spring plates of the semi-resilient mounting which is provably caused by improper chocking.

The approval may at any time be reconsidered in case of dissatisfactory service experience with your product "EPY" or non compliance to the approval conditions.

Kind regards

MAN B&W Diesel Aktiengesellschaft

i.A.


MAN Diesel & Turbo

Certificate of Approval

This is to certify that EPY chocking compound from

Marine Service Jaroszewicz S.C.
ul. Bielańska 23
PL-70 703 Szczecin
Poland

Tel.: +48 914 606 624
Fax: +48 914 313 075
E-mail: msj@epyresin.eu
www.epyresin.eu

has been approved for chocking of all MAN B&W two-stroke diesel engines.

Copenhagen, 1 April 2011

MAN Diesel & Turbo


New Sulzer Diesel

Marine Service
Jaroszewicz
Mr. W. Jaroszewicz
ul. Bielańska 23
PL-70-703 Szczecin
Polen

7058 M. Lüthig
252 44 89
212 09 26
08.07.98

Approval of EPY Epoxy Resin Material for Sulzer Engine Chocking

Dear Mr. Jaroszewicz,

We refer to our meeting held in Winterthur on 7th June, 1998 and are pleased to inform you that our approval of 26th March, 1991 is hereby renewed with this letter.

Your EPY chocking material is approved for use with all Sulzer diesel engine types.

This approval means that the following requirements are fulfilled:

- The arrangement of the epoxy resin chocks and the tension of the foundation bolts must comply with Sulzer standard arrangement drawings "Engine seating with epoxy resin chocks".
- The preparatory work, pouring and curing process are to be supervised by experts of the Marine Service Jaroszewicz company.

We trust to have been of service to you and remain

with kind regards,

New Sulzer Diesel Ltd.

M. Lüthi   ppa. F. Porchet


Polski Rejestr Statków

ŚWIADECTWO UZNANIA TYPU WYROBU

PODKŁADKI WYLEWANE
DO POSADAWIANIA MASZYN I URZĄDZEŃ OKRĘTOWYCH

Tworzywo chemoutwardzalne EPY

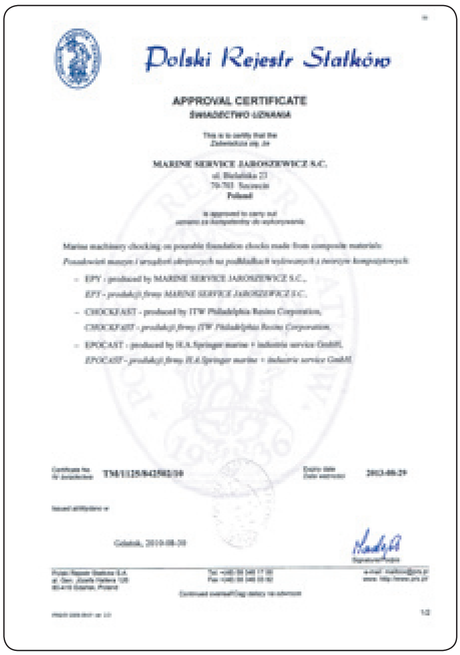
MARINE SERVICE JAROSZEWICZ S.C.
ul. Bielańska 23
70-703 Szczecin

Przepisów klasyfikacji i budowy statków morskich, PRS

TM/1124/800002/10   2015-09-06

Gdańsk, 2010-08-30

1/2


Polski Rejestr Statków

APPROVAL CERTIFICATE
ŚWIADECTWO UZNANIA

MARINE SERVICE JAROSZEWICZ S.C.
ul. Bielańska 23
70-703 Szczecin
Poland

Marine machinery chocking on pourable foundation chocks made from composite materials

- EPY - produced by MARINE SERVICE JAROSZEWICZ S.C.,
- CHOCKFAST - produced by ITW Philadelphia Resins Corporation,
- EPOCAST - produced by H.A.Springer marine + industrie service GmbH,

TM/1125/842502/10   2013-08-29

Gdańsk, 2010-08-30

1/2

TYPE APPROVAL CERTIFICATE
No. MAC13661XG

This is to certify that the product identified below is in compliance with the regulations herewith specified.

Description	Epoxy resin for machinery chocking
Type	EPY
Applicant	MARINE SERVICE JAROSZEWICZ UL. BIELANSKA 23 70-703 SZCZECIN POLAND
Manufacturer *Place of manufacture*	MARINE SERVICE JAROSZEWICZ UL. BIELANSKA 23 70-703 SZCZECIN POLAND
Reference standards	Part C, Chapter 1, Section 2 of RINA Rules for the classification of ships
Reference documents	RINA TYPE APPROVAL SYSTEM

Issued in HAMBURG *on* November 14, 2012. *This Certificate is valid until* November 13, 2017

RINA
Giuseppe Russo

This certificate consists of this page and 1 enclosure

RINA

STATEMENT

RINA FILE N° 2010/XP/01/74

Further the ascertainment carried out and on basis of the supplied documentations, summarized by internal quality and working procedures officially in act, We hereby

DECLARE that

COMPANY	„MARINE SERVICE JAROSZEWICZ S.C."
PRODUCTS	• SEATINGS OF MACHINERY ON RESIN CHOCKS • PRODUCTION OF "EPY" EPOXY COMPOUND

On the basis of the qualification presented and upon the satisfactory results of the resin chocks & tests carried out on board of RINA Ships, the following certification

WORKSHOP APPROVAL

has been issued for the Approval of the Company, in accordance with the applicable RINA Rules and within the scope of application specified by the individual jobs.

THE PRESENT STATEMENT HAS VALIDITY 4 YEARS, EXPIRING ON APRIL 2014

Issued at Szczecin, Poland on 1st APRIL 2010

RINA

СВИДЕТЕЛЬСТВО О ТИПОВОМ ОДОБРЕНИИ
TYPE APPROVAL CERTIFICATE

Manufacturer: MARINE SERVICE JAROSZEWICZ S.C.

Address: ul. Bielanska 23, 70-703 Szczecin, Poland

Product*
two component polymer material on the base of epoxy EPY

This Type Approval Certificate is valid until 02.08.2016

Date of issue 02.08.2012

№ 11.00477.250

Российский морской регистр судоходства
Russian Maritime Register of Shipping

RUSSIAN REGISTER CERTIFICATION SYSTEM

CERTIFICATE
OF QUALITY MANAGEMENT SYSTEM CONFORMITY

This is to certify that the Quality Management System of

Marine Service Jaroszewicz s.c.
Poland, 70-703 Szczecin, ul. Bielanska, 23

has been assessed and found to be in accordance with the requirements of

ISO 9001:2008

in respect of production of EPY-Epoxy Compound and seating services of marine and industrial machinery on "EPY", "Chockfast" and "Epocast" resin chocks

No: 11.0823.026
of 29th August, 2011

Management system certified since 2000

This certificate is valid until 29th August, 2014

RUSSIAN REGISTER RUSSIAN REGISTER

007623

IQNet

РОССИЙСКИЙ МОРСКОЙ РЕГИСТР СУДОХОДСТВА
RUSSIAN MARITIME REGISTER OF SHIPPING

СВИДЕТЕЛЬСТВО О ПРИЗНАНИИ ИЗГОТОВИТЕЛЯ
RECOGNITION CERTIFICATE FOR MANUFACTURER

MARINE SERVICE JAROSZEWICZ S.C.
ul. Bielańska 23, 70-703 Szczecin, Poland

the foundation linings produced by using two-component polymer material on epoxy base - EPY, CHOCKFAST ORANGE (PR-610TSF), EPOCAST 36

TRANSPORTOWY DOZÓR TECHNICZNY
CERTIFICATION BODY
TDT-CERT

CERTIFICATE
No. 7 2229 207 2011 Q

confirms that

MARINE SERVICE
JAROSZEWICZ
SPÓŁKA CYWILNA

PL 70-703 Szczecin ul. Bielańska 23

Confirms requirements of standard:
PN-EN ISO 9001:2009

WÄRTSILÄ NSD

Wärtsilä NSD Finland Oy

Marine
Engineering
Per-Åke Furu/HMMi

4 May 2000

Marine Service Jaroszewicz
ul. Bielańska 23
70-703 SZCZECIN
Poland

Approval of EPY epoxy resin for chocking of Wärtsilä engines

Dear Sirs

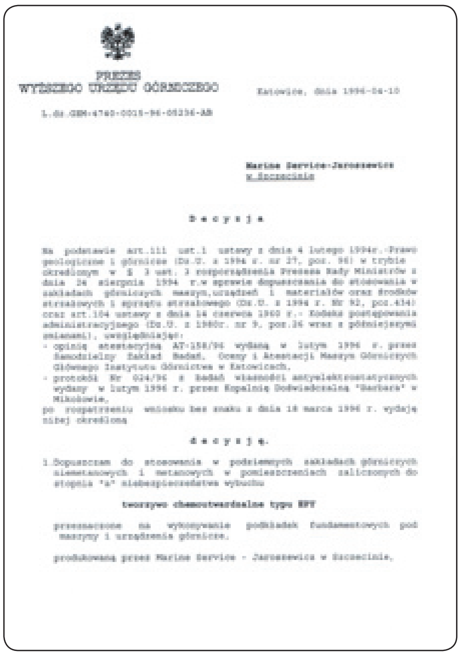
We refer to your letter of 19 November 1999 with product information about EPY chocks and regret the delay in replying to it.

After having examined the documentation we received we would like to inform you that we approve the use of EPY epoxy resin as chocking material for Wärtsilä engines.

However, the dimensioning of the chocks and the casting of the chocks must be approved by the Classification Society for each specific project.

Yours faithfully
WÄRTSILÄ NSD FINLAND OY
Marine

Per-Åke Furu
General Manager, Engineering



PREZES
WYŻSZEGO URZĘDU GÓRNICZEGO

Katowice, dnia 1996-04-10

Marine Service-Jaroszewicz
w Szczecinie

Decyzja

decyduję

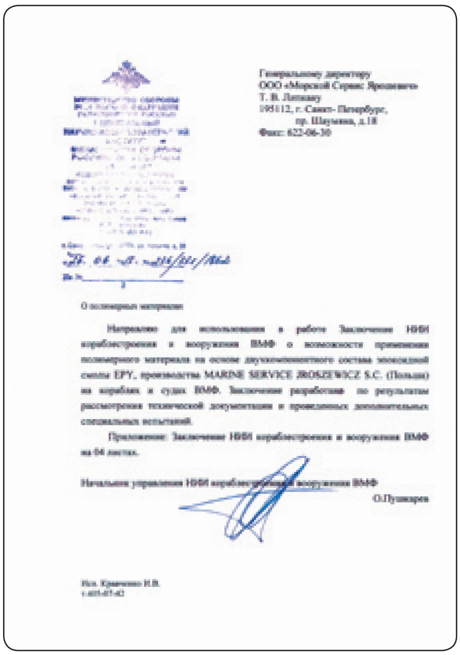
tworzywo chemoutwardzalne typu EPY

produkowane przez Marine Service - Jaroszewicz w Szczecinie.


Główny Instytut Górnictwa
JEDNOSTKA CERTYFIKUJĄCA
Pl. Gwarków 1
40 - 166 KATOWICE
CERTYFIKAT NR B/2347/2012


РОССИЙСКИЙ РЕЧНОЙ РЕГИСТР
RUSSIAN RIVER REGISTER
СВИДЕТЕЛЬСТВО О ПРИЗНАНИИ
RECOGNITION CERTIFICATE
№ 13716


РОССИЙСКИЙ РЕЧНОЙ РЕГИСТР
RUSSIAN RIVER REGISTER
СЕРТИФИКАТ ОБ ОДОБРЕНИИ типового материала
TYPE APPROVAL CERTIFICATE for the Material




URZĄD - HARMONIZACJI RYNKU WEWNĘTRZNEGO
ZNAKI TOWAROWE I WZORY

ŚWIADECTWO REJESTRACJI

Niniejsze Świadectwo Rejestracji zostało wystawione dla przedstawionego poniżej Wspólnotowego Znaku Towarowego. Wszystkie dane dotyczące tego znaku zapisane są w Rejestrze Wspólnotowych Znaków Towarowych.

OHIM – OFFICE FOR HARMONIZATION IN THE INTERNAL MARKET
TRADE MARKS AND DESIGNS

CERTIFICATE OF REGISTRATION

This Certificate of Registration is hereby issued for the Community Trade Mark identified below. The corresponding entries have been recorded in the Register of Community Trade Marks.

Zarejestrowano, dnia / Registered
18/03/2011

No 009213117

EPY

Prezes / The President

António Campinos

at unification of the requirements and procedures for the obtaining of common certificates concerning certain products, which have to be respected by all the EU recognized organizations supervising shipbuilding and ship repair work. The issue which is the subject of the decree (EC) No. 391/2009 of EU in a general outline has been in a greater detail discussed in the previous section of this chapter, as far as the compounds intended for machinery foundation chocks are concerned.

As the decree entered in force on 1st January 2013, MSJ company undertook immediately an appropriate action aimed at obtaining such new certificate for EPY compound, which would have a broad range of approval. To this end, it was necessary to perform relevant tests of the compound in compliance with the requirements contained in the above mentioned EU decree, choose one of the EU recognized organizations (ROs) and execute given procedures of proceeding. The relevant documentation together with the results of the tests (listed in Tab. 2.3) have been sent to Maritime Register of Shipping which is one of the twelve, EU-recognized organizations (EU ROs), authorized to issue such documents. The full names of the organizations have been given in the previous section, and their logos shown in Fig. 2.4.

The submitted test results have been approved as those which fulfilled the relevant requirements and — in consequence — confirmed by the special certificate "RU RO Mutual Design Evaluation Certificate", issued with the date of 4th February 2014. It was the basis for issuing the document "EU RO Mutual Recognition Type Approval Certificate", with the date of 25th February 2014. This is the certificate of common approval of the EPY compound by all the EU-recognized organizations for supervision of shipbuilding and ship repair operations (listed in Fig. 2.4). The document is

Table 2.3. List of tests on EPY compound and their results

№	Quantity	Recommended standard of tests	Method of testing	Result	Test report
1	Compression strength, MPa	ASTM D-695 - ISO 604	ASTM D-695 - ISO 604	150	Report ZUT 4-2012; p. 4.2
2	Tensile strength, MPa	ASTM D-638 - ISO 527	ASTM D-638 - ISO 527	54.9	Raport ZUT 7-MSJ-2011; p.3.3
3	Modulus of elasticity, MPa	ASTM D-695 - ISO 604	ASTM D-695 - ISO 604	4255.4	Report ZUT 4-2012; p. 4.2
4	Elasticity modulus in shear, MPa	ASTM D 4065	ISO 6721-2	2187	Raport z PD PS 1998; p.4.4, t.3.1
5	Temperature of deflection under load, °C	ASTM D 621 - ISO 175-2	ASTM D 621 - ISO 175-2	96.8	Report ZUT 4-2012; p. 4.5
6	Impact strength, kJ/m^2	ASTM D 256 - ISO 180	ASTM D 256 - ISO 180	16.2	Report ZUT 4-2012; p. 4.4
7	Hardness, °Barcol	ASTM D-2583	ASTM D-2583	49.8	Report ZUT 4-2012; p. 4.3
8	Bending strength, MPa	ASTM D 790	EN ISO 178	73.3	Raport ZUT 5-2013; p. 3
9	Linear shrinkage in curing	ASTM D 2566	ASTM D 2566	0.0002	Raport PS 12-2000; p.4
10	Fatigue strength under compression, MPa	DIN 50100	DIN 50100	60	Report PS 09.1995
11	Combustibility, mm/min	ASTM D 635	ASTM D 635	0	Report ZUT TZ-ASTM D 635A-025-2014
12	Ageing, h	–	MSJ made	195000	MSJ Reference list
13	Thermal expansion coefficient, °C^{-1}	DIN 53752	ASTM D 696-91	$(40 \div 50) \times 10^{-6}$	Report PS 1-2004
14	Dielectric strength, kV/mm	DIN 53481	PN-86/E-04404	15.7	Raport PS 12.1995; p.5.3
15	Insulation ohmic resistance, Ω	DIN 53482	PN-88/E-04405	8×10^{12}	Raport PS 12.1995; p.5.4
16	Friction factor	–	PS made	0.36÷0.62	Report PS 19-1991
17	Oil absorption capacity, %	ISO 175	ISO 175	0.013	Report ZUT 4-2012; p. 4.8
18	Density, g/cm^3	ISO 1675	EN ISO 1183-1	1.57	Raport ZUT 6-2013; p. 3
19	Contraction in volume, %	ISO 3521	ISO 3521	2.95	Raport ZUT 7-2013
20	Glass transition temperature, °C	ISO 11357	ZUT made; Method DSC	95.6	Raport ZUT 8-2011; p. 3
21	Water absorption capacity, %	ISO 175	ISO 62	0.164	Report ZUT 4-2012; p. 4.7
22	Creep, %	–	ZUT made; 5MPa, 1000h, 80°C Indicators type S229 SYLVAC	0.183	Report ZUT 4-2012; p. 4.6
23	Exotherme temperature measurement, °C	–	ZUT made; Thermometer CHY type 506R Thermocouple type K	63.1	Report ZUT 4-2012; p. 4.1
24	Compound viscosity in pouring, mPas	–	PS made; RVT Brookfield's viscometer	47200	Raport PS 23-94

of a worldwide validity which results from the fact of belonging them to the group of EU-recognized organizations (EU ROs), and also similar organizations from other significant countries (USA, China, Japan and South Korea). Because the above mentioned certificates are new and important their copies are presented entirely.

It should be also noticed that the hitherto issued certificates are also respected in practice. Transition from these certificates to the new, mutually recognized certificates (EU RO MR TAC) is a process which is verified in practice. Production of EPY

Fig. 2.4. Logotypes of EU recognized organizations for supervision of ship construction and repair

compound and seating operations of machines and devices, based on it, are carried out in compliance with the quality management system according to the standard DIN EN ISO 9001:2009, which is confirmed by the Germanischer Lloyd certificate No. QS-244 HH, obtained by MSJ Company in 1994, the certificate No. 00.017.258 of the Russian Maritime Register of Shipping, issued in 2000, as well as the certificate No. 7 351 058 2008 Q granted by the Polish Technical Inspection of Transport (Transportowy Dozór Techniczny) in 2008.

In the further research and development projects aimed at more detailed recognition and improvement of operational properties of EPY compound many scientific workers of the Chair of Mechanics and Machine Elements of the Technical University of Szczecin, took part, in particular it was: Mr Konrad Konowalski (DEng), Mr Ryszard Kawiak (DEng), Mr Paweł Grudziński (DEng) and Mr Jędrzej Ratajczak (DEng), Mrs Magdalena Urbaniak (DEng). In the implementation work conducted by MSJ company and supervised by Mr Wiesław Jaroszewicz (DEng), a significant contribution was given by: Mr Zbigniew Kępkiewicz (MScEng) (Gdańsk Shipyard), Mr Andrzej Skierkowski (MScEng) (Szczecin

РОССИЙСКИЙ МОРСКОЙ РЕГИСТР СУДОХОДСТВА
RUSSIAN MARITIME REGISTER OF SHIPPING

6.5.32 MR

№ 14.09099.381

EU RO Mutual Recognition

СВИДЕТЕЛЬСТВО
О СООТВЕТСТВИИ ТИПОВОГО ОБРАЗЦА ИЗДЕЛИЯ*
DESIGN EVALUATION CERTIFICATE*

Тип, марка, назначение
Type, model, purpose

Двухкомпонентный полимерный материал на основе эпоксидной смолы EPY
Two Component Polymer Material on the Base of Epoxy EPY

Предприятие-изготовитель
Manufacturer

Marine Service Jaroszewicz S.C.

Адрес
Address

ul. Bielanska 23, 70-703 Szczecin, Poland

Авторизованный(е) представитель(ли)
Authorized Representative(s)

--

Документация (наименование и номер документа, дата и номер документа об одобрении Российским морским регистром судоходства)
Documentation (name and number of document, date and number of document of approval by Russian Maritime Register of Shipping)

Комплект технической документации "TWO COMPONENT POLYMER MATERIAL ON THE BASE OF EPOXY EPY. Одобрен РС письмом No.381-09-273775 от 30.12.2013.
The set of technical documentation for the "TWO COMPONENT POLYMER MATERIAL ON THE BASE OF EPOXY EPY". Approved by RS Letter No.381-09-273775 dated 30.12.2013.

проведены освидетельствования и испытания в соответствии с техническими требованиями взаимного признания ЕС по программе, одобренной Российским морским регистром судоходства, при этом:
carried out surveys and tests in according to EU RO MR Technical Requirement according to the programme approved by Russian Maritime Register of Shipping which showed the following:

В ходе освидетельствования были рассмотрены результаты испытаний, выполненные независимыми лабораториями (Лаборатория кафедры механики и материалов и Лаборатория огневых испытаний Западно-Поморского технологического университета в г. Щецине, Польша). Лаборатории имеют аккредитацию национальных органов на проведение соотетсвующих испытаний.
Объем и результаты испытаний в полной мере соответствуют применимым техническим требованиям EU RO MR.
Результатты испытаний приведены в отчетах и протоколах испытаний: Report ZUT4-2012 от 02.2012, Raport ZUT 7-MSJ-2011 от 12.2011, Raport ZUT 5-2013 от 12.2013, PS 12/2000 от 12.2000, Report TZ/ASTM B 635A/025/2014 от 04.02.2014, Raport ZUT 6-2012 от 12.2013, Raport ZUT 8-2011от 06.2011, Report 1/2004 от 02.2004, Report PS 12.1995 от 02.10.1995, Report 19/1991 от 07.1991.

The results of tests that were carried out by Nationally accredited testing laboratories, i.e. "Laboratorium Wytrzymalosci Materialov" and "Laboratorium Badan Cech Pozarowych Materialow" of the "Zachodnipomorski Uniwersytet Technologiczny w Szczecinie"has been reviewed. The Scope and the results of tests are fully comply with the applicable EU RO MR technical requirements.
Test results are available in the the following test reports: Report ZUT4-2012 dd. 02.2012, Raport ZUT 7-MSJ-2011 dd. 12.2011, Raport ZUT 5-2013 dd. 12.2013, PS 12/2000 dd. 12.2000, Report TZ/ASTM B 635A/025/2014 dd. 04.02.2014, Raport ZUT 6-2012 dd. 12.2013, Raport ZUT 8-2011dd. 06.2011, Report 1/2004 dd. 02.2004, Report PS 12.1995 dd. 02.10.1995, Report 19/1991 dd. 07.1991.

* Изделие может быть допущено к установке на суда только при условии наличия СТО EU RO MR.
The product can be accepted for installation on board of ship with valid TAC EU RO MR only.

Технические данные:
Technical data:

Полимерный материал предназначен для использования в качестве подкладок для судовых главных и вспомогательных двигателей, передач главных и вспомогательных двигателей, рулевых машин, подшипников валопровода, дейдвудных труб, палубных и других вспомогательных механизмов.

Максимальные допустимые величины давления на подкладку следующие:

максимальная температура эксплуатации, °C:	40	50	60	70	80
для центруемых механизмов, Н/мм²:	10,0	8,7	7,8	6,4	5,0
для нецентруемых механизмов Н/мм²:	30,0	30,0	30,0	15,0	15,0

Максимальная удельная нагрузка на подкладку от массы механизма: 0,9 Н/мм²)

Ограничения:

1. Установка механизмов с использованием материала должна осуществляться в соответствии с технической документацией, которая одобряется на соответствие требованиям признанной организации EU RO. Техническая документация, предоставляемая на одобрение, должна включать, как минимум, следующую информацию:

- *масса устанавливаемых механизмов;*
- *количество, размер, расположение, тип и материал используемых болтов;*
- *расчеты удельных нагрузок для принятых размеров подкладок от массы механизма и затяжки фундаментных болтов, а также расчеты моментов затяжки фундаментных болтов и соответствующих напряжений в болтах;*
- *фиксирующие устройства для болтов и расчет удлинения болтов для фиксации болтовых соединений;*
- *информация об устройствах для предотвращения продольного и поперечного смещения;*
- *информация об уплотнительных устройствах (при установке дейдвудных труб или опорных подшипников);*
- *информация об используемых стопорных устройствах (для подшипников валопровода, подшипников и втулок баллера руля);*
- *инструкция изготовителя.*

2. Укладка подкладок может выполняться только компаниями, которые авторизованы изготовителем - Marine Service Jaroszewicz S.C., в рамках ограничений предусмотренных технологическим процессом. По запросу инженера-инспектора должны быть представлены документы изготовителя - Marine Service Jaroszewicz S.C., подтверждающие факт обучения персонала авторизованной компаний выполнению технологического процесса установки подкладок.

The chocking compound is approved for foundation choking of main and auxiliary engines, reduction gears, rudder actuators, stern tubes and bearings, deck machinery and other auxiliary machinery.

Maximum total surface pressure:

Max. service temperature, °C:	40	50	60	70	80
For equipment that should be aligned, N/mm²:	10,0	8,7	7,8	6,4	5,0
For equipment that should not be aligned, N/mm²:	30,0	30,0	30,0	15,0	15,0

Max. specific load due to weight: 0,9 N/mm²

Application limitations:

1. Each specific installation of cast resin chocks is to be carried out in compliance with installation drawings approved on case-by case basis, according to each specific R.O.'s Rules. Such specific approval will normally take into account, as minimum the following:

- *Total deadweight of supported machinery;*
- *Number, size, arrangement and material of chocks and bolts, complete with relevant detailed (dimensioned) drawings;*
- *Bolts pre-loaded and/or elongation, complete with details of tightening procedures;*
- *Locking arrangements for bolts and calculations of bolt elongation for bolt connection securing;*
- *Longitudinal and lateral stopping arrangements;*
- *Sealing arrangements (for installation in stern tube or shafts struts);*
- *Anti-rotation devices (for shaft bearings and rudder stock bearings/bushes);*
- *Manufacturer instructions (including instruction for special cases e.g. Thin small chock height or cracks in chocks).*

2. The chocks may only be poured by companies authorized by the cast resin manufacturer whilst maintaining the boundary conditions required by the process. Authorization respectively evidence of training the personnel performing the cast resin process by the cast resin manufacturer has to be presented to the local surveyor.

ЗАКЛЮЧЕНИЕ
CONCLUSION

На основании проведенных освидетельствований и испытаний установлено, что:
As a result of the surveys it was found that:

Двухкомпонентный полимерный материал на основе эпоксидной смолы EPY соответствует техническим требования EU RO MR.

Two Component Polymer Material on the Base of Epoxy EPY is comply with EU RO technical requirements for Resin Chocks.

Область применения и ограничения: ***см. Технические данные***
Application and limitations: ***see Technical data***

Код номенклатуры ***13350000***
Code of nomenclature

Настоящее Свидетельство теряет силу в случаях, установленных Процедурой взаимного признания Организаций, признанных Европейским Союзом.
This Certificate becomes invalid in case stipulated in European Union Recognized Organization Mutual Recognition Procedure.

Место выдачи ***г. Санкт-Петербург, Россия*** Дата выдачи ***04.02.2014***
Place of issue ***Saint-Petersburg, Russia*** Date of issue

Российский морской регистр судоходства
Russian Maritime Register of Shipping

М.П.
L.S.

(подпись / signature)

А.Ю. Захаров/A. Zakharov
(фамилия, инициалы / name)

РС 6.5.32 MR 04/2013

РОССИЙСКИЙ МОРСКОЙ РЕГИСТР СУДОХОДСТВА
RUSSIAN MARITIME REGISTER OF SHIPPING

6.8.3 MR

EU RO Mutual Recognition

СВИДЕТЕЛЬСТВО О ТИПОВОМ ОДОБРЕНИИ
TYPE APPROVAL CERTIFICATE

Изготовитель
Manufacturer *Marine Service Jaroszewicz S.C.*

Адрес
Address *ul. Bielanska 23, 70-703 Szczecin, Poland*

Изделие*
Product* *Двухкомпонентный полимерный материал на основе эпоксидной смолы EPY*
Two Component Polymer Material on the Base of Epoxy EPY

Код номенклатуры
Code of nomenclature *13350000*

На основании освидетельствования и проведенных испытаний удостоверяется, что вышеупомянутое(ые) изделие(я) удовлетворяет(ют) Согласованным техническим требованиям Организаций, признанных Европейским Союзом и нижеуказанным требованиям Правил/Стандартам:

This is to certify that on the basis of the survey and tests carried out the above mentioned product(s) comply with the Agreed Technical Requirements of European Union Recognized Organization and below mentioned Rules/Standards:

EU RO Technical Requirements for Resin Chocks, version 1.0 dated 01.01.2013

Настоящее Свидетельство о типовом одобрении действительно до
This Type Approval Certificate is valid until *25.02.2019*

Настоящее Свидетельство о типовом одобрении теряет силу в случаях, установленных Процедурой взаимного признания Организаций, признанных Европейским Союзом.

This Type Approval Certificate becomes invalid in cases stipulated in European Union Recognized Organization Mutual Recognition Procedure.

Место выдачи *Санкт-Петербург, Россия* Дата выдачи *25.02.2014* № *14.09101.381*
Place of issue *Saint-Petersburg, Russia* Date of issue

Российский морской регистр судоходства
Russian Maritime Register of Shipping

М.П.
L.S.

(подпись / signature)

А.В. Филиппов / A. Filippov
(фамилия, инициалы / name)

*Дополнительную информацию смотри на обороте.
Additional information see overleaf.

Технические данные
Technical data

Максимальные допустимые величины давления на подкладку следующие:

максимальная температура эксплуатации, °C:	*40*	*50*	*60*	*70*	*80*
для центруемых механизмов, Н/мм²:	*10.0*	*8.7*	*7,8*	*6,4*	*5,0*
для нецентруемых механизмов Н/мм²:	*30.0*	*30,0*	*30,0*	*15,0*	*15,0*

Максимальная удельная нагрузка на подкладку от массы механизма: 0,9 Н/мм²;

Maximum total surface pressure:

Max. service temperature, °C:	*40*	*50*	*60*	*70*	*80*
For equipment that should be aligned, N/mm²:	*10.0*	*8.7*	*7,8*	*6,4*	*5,0*
For equipment that should not be aligned, N/mm²:	*30.0*	*30,0*	*30,0*	*15,0*	*15,0*

Max. specific load due to weight: 0,9 N/mm².

Свидетельство о соответствии типового образца изделия (EU DE) No. *14.09099.381* от *04.02.2014*
Design Evaluation Certificate No. of

выдано *RS* являющимся(-ейся) организацией признанной ЕС в соответствии со Ст.10 Правила No. 391/2009
issued by which is EU RO and meets Article 10 of Regulation (EC) No.391/2009

Европейского Парламента ЕС.
of the European Parliament.

Оценка качества производства (PQA) выполнены Российским морским регистром судоходства
Production quality assurance assessment has been carried out by Russian Maritime Register of Shipping

Акт № *14.09100.381* от *25.02.2014*
Report No. of

Область применения и ограничения
Application and limitations

Полимерный материал предназначен для использования в качестве подкладок для судовых главных и вспомогательных двигателей, передач главных и вспомогательных двигателей, рулевых машин, подшипников валопровода, дейдвудных труб, палубных и других вспомогательных механизмов.

The chocking compound is approved for foundation choking of main and auxiliary engines, reduction gears, rudder actuators, stern tubes and bearings, deck machinery and other auxiliary machinery.

Ограничения приведены в Дополнении к настоящему свидетельству.
The limitations are listed in the Supplement to this Certificate .

Изделие должно поставляться с копией настоящего Свидетельства о типовом одобрении
The product shall be delivered with a copy of this Type Approval Certificate

06/2013

ДОПОЛНЕНИЕ
SUPPLEMENT

к Свидетельству № / to Certificate No. **14.09101.381**

Ограничения:

1. Установка механизмов с использованием материала должна осуществляться в соответствии с технической документацией, которая одобряется на соответствие требованиям признанной организации EU RO. Техничекая документация, предоставляемая на одобрение, должна включать, как минимум, следующую информацию:

- масса устанавливаемых механизмов;

- количество, размер, расположение, тип и материал используемых болтов;

- расчеты удельных нагрузок для принятых размеров подкладок от массы механизма и затяжки фундаментных болтов, а также расчеты моментов затяжки фундаментных болтов и соответствующих напряжений в болтах;

- фиксирующие устройства для болтов и расчет удлинения болтов для фиксации болтовых соединений;

- информация об устройствах для предотвращения продольного и поперечного смещения;

- информация об уплотнительных устройствах (при установке дейдвудных труб или опорных подшипников);

- информация об используемых стопорных устройствах (для подшипников валопровода, подшипников и втулок баллера руля);

- инструкции изготовителя.

2. Укладка подкладок может выполняться только компаниями, которые авторизованы изготовителем - Marine Service Jaroszewicz S.C., в рамках ограничений предусмотренных технологическим процессом. По запросу инженера -инспектора должны быть представлены документы изготовителя - Marine Service Jaroszewicz S.C., подтвержадющие факт обучения персонала авторизованной компаний выполнению технологического процесса установки подкладок.

Application limitations:

1. Each specific installation of cast resin chocks is to be carried out in compliance with installation drawings approved on case-by case basis, according to each specific R.O.'s Rules. Such specific approval will normally take into account, as minimum the following:

- Total deadweight of supported machinery;

- Number, size, arrangement and material of chocks and bolts, complete with relevant detailed (dimensioned) drawings;

- Bolts pre-loaded and/or elongation, complete with details of tightening procedures;

- Locking arrangements for bolts and calculations of bolt elongation for bolt connection securing;

- Longitudinal and lateral stopping arrangements;

- Sealing arrangements (for installation in stern tube or shafts struts);

- Anti-rotation devices (for shaft bearings and rudder stock bearings/bushes);

- Manufacturer instructions (including instruction for special cases e.g. Thin small chock height or cracks in chocks).

2. The chocks may only be poured by companies authorized by the cast resin manufacturer whilst maintaining the boundary conditions required by the process. Authorization respectively evidence of training the personnel performing the cast resin process by the cast resin manufacturer has to be presented to the local surveyor.

Инженер-инспектор / Surveyor (подпись / signature) **А.В. Филиппов / A. Filippov** (фамилия, инициалы / name)

М.П. / L.S.

Shipyard), Mr Jędrzej Ratajczak (DEng) (PS, MSJ), Mrs Dorota Ratajczak (MScEng) (MSJ), and Mr Stanisław Kłoczko (Eng) (MSJ).

In the practical application of EPY compound to repair and modernization of seating arrangements of large reciprocating compressors in many natural gas compression plants located over the entire Polish territory, as well as in chemical industry, a significant role was played by the Construction and Expertise TECHMARIN Ltd Co. (Zakład Konstrukcji i Ekspertyz) in Świnoujście, managed by Mr Włodzimierz Kołodziejski. The novel, developed by him, modernizing solutions dealing with the seating arrangement of compressor units with the use of EPY compound, successfully passed exam in practice and reached high recognition from the side of specialists and users of the objects of this kind.

The currently used resin compounds for foundation chocks have been developed in order to improve the technology and technical quality of machinery seating operations and to ensure suitable precision and stability to its mounting and rigidity of fixing. In this range the compounds play their role much better than the traditionally used metal chocks. As observed in practice, the developed compounds are also able to contribute in mitigating vibration and noise, and structural sound in particular. Many users of machines and technical objects are interested in the problem, on which intensive investigations have been presently carried out by MSJ company and worldwide.

In order to ensure further development of the technology, Marine Service Jaroszewicz Company cooperates closely with the Chair of Mechanics and Machine Elements of the Technical University of Szczecin (transformed into the West Pomeranian University of Technology in January 2009).

This also includes conducting systematic research and development projects aimed at further improvement of thermo-mechanical properties of the compound and machinery seating technology based on it, as well as finding solutions for many scientific technical problems associated with broadening of the range of application of this technology to engineering practice.

3 Theoretical and experimental essentials of testing and description of curing process of epoxy systems

3.1. General characteristics of curing process of epoxy systems

Curing process of epoxy compounds results from chemical reaction between functional groups (epoxy and hydroxide) contained in resin and curing agent, which have more than two functional groups. The process is of a poly-addition character which means that it runs without discharging small particle by products. Cross--linking reaction of epoxy resins is complicated due to interaction of chemical reaction kinetics and other physical processes such as gelation and glass transition, which cause crucial changes in macroscopic physical features of reacting system [51, 52]. Initially fusible and soluble resin system is transformed into a spatially cross-linked compound which is non-fusible and non-soluble in organic solvents. Run of cross--linking reaction determines morphology of reacting system which passes from viscous liquid state through an intermediate state (called gelation) up to rigid glass transition state. Consecutive phases of the cross-linking process are schematically shown in Fig. 3.1 [53]. The cross-linking reaction begins from the forming and linear growing of chains which immediately start branching and then joining into a spatial cross-linked structure.

In the cross-linking process of epoxy resin, reactions initially run very fast, its molecular weight grows and gelation temperature (T_g) increases as a result of increasing cross-linking density of the material. Reaction rate increases up to a certain state of mutual reaction of functional groups, at which viscosity of the system rapidly grows and a cross-linked structure appears. The instant in which the cross-linked structure appears and the viscous liquid is suddenly and irreversibly transformed into a flexible gel, is called *gelation point*. Since then chemical reaction mechanism (reactivity of functional groups) becomes weaker and its rate drops. The gelation, a molecular phenomenon takes place in an usually determinable phase of chemical reaction i.e. at a determined level of reaction progression within the system. Run of chemical reaction and its progression which is more generally called conversion, is affected by functionality, reactivity and stoichiometry of reagents. Level of conversion is determined by a level of reaction progression between functional groups

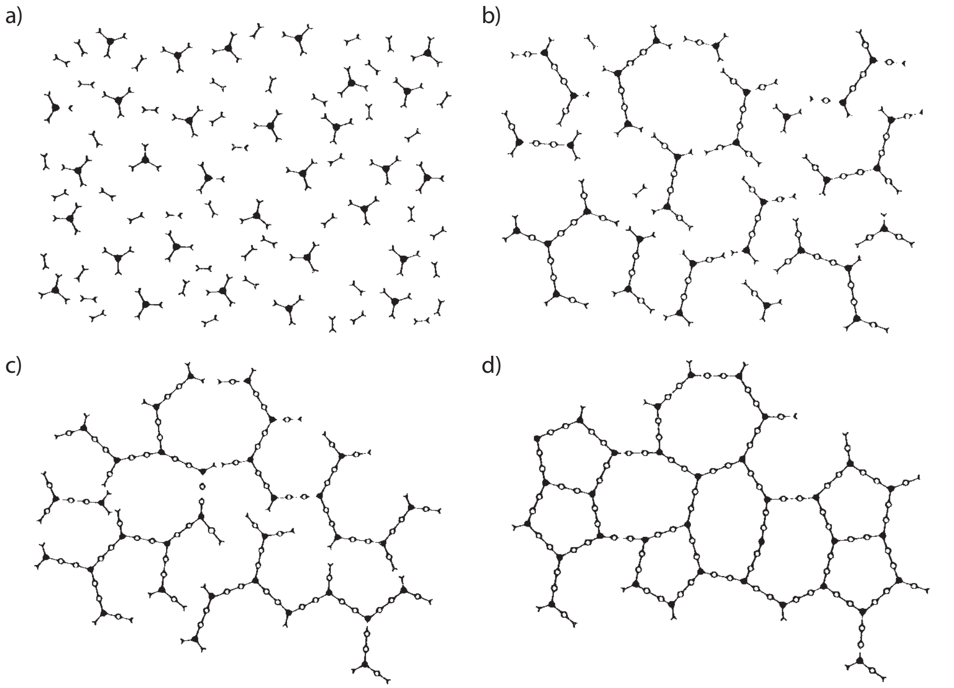


Fig. 3.1. Two-dimensional diagram of cross-linking process in epoxy systems : a) mixture of monomers; b) uniform linear growth and branching of chains (below gelation point); c) further formation of a gelled, but not fully cross- linked spatial structure; d) fully cross-liked spatial structure, [53]

(amine, anhydride and epoxy one etc) which take part in curing reaction. It can be measured from the beginning of curing up to the instant when content of functional groups may be still determined and changes in the content are already non measurable (after gelation). Further progression of the reaction is measured by increase of cross-linking rate. The gelation of epoxy systems usually takes place between 0.55 and 0.80 value of conversion rate [53÷55]. Its macroscopic consequence is the viscosity of an infinitely large value fast reached by the system and loss of processing capacity as a result of obtaining elastic properties which have been not yet present (in pre-gel) [53, 56].

The approaching of epoxy system to the gelation point is accompanied by growth in size of polymer particle, resulting from the reaction and increasing number of final groups. The greater number of multi-functional (branching) elements in a particle chain, the more reacting and more easily adjoining other elements, particle. Along with reaction progression the branched chains join to each other building this way huge macro-particles of tens and even hundreds of functional groups capable of joining other particles which have functional groups. Growth of the particles progresses fast and fast and leads to the state in which the whole system become a huge “macro-particle” of an infinitely large, in molecular scale, molecular weight. Finally, a physically uniform phase of “rigid body” character (*gel*) is formed [57].

After reaching the gelation point (*postgel*), apart from gel fraction a soluble and fusible fraction (*sol*) still remains. During further run of cross-linking reaction more and more particles are attached to the spatial network and cross-linking density increases. It means that share of gel fraction grows at the expense of sol fraction, and the mean molecular weight of the system (M_w) as such tends to infinity, though the increase of the numerically mean molecular weight (M_n) is rather small [58÷61]. The cross-linking density still increases and the gelation temperature as well.

When the gelation temperature becomes equal to the cross-linking temperature ($T_g = T_c$) the phenomenon of *glass transition* (*vitrification*) of resin system takes place. The glass transition is a transition from the elastic state of gel to the glassy state of not fully hardened gel (*sol/gel glass*) as a result of increase of cross-linking density. The glass transition is also possible due to the effect of over-cooling the viscous liquid, but then it is not preceded by gelation, and this state is in contrast called the glassy — semi gelation state (*sol glass*) [51]. The glass transition point signifies a change in mechanism of the reaction which now passes from the state controlled by chemical reactivity of functional groups to the state controlled by diffusion [62, 63]. When the system undergoes glass transition, the mobility of reacting functional groups becomes more and more limited and the chemical reaction rate drops significantly. The limitation finally causes that the reaction is practically stopped, making thus the reacting system to reach full conversion impossible [64, 65]. The glass transition of the system which occurs at such not fully ended reaction, is a conversion which can be started again. In a not fully cross-linked material, during its repeated heating, further cross-linking occurs in its “rigid state” (post cross-linking). The added heat triggers chemical reactions, that is called *devitrification* (inverted glass transition) [53]. Due to these reactions the cross-linking density of the consolidating material and — simultaneously — also its glass transition temperature increases.

When characterizing the epoxy resin cross-linking process, a few remarks and references to some technological aspects of the process, should be given. The reactions between resin and curing agent are strongly exothermic. The emanated reaction heat causes (especially when curing a large amount of resin in one portion) temperature of the system to grow. It increases mobility of particles, that accelerates the running of reactions between epoxy groups and curing agent. The cross-linking rate depends on reactivity of resin and curing agent, which is determined by their chemical structure. The low heat conductivity of the resin results in that the increase of temperature inside large casts in particular may be excessive and thus leading to local overheating and a state of high residual stresses in the casts, and even to fractures within them. The excessive temperature growth can be mitigated by adding, to the resin, a large amount of a mineral filling material (filler) which facilitates to carry away the emanated reaction heat. However the addition of mineral fillers results first of all in lowering the curing shrinkage, that is very important not only for large casts. Moreover, their addition substantially lowers the linear expansion coefficient of resin compound, that is especially important in the case when it has to work together with other materials without a hazard of occurrence of higher stresses and even fractures under temperature changes. Suitable heat conductivity of the fillers makes that the emanated reaction heat is carried away faster and the cross-linking process runs more uniformly. All the above results in that the resin compound thermal resistance and stability increases and some its mechanical properties improve. However, susceptibility of the fillers to sedimentation may result in non-uniformity of the compound and, in consequence, also of its properties inside cast mass [66].

The introduction of fillers usually extends the so called life of composition, i.e. a period in which its casting during a given technological process, is still possible. The casting is to be performed before the composition reaches the so called critical viscosity after which its viscosity rapidly increases leading to gelation of the system. The addition of fillers may also cause an increase in viscosity of the composition, that makes its processing and — in particular — its de-aeration more difficult. In such case in order to prepare a cast, heating the composition or using solvents, is necessary. This is the resin compound reactivity dependent on content of epoxy groups, curing agent reactivity and presence of solvents, which decides on the growth of viscosity in a given temperature [66].

The cross-linking process, after its initiation, runs very fast up to a certain progressing level of reaction of functional groups, then the rate of the action decreases. The decrease of reaction rate is caused by growth of viscosity as a result of formation of spatial network, that makes rate of diffusion of cross-linking substances within an only partly cross-linked system, lower. The curing process is accompanied with a rather small drop in volume of the compound due to a shrink resulting from an increase of its density. In its final phase the cross-linking process occurs in glassy state [67]. Therefore the cured polymer reaches its optimum mechanical properties as late as after a certain time. Hence the post- curing of resin system, i.e. holding it in an elevated temperature, is favourable. It especially concerns polymers curing in room temperature. The post-curing increases the cross-linking density of the resin system, and this way elevates its glass transition temperature which determines an ultimate temperature of application of a given polymer compound. Knowledge of the run and thermal effect of cross-linking process of an epoxy system, especially information on the phenomena of gelation and glass transition occurring when the process is under way, is necessary to characterize the system. Because the gelation and glass transition decide on physical, chemical and mechanical properties of the final material. This information is necessary for determination of effective cross-linking procedures which should ensure optimum properties of a resin compound intended for a given application.

As the gathered information is presented in the form of diagrams of various kinds, it is possible to describe run of cross-linking process in a possibly simple and comprehensible manner, both from physical and chemical point of view. The cross--linking diagrams may serve as an intellectual basis for analysing and designing cross-linking cycles of resin systems.

3.2. Cross-linking diagrams for epoxy compounds

3.2.1. General remarks

It is difficult, due to complexity of phenomena occurring in the cross-linking process, to determine *ad hoc* processing conditions in such a way as to obtain optimum properties of a resin compound intended for various specific applications. To this end, it is necessary to collect information data on run of cross-linking, gelation and glass transition in particular, which are needed to characterize an epoxy resin system.

The characteristic data connected with run of curing the epoxy system, such as e.g. changes in its viscosity, changes in rate of conversion and cross-linking, data on its gelation and glass transition, obtained with the use of relevant testing techniques, are usually not available in practice, or difficult for interpretation. However if the results obtained from experimental tests, e.g. by means of scanning differential calorimetry or rotational viscometry, are properly collected and numerically elaborated, then it will be possible to present complex relations between time, temperature and run of curing process in a graphic form, convenient in using and easy for interpretation. For analysing and designing the cross-linking cycles of epoxy compounds the following three diagrams are of crucial importance:

— TTT diagram, i.e. *Time—Temperature—Transformation*;
— CTT diagram, i.e. *Conversion—Temperature—Transformation;*
— T_gTP diagram, i.e. *Glass transition temperature—Temperature—Property.*

Elaboration of such diagrams makes it possible to achieve complete insight into behaviour of a given epoxy system during its cross-linking process and in consequence to select optimum conditions for its processing dealing with a given application, e.g. curing conditions for machinery foundation chocks. The above mentioned diagrams, because of their great theoretical and practical importance, are presented below first in a general way and then determined and discussed in application to EPY compound.

3.2.2. TTT diagram: Time—Temperature—Transformation

The TTT isothermal cross-linking diagram (*Time—Temperature—Transformation*), elaborated by John K. Gillham [51, 68], presents in a simple and clear way complex relations between time, temperature and phenomenological changes within the three states: *liquid, gel and solid,* which epoxy resins undergo during cross-linking reaction. Every transition occurring within the three states are schematically presented in the TTT diagram (Fig. 3.2) by the contours of time to gelation and glass transition at various values of the cross-linking temperature (T_c). The time runs of cross-linking process are usually contained between the glass transition temperature line for not fully cross-linked system (T_{g0}) and the glass transition temperature line for fully cross--linked system ($T_{g\infty}$). Transitions from one state to another cause significant changes in thermo-mechanical properties of epoxy system and contain two, macroscopically clearly observable, phenomenological changes in the resin, namely: the gelation, i.e. transition from liquid state to gel state and the glass transition i.e. transition from liquid or gel state to solid (glass) state. In the TTT diagram (Fig. 3.2) the transitions are illustrated by sets of the gelation and glass transition points which form, respectively, sloping curve of gelation and S-shaped curve of glass transition of the system. In the gelation point the resin ends to be liquid and loses capability to further processing, and in the glass transition point where flexibility of the resin suddenly grows, the glass transition temperature (T_g) reaches the upper value of processing temperature.

Within the three states in the TTT diagram (Fig. 3.2), a few sub-zones which illustrate the intermediate states of cross-linking process, dependent on temperature, time and specific properties of epoxy system, (T_{g0}, ${}_{gel}T_g$, $T_{g\infty}$), can be distinguished [51, 53, 58, 69÷72]. The sub-zones of the diagram, separated by the gelation curve, the S-shaped glass transition curve and the complete cross-linking line (Fig. 3.2), represent the following seven states of the system:

— *liquid* state;
— *sol glass* state, i.e. fully not cured glassy material;
— *sol/gel rubber* state, i.e. fully gelled, but not fully cured material;

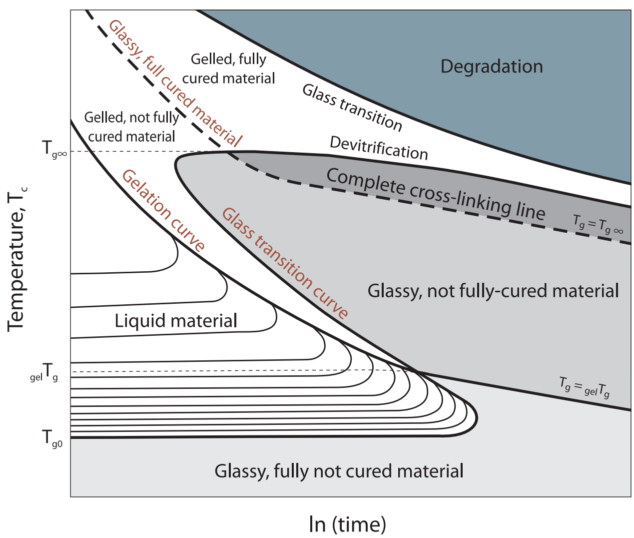


Fig. 3.2. The schematic cross-linking diagram TTT (time—temperature—transformation) for epoxy resins, which shows their various morphological states [58]

— *gel rubber* state, i.e. fully cured material*;*
— *sol/gel glass* state, i.e. glassy, not fully cured material;
— *gel glass* state, i.e. glassy, fully cured material;
— *char*, i.e. degraded material.

On TTT diagram also other information concerning run of cross-linking, e.g. those dealing with changes in viscosity (iso-viscosity lines) as well as relations between conversion progress and glass transition temperature (iso-conversion lines), may be presented. Such diagram allows to get full insight into thermo-mechanical behaviour of epoxy composition during cross-linking process and serves as a useful tool for visualization, understanding, analysing and designing cross-linking cycles of epoxy systems and determination of their properties. The diagram enables to select an appropriate cross-linking path expressed in the time –temperature coordinate frame so as the gel and glass transition processes, on whose run both the processing and thermo-mechanical properties of the compound depend, would be carried out in a controlled way in order to obtain desired features of a final product [58, 72].

The basis for the isothermal cross-linking diagram consists of three characteristic temperatures: T_{g0} — the glass transition temperature of non-cross-linked reagents; $_{gel}T_g$ — the temperature in which gelation and glass transition occur simultaneously and $T_{g\infty}$ — the glass transition temperature for fully cross-linked system, and moreover: the contours of time to gelation and glass transition of the compound at various cross-linking temperatures.

The line between the temperatures T_{g0} and $T_{g\infty}$, put in the TTT diagram (Fig. 3.2), determining the time along which glass transition takes place, is of a characteristic S-shaped form. Its outline results from that reaction rate increases along with temperature increasing, and the time to glass transition reveals two extremum points within this interval. The first one occurs in the cross-linking temperature a little above T_{g0} when the time to glass transition reaches its maximum due to a large amount of reagents at constant reaction rate. The other — in the temperature a little below $T_{g\infty}$, when the time to glass transition reaches its minimum as a result of lowering concentration of reagents and high reaction rate in elevated temperature. Hence the shape of the glass transition curve is a function of reaction kinetics, values of the temperatures T_{g0}, $_{gel}T_g$ and $T_{g\infty}$ of the system as well as the relation between the glass transition temperature and conversion [51, 71]. The sloping gelation curve depicted on the diagram (Fig. 3.2), illustrates extension of time to glass transition along with lowering cross-linking temperature and crosses the glass transition curve at the characteristic temperature $_{gel}T_g$, in which gelation and glass transition of the system takes place simultaneously.

Into the solid state zone in the TTT diagram, limited by the gelation curve (above $_{gel}T_g$) and the glass transition curve (below $_{gel}T_g$), iso-viscosity lines are usually drawn for consecutive orders of magnitude. They illustrate rapidly growing viscosity of the system [58]. It should be noticed that the glass transition curve below $_{gel}T_g$ turns out to be the contour of iso-viscosity zone. The change of viscosity along with time is one of the most important technological parameters of the cross-linking process, and the level of iso-viscosity is usually taken as a practical measure of gelation. And, the iso-conversion curves in the TTT diagram are drawn approximately parallel to the line of complete cross-linking and the gelation line as well, because the gelation is considered an iso-conversion state [58, 73].

When reading the cross-linking runs at particular temperatures T_c, presented in the diagram, it should be remembered that generally no chemical reaction takes place below the temperature T_{g0} (Fig. 3.2). The lack of reactivity of the system below T_{g0} results from the freezing of mobility of particles. Therefore the material is in glassy state which contains sol fraction only. Hence the temperature T_{g0} serves for determination of temperature of storing the resins which has not underwent any reaction.

During the cross-linking process of the system above T_{g0}, its particles react to each other, grow and branch — thus cross-linking density and glass transition temperature of the system increases. If curing temperature is maintained within the range between T_{g0} and $_{gel}T_g$ (Fig. 3.2), the initially liquid resin will react without any gelation till the instant when the continuously growing temperature of glass transition is equal to the cross-linking temperature ($T_g = T_c$) and glass transition phase then starts. As the material undergoes glass transition without gel fraction, such state, soluble and fusible, is called *sol glass* state, i.e. fully not cured glassy state. The glass transition stops chemical reaction and prevents gelation. In the conditions of rapidly dropping rate of reaction, any greater number of covalent bonds (rigid, strong bonds creating the main polymer chain) which are the most favourable as regards strength of the compound, can be formed. As a result, among particles of the resin only weak physical interactions (cohesion forces) will prevail. Therefore a potential strength of the so "cured" resin would be utilised only to an insignificant degree. The temperature $_{gel}T_g$, in which gelation and glass transition simultaneously occur, determines the end of occurrence of this state.

If the cross-linking process runs within the temperature range between $_{gel}T_g$ and $T_{g\infty}$ (Fig. 3.2), the gelation of the system occurs at first, i.e. the forming of a spatial cross--linking structure. The then following glass transition takes place only when the continuously growing glass transition temperature reaches the cross-linking temperature ($T_g = T_c$). After the gelation, the glass transition temperature increases as a result of an increase of cross-linking density and the numerically mean molecular weight (M_n) (sol/gel mixture) [74]. After the gelation, reactive molecules react further and increase gel fraction until the glass transition significantly constrains molecular and sub-molecular mobility. Because of a lack of mobility of molecules a still large number of functional groups present in the system is not able to react and chemical reactions are practically stopped. Nevertheless a large number of the formed covalent bonds ensures strength properties of the resin system, equivalent to its level of reaction progression. At lack of its full cross-linking the vitrified material, in temperature between ${}_{gel}T_g$ and $T_{g\infty}$, will contain components of both sol and gel fraction. Such state of the material is called the *sol/gel glass* state, i.e. glassy, not fully cured state, which is non-soluble and non-fusible.

The resin system reactions are close to be completed relatively fast in the cross-linking temperature above $T_{g\infty}$, and significantly slower during cross-linking in the full cross-linking temperature ($T_g = T_{g\infty}$) — Fig. 3.2. The glassy state between ${}_{gel}T_g$ a $T_{g\infty}$ is divided by the above mentioned line into two zones: that below the line, where the cross-linking process is not yet fully completed, called the *sol/gel glass* state, and that above the line, where the resin system has fully undergone the reactions, called the *gel glass* state (i.e. glassy, fully cured state).

If the cross-linking process runs above $T_{g\infty}$ temperature, the resin system will undergo the gelation, but not glass transition, and any increase of cross-linking temperature will be able to lead to its degradation. The line of the complete cross-linking in the zone above $T_{g\infty}$ temperature of the system separates the *sol/gel rubber* state (i.e. that fully gelled, but not fully cured) from the *gel rubber* state (i.e. that fully cured) which can be obtained as a result of the extended isothermal cross-linking [51, 53, 58, 70, 71].

At higher temperature values (above $T_{g\infty}$) the material is exposed to thermal degradation [75, 76]. In the TTT diagram two cases of it can be distinguished: *devitrification* after which the material passes from its glassy state to elastic one, and *revitrification* which practically is the beginning of charring. The case of devitrification is associated with a drop in the glass transition temperature from that above the isothermal cross-linking temperature to that below it. This drop results from a lower number of bonds and higher elasticity of the material. The instant in which this case occurs, is considered a limit of time during which the material is capable of carrying loads. Another case is the transition from elastic state to glass state of high rigidity, resulting from an increasing number of bonds or the volatilizing of a more elastic material having low molecular weight, that leads to a state in which charring may be triggered [58, 71, 77].

Comparison of properties of different materials may lead to correct conclusions only if the materials are in the same state of cross-linking. Therefore, the determination of structure — properties relations is first of all performed for not fully cross-linked resin systems, which can be obtained most easily by carrying out the cross-linking in a temperature close to $T_{g\infty}$ for a given resin system without exposing it to degradation.

3.2.3. CTT diagram: Conversion—Temperature—Transformation

Making use of the data similar to those applied in the case of TTT diagram, Adabbo and Williams [78] developed another diagram placed in the coordinate frame: conversion—temperature—transformation, called the CTT diagram, simple and useful in analysing runs of the cross-linking process in epoxy resins.

The CTT diagram presented schematically in Fig. 3.3, shows relations between chemical conversion progression in a chemically cured polymer, increase of glass transition temperature and phenomenological changes which occur during cross--linking [70, 78÷80]. Such diagram can be obtained by an appropriate transformation of TTT diagram (Fig. 3.2), with taking into account the fact that gelation of a given epoxy system occurs at one and the same level of chemical conversion, disregarding cross-linking temperature [70]. Hence the gelation curve given in TTT diagram is transformed here into the gel conversion line (α_{gel}), and the glass transition curve is represented in CTT diagram (Fig. 3.3) by the curve ($\alpha_g - T_g$): conversion of glass transformation versus glass transition temperature.

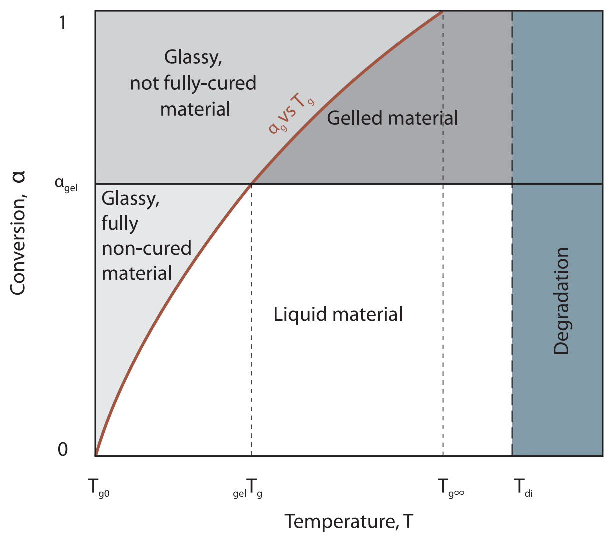


Fig. 3.3. The schematic cross-linking diagram CTT (conversion—temperature—transformation) for epoxy resins, which shows their various morphological states [78]

The CTT diagram shows in a more general way behaviour of chemically-cured resin composition during cross-linking process. The area of CTT diagram, divided by the lines: α_{gel} and α_g versus T_g, crossing each other in the gelation point, presents four morphological states of cross-linking system, which take place depending on level of conversion (cross-linking) and its temperature:

— *liquid* state;
— *sol glass* state, representing a glassy, fully non-cured material;
— *sol/gel glass* state, representing a glassy, not fully cured material;
— *rubber* state, representing a gelled material.

and, the additionally drawn line of the degradation beginning temperature (T_{di}) makes it possible to show the decomposition (thermal degradation) zone of the compound.

Location of the gel conversion line α_{gel} in CTT diagram depends on functionality of reagents but not on temperature. However, temperature is able to modify reactivity of functional groups, or to generate group substitution effects or intermolecular reactions, which in consequence change α_{gel} value [78]. The α_g value is here the conversion which leads to glass transition of the resin system in the glass transition temperature (T_g). Increase of T_g along with the conversion progressing takes place due to increasing level of cross-linking [81, 82]. The denotations of particular temperatures (T_{g0}, $_{gel}T_g$, $T_{g\infty}$) in the CTT diagram (Fig. 3.3) are the same as those used in the TTT diagram (Fig. 3.2), and T_{di} stands for the degradation beginning temperature of the compound.

3.2.4. TgTP cross-linking diagram: Glass transition Temperature—Temperature—Property

The cross-linking diagram drawn in the coordinate frame: *Glass transition temperature—Temperature—Property*, called T_gTP diagram, where P stands for a given material property (e.g. modulus of lossiness, density, rate of physical ageing), is shown in Fig. 3.4. It was developed by Wang and Gillham [83, 84].

The T_gTP diagram forms an overall frame for the formulating and understanding of relations between progression of cross-linking reactions of the system at various temperatures and its properties in particular states –from liquid state to glassy state [83, 84]. The axis of abscissae of T_gTP diagram represents progression of cross-

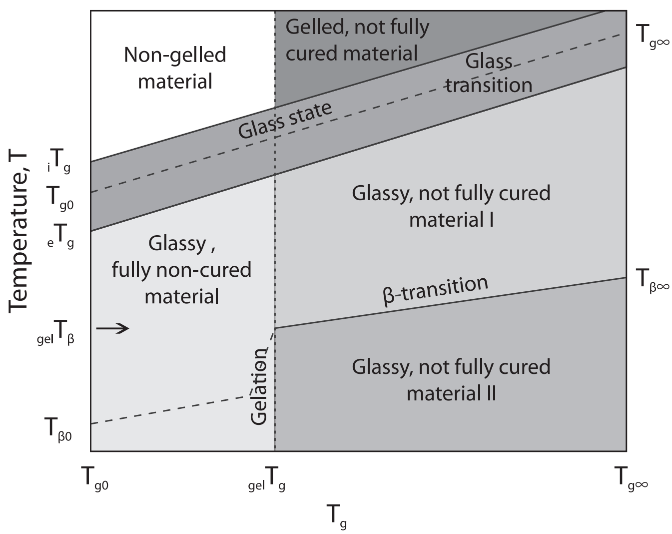


Fig. 3.4. The schematic cross-linking diagram TgTP (glass transition temperature—temperature—property) for epoxy resins, which shows their various morphological states [83]

-linking reaction expressed by measurements of the glass transition temperature (T_g) of epoxy system, and the axis of ordinates — temperature of the system. The straight lines in the diagram represent progression level of the cross-linking conversion, related to the characteristic temperatures of the system, i.e. the temperature of glass transition (T_g), the temperature of its beginning (${}_iT_g$) and its ending (${}_eT_g$), the temperature of β-transition ($T_β$), as well as the temperature in which gelation and glass transition occur simultaneously (${}_{gel}T_g$). The diagram is divided by these lines into six zones which represent different states of a cross-linking material:

— *ungelled glass* (a glassy, fully not cured material);
— *gelled glass I* (a glassy, not fully cured material I);
— *gelled glass II* (a glassy, not fully cured material II);
— *glass transition* (a glassy material);
— *sol fluid* (a liquid material);
— *sol-gel rubber* (a gelled, not fully cured material).

The so prepared diagram is aimed at demonstrating the impact of conversion of the system (measured by T_g value) on isothermal properties of the material. The zones marked in the diagram, show that structural changes occur along with the conversion progressing, and particular lines of the diagram make it possible to indicate maximum and minimum values for selected properties, depending on conversion of the system. Therefore T_gTP diagram makes it possible to determine physical properties of the material in function of progression level of cross-linking of the system, depending on its temperature and T_g temperature.

T_gTP diagram plays similar role as TTT diagram (Fig. 3.2), with the difference that the first deals rather with the properties of the system after cross-linking process than during its run [51]. Their ordinate axes (measurement temperature) are the same. However their axes of abscissae represent different quantities; in T_gTP diagram it is the glass transition temperature, and in TTT diagram — duration time of reaction, that substantially changes representation of the system's conversion. In TTT diagram progression level of the conversion is represented by iso-conversion curves, whereas T_gTP diagram shows progression level of the conversion directly on the axis of abscissae and the glass transition temperature ($T_{g)}$ is used as its measure. Measurement of T_g is more exact than that of level of conversion, especially at its greater values [85], owing to this the measured value of T_g better represents progression leveof the cross-linking reaction and is a more sensitive indicator of changes in cross-linking structure. Hence the glass transition temperature is associated with the structure and this way with state and properties of the material. It should be also mentioned that physical properties of the system in the glass transition state (e.g. density, modulus, rate of physical ageing) in function of cross-linking progression level are mainly determined by the temperature interval T_g—T [83], and their changes are caused by T_g and $T_β$ transitions, whose temperatures increase along with cross-linking progression in epoxy system.

3.3. TTT, CTT and T_gTP cross-linking diagrams for EPY compound

3.3.1. Method of preparation of TTT, CTT and T_gTP diagrams

Preparation of TTT, CTT and T_gTP cross-linking diagrams only on the basis of results of experimental tests would be extremely labour-consuming and expensive. Therefore to prepare such diagrams are used not only results of direct experimental tests but also empirical models of cross-linking process, which describe relations T_g and α versus temperature and duration time of cross-linking process of a given resin system. The models make it possible, by means of numerical calculations, to appropriately process results of made experimental tests and this way to reduce as much as possible number of tests necessary to prepare the cross-linking diagrams for EPY compound.

The experimental tests cover determination of:

— characteristic glass transition temperatures (T_{g0}, $T_{g\infty}$) by means of DSC technique, using dynamic method;

— cross-linking progression level and glass transition temperature of cross--linking compound in various temperatures and duration times, by means of DSC technique, using dynamic and isothermal methods;

— gelation point of the compound by means of rotational viscometry technique, using dynamic method;

— degradation initial temperature (T_{di}) by means of TG-DTA technique;

— lossiness modulus (E") by means of DMTA technique.

The empirical models formed on the basis of results of empirical tests, achieved from DiBenedetto equation [81, 86], make it possible:

— to inter-relate increase of the glass transition temperature (T_g) and the cross--linking progression level (α);

— to predict cross-linking progression level during gelation (α_{gel});

— to forecast cross-linking progression level, depending on duration time and temperature.

The models, if appropriately linked, enable to forecast results of experimental tests and perform the numerical mapping of the contours and lines in TTT, CTT and T_gTP cross-linking diagrams. The cross-linking diagrams obtained in the experimental and theoretical manner, make it possible to achieve full insight into behaviour of a given epoxy system under curing without necessity of conducting many experimental tests. The way of preparation of the diagrams in question is schematically presented in Fig. 3.5, 3.6 and 3.7, respectively.

3.3.2. TTT cross-linking diagram for EPY compound

The isothermal cross-linking diagram TTT (Time—Temperature— Transformation) prepared for EPY compound is presented in Fig. 3.8. The characteristic temperatures of the compound under testing, necessary for depicting contours of the diagram, are the

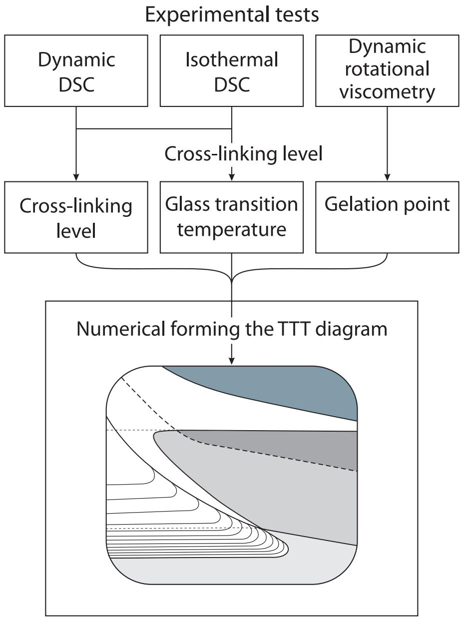


Fig. 3.5. Schematic box diagram for preparation of the cross-linking diagram TTT

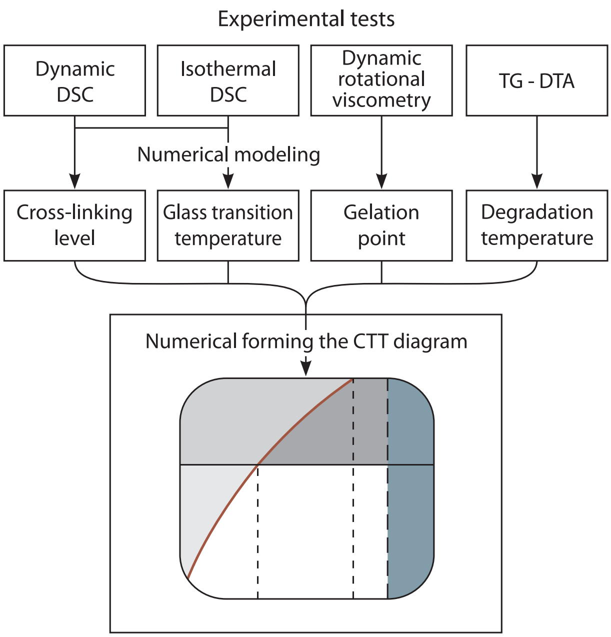


Fig. 3.6. Schematic box diagram for preparation of the cross-linking diagram CTT

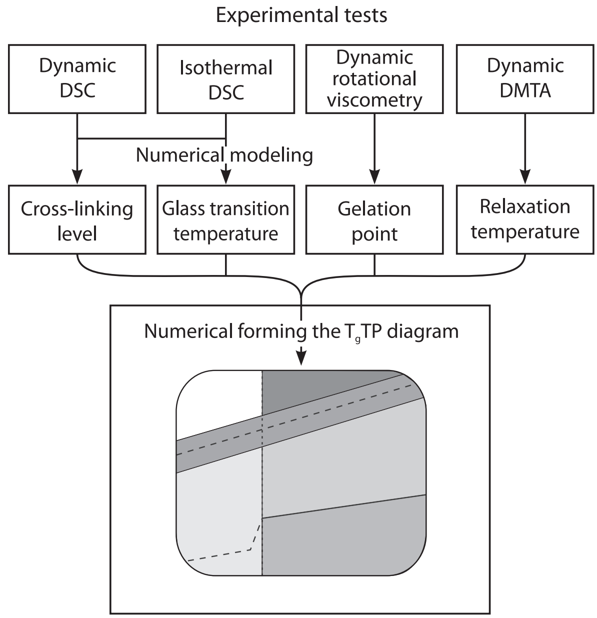


Fig. 3.7. Schematic box diagram for preparation of the cross-linking diagram T_gTP

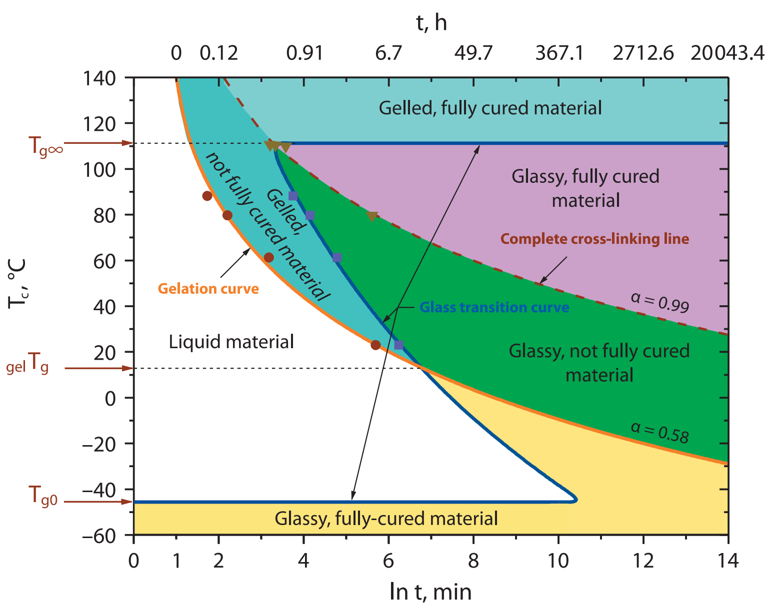


Fig. 3.8. The cross-linking diagram TTT (time—temperature—transformation) for EPY compound, which shows its various morphological states

following: the glass transition temperature of non-cross-linked reagents $T_{g0} = -45.6°C$ and the glass transition temperature of the fully cross-linked compound $T_{g\infty} = 111.2°C$. The values were determined experimentally by means of DSC method. Whereas the temperature in which gelation and glass transition occur simultaneously ${}_{gel}T_g = 12.5°C$ was calculated by using DiBenedetto equation [86] and the level of cross-linking progression at gelation, $\alpha_{gel} = 0.58$, was obtained experimentally by means of ARES and DSC methods. The detail descriptions and results of experimental tests as well as ways of determination of the aforementioned characteristic temperatures are given in the publications [87, 88].

The TTT diagram (Fig. 3.8) was produced by calculating duration time to gelation and glass transition for different cross-linking temperatures, with taking into account that the gelation curve and glass transition curve cross each other in the time point which corresponds to ${}_{gel}T_g$ value. For depicting contours of both the curves, results obtained from experimental tests and relevant computations, were used [87, 88]. Into the diagram also iso-conversion contours corresponding to the values $\alpha = 0.58$ and 0.99, are introduced. The iso-conversion curves were determined by means of numerical integration of a kinetic model which takes diffusion into account.

The glass transition curve contour for EPY compound, i.e. a set of geometrical loci of the cross-linking times in which condition $T_g = T_c$ is satisfied, was determined by transforming values of cross-linking progression level into T_g values with the use of a relevant equation based on DiBenedetto relationship [87, 88]. The gelation curve contour coincides with that of the ideal molecular gelation which occurs (acc. Flory theory) at the conversion of 0.577 in value, and which corresponds exactly to the value of $\alpha_{gel} = 0.58$ experimentally determined by using ARES and DSC methods [87, 88]. In the experimentally determined gelation points it was observed that the conversion remains almost constant irrespective of heating temperature and its progression in the system. Hence it can be assumed that the gelation contour is iso-conversional. A good conformity was observed between the experimental values and those calculated in accordance with the selected models of gelation and glass transition curves.

The iso-conversion curve corresponding to the cross-linking progression level $\alpha = 0.99$ was assumed to be the complete cross-linking line. The curve corresponds to the maximum conversion obtained during the performed experimental tests.

In TTT diagram the glass transition curve is S-shaped (Fig. 3.8), hence values of the time to glass transition reach their maximum in the cross-linking temperature just above T_{g0}, and their minimum — just below $T_{g\infty}$. The occurrence of the maximum of time to glass transition is caused by the simultaneously occurring effects of increasing reactivity and decreasing viscosity along with temperature rising, and the occurrence of its minimum value — by the effects of increasing reaction rate coefficient and increasing conversion level at glass transition along with temperature rising [77, 89].

The determined contours and lines of TTT diagram (Fig. 3.8) indicate particular morphological states in which the EPY epoxy compound under testing may be found, in given cross-linking conditions:

— *liquid* state;
— *sol glass* state, representing a glassy, fully non-cured material;
— *sol/gel rubber* state, representing a gelled, not fully cured material;
— *gel rubber* state, representing a gelled, fully cured material;
— *sol/gel glass* state, representing a glassy, not fully cured material;
— *gel glass* state, representing a glassy, fully cured material.

In compliance with TTT diagram, when the epoxy system is cross-linking, its glass transition temperature increases along with conversion progressing. When T_g reaches value of the isothermal cross-linking temperature (T_c) the material undergoes glass transition. In the neighbourhood of the glass transition phase, mobility of segments drops and the total reaction rate is controlled by a limited diffusion of reacting components [90].

The temperature $T_{g0} = -45.6°C$ corresponds to that of glass transition of EPY compound at the conversion progression level $\alpha = 0$. Below this temperature the compound is a glassy body soluble in appropriate solvents. In the temperature below T_{g0} the resin system does not react. The temperature ${}_{gel}T_g = 12.5°C$ is that in which EPY compound simultaneously undergoes gelation and glass transition.

Between T_{g0} and ${}_{gel}T_g$ temperatures ($-45.6°C < T_c < 12.5°C$) the system will react until its continuously increasing temperature reaches the cross-linking temperature ($T_g = T_c$). Then the glass transition phase starts without gelation and the reaction is controlled by diffusion. At glass transition below ${}_{gel}T_g$ the material is of a low molecular mass and passes from the liquid state to the *sol glass* state, in which it becomes glassy, but fully non-cured, and floats under heating.

Between ${}_{gel}T_g$ and $T_{g\infty}$ temperatures ($12.5°C < T_c < 111.2°C$) the reacting EPY compound reaches its point of gelation before glass transition. After gelation the cross--linking material contains both sol and gel fractions. The initially formed gel is weak and can be easily disrupted. Beyond the gelation point (the conversion in the gelation point $\alpha_{gel} = 0.58$) more and more particles join the spatial network and the gel fraction grows at the expense of the sol fraction which diminishes up to null when the material reaches the maximum conversion progression level. At the glass transition ($T_g = T_c$) the reaction is generally blocked as a result of lacking mobility of particles, with a certain number of not yet reacting functional groups left in the compound. Consequently, the reaction progression level close to complete one ($\alpha = 1$) may be obtained by the system only after additional cross-linking in the temperature above $T_{g\infty}$, that is shown in Fig. 3.9 for the tested compound.

The zone between the temperatures ${}_{gel}T_g$ and $T_{g\infty}$, in which material passes from the *liquid* state to *sol/ gel rubber* state and then to *sol / gel glass* state is, for practical reasons, most inferring for typical cross-linking processes.

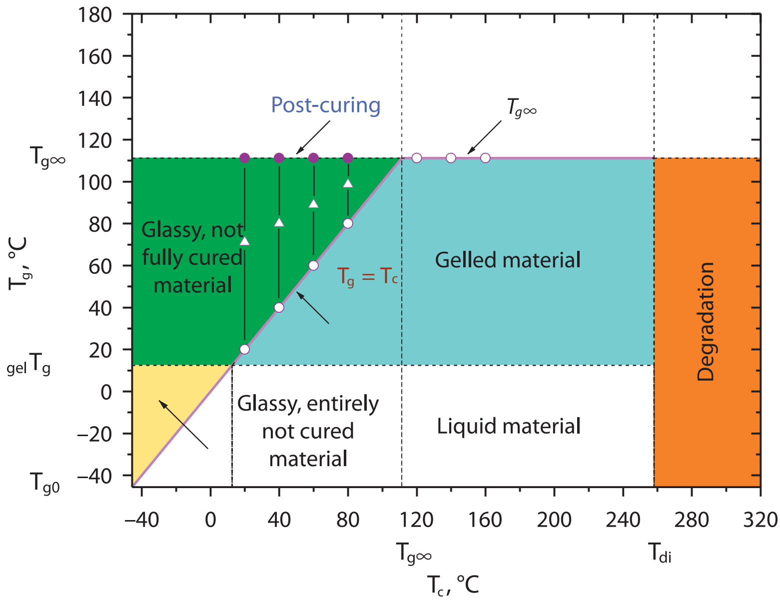


Fig. 3.9. Glass transition temperature (T_g) in function of isothermal cross-linking temperature (T_c) for EPY compound

If the cross-linking reaction runs in the temperature above $T_{g\infty}$ (111.2°C) the material undergoes gelation but glass transition will not occur at all. Such high cross-linking temperature may only lead to its chemical degradation then to thermal one and finally to loss of all of its usage properties. The initial thermal degradation temperature of EPY compound is equal to T_{di} = 258°C, that was determined by means of the experimental method TG-DTA [87, 88].

3.3.3. CTT cross-linking diagram for EPY compound

The CTT cross-linking diagram (conversion—temperature—transformation) produced for EPY compound, is presented in Fig. 3.10. It contains relations between progression level of chemical conversion in the compound in question, rise of glass transition temperature and phenomenological changes during its cross-linking.

The characteristic temperature values: T_{g0} = –45.6°C, ${}_{gel}T_g$ = 12.5°C i $T_{g\infty}$ = 111.2°C for EPY compound (see p. 3.3.2) were determined experimentally or calculated in accordance with the assumed model (DiBenedetto equation) [87, 88, 91]. And, the initial degradation temperature T_{di} = 258°C of the compound was experimentally determined by using TG-DTA method [87, 91].

The main profile in the CTT diagram, i.e. the curve which determines level of conversion progression during glass transition in function of temperature (α vs. T_g), was determined with the use of DiBenedetto equation [87, 91].

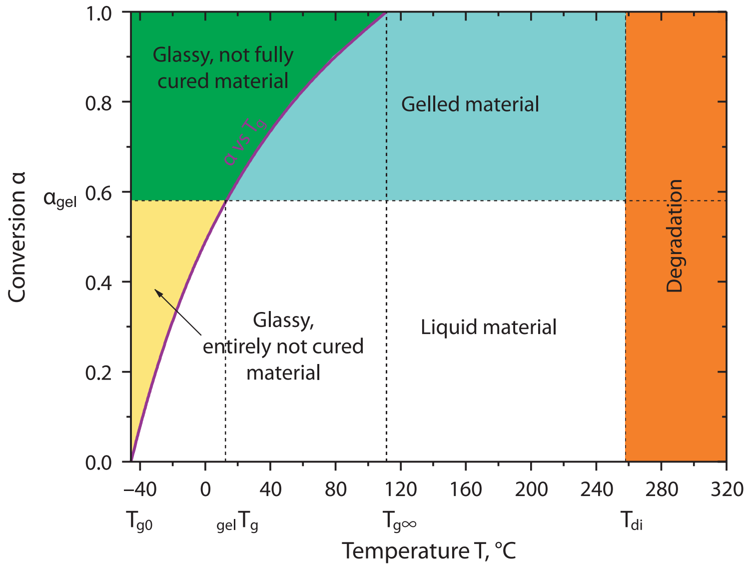


Fig. 3.10. The cross-linking diagram CTT (conversion—temperature—transformation) for EPY compound, which shows its various morphological states

Details concerning the determination of the relation of gelation point and cross--linking progression level in function of temperature, by using ARES and DSC testing methods, can be found in the publications [87, 88, 91]. As results from them, gelation of EPY compound runs at cross-linking progression level $\alpha_{gel} \approx 0.58$ almost regardless of heating rate, generally.

In CTT diagram (Fig. 3.10) the conversion line in the gelation point (α_{gel}) together with the conversion curve of glass transition in function of temperature (α vs. T_g), crossing it in the gelation point, determine four zones which represent morphological states of the compound in question:

— *liquid* state;
— *ungelled glass* state, representing a glassy, not cured material;
— *gelled glass* state, representing a glassy, not fully cured material;
— *rubber* state, representing a gelled material.

Moreover, the line of temperature T_{di} depicted in the diagram, makes it possible to represent another morphological state of the compound, namely the state of degradation (*decomposition*).

As shown in the diagram (Fig. 3.10), during cross-linking process of the compound in question its glass transition temperature (T_g) increases linearly, beginning from its initial temperature $T_{g0} = -45.6°C$ (at the conversion progression level $\alpha = 0$) through its value corresponding to gelation, i.e. $_{gel}T_g = 12.5°C$ ($\alpha = 0.58$) up to its maximum value of $T_{g\infty} = 111.2°C$ (at the maximum value of conversion progression level $\alpha = 1$)

as a result of cross-linking density increasing. The relation between gelation temperature and conversion, described by the gelation curve, enables to use T_g values as a direct measure of conversion progression level which may serve in practice as an indicator of thermo-mechanical properties of the compound [92, 93]. In the diagram it was also shown that, beginning from the temperature T_{di} = 258°C, the thermal degradation of the material takes place (loss of all its usage properties) which may be caused by using an excessively high temperature ($T_c >> T_{g\infty}$ = 111.2°C) during its cross-linking process.

It should be emphasized that CTT diagram can be prepared by means of an appropriate transformation of TTT diagram (Fig. 3.8), with taking into account that gelation of a given composition occurs at the same chemical conversion, regardless of temperature [53, 70]. For this reason the gelation curve of TTT diagram is now presented as the gel conversion line (α_{gel}), and the glass transition curve of TTT diagram is presented in CTT diagram as the glass transition curve in function of temperature.

Therefore the so produced CTT diagram (Fig. 3.10) makes it possible to have an insight into run of phenomenological changes in EPY epoxy compound in function of progressing cross-linking reaction and increasing glass transition temperature, owing to this it may serve as a useful tool for control and assessment of quality of cross-linking process [94].

3.3.4. T_gTP cross-linking diagram for EPY compound

The cross-linking diagram T_gTP (glass transition temperature—temperature—property) made for EPY compound, is presented in Fig. 3.11, where P stands for a selected property of the compound, i.e. its lossiness modulus (E”). The axis of abscissae is the conversion measured by means of T_g temperature value, and the axis of ordinates — measurement temperature.

The values of EPY compound characteristic temperatures, i.e. T_{g0} = −45.6°C, $_{gel}T_g$ = 12.5°C i $T_{g\infty}$ = 111.2°C (see p. 3.3.2) were determined experimentally or calculated by using the model (DiBenedetto equation) [87, 88, 95].

The main lines of the T_gTP diagram are straight ones (Fig. 3.11) which represent gelation and glass transition conversions forming material properties. The gelation is denoted by a vertical broken line which demarcates the zones of sol and sol/gel fractions in the temperature $_{gel}T_g$ = 12.5°C. And, the glass transition is shown in T_gTP diagram by means of a skew line representing the condition of T_g = T. In the diagram, the line of the glass transition beginning ($_iT_g \approx T_g - 20$°C) and its end ($_eT_g \approx T_g + 35$°C) is also depicted. The run of changes in the β-relaxation temperature (T_β), represented in the range of low conversions by a broken line and in the range of high ones — by a skew line, is also illustrated. The β-relaxation temperature (T_β) associated with local movements of sub-segments at β-transition below T_g. The way of determination of T_β by applying DMTA method is highlighted in the publications [87, 95].

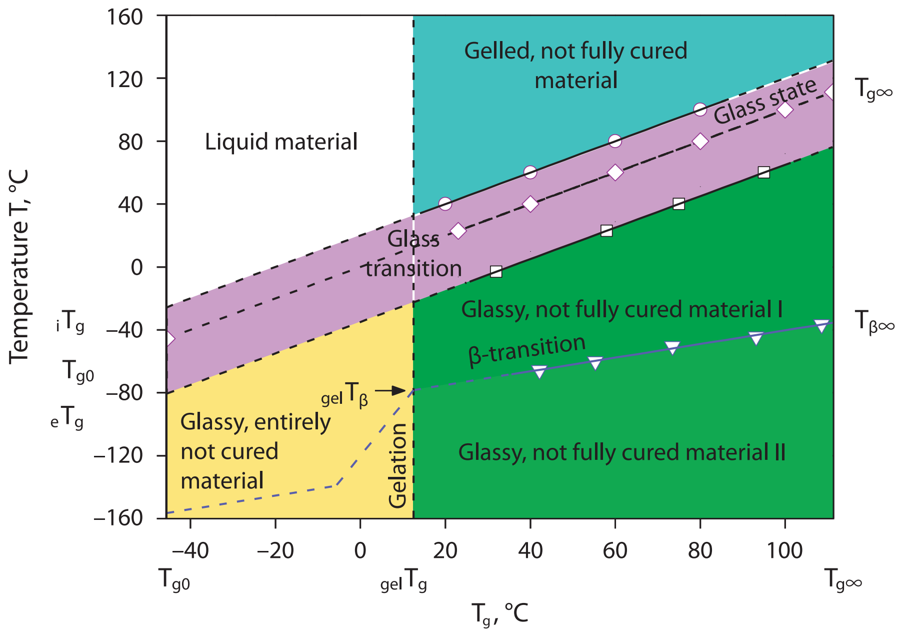


Fig. 3.11. The cross-linking diagram T_gTP (glass transition temperature—temperature—property) for EPY compound

The T_gTP diagram (Fig. 3.11) is divided by the above mentioned lines into particular zones of epoxy material cross-linking progression in a selected cross-linking temperature. In each of the zones the material is characterized by different physical properties. When considering properties of the compound in question at different cross-linking temperatures, in the aspect of changes in its lossiness modulus (E”), the following zones can be distinguished in the diagram:

— *ungelled glass* state (within the temperature range of — $T < {}_eT_g$ and $-45.6°C < T_g < 12.5°C$) in which the lossiness modulus (E”) linearly increases along with the cross-linking progressing.

— *gelled glass I* state, i.e. of a glassy, not fully cured material, ($T_\beta < T < {}_eT_g$ and $12.5°C < T_g < 111.2°C$; in which the lossiness modulus (E”) linearly decreases along with the cross-linking progressing.

— *gelled glass II* state ($T < T_\beta$ and $12.5°C < T_g < 111.2°C$) in which the lossiness modulus (E”) linearly increases along with the cross-linking progressing in a similar manner as in the *ungelled glass* state.

— *glass transition* state (${}_eT_g < T < {}_iT_g$ and $-45.6°C < T_g < 111.2°C$) in which the lossiness modulus (E”) intensively increases along with the cross-linking progressing as a result of glass transition, reaching its maximum value in the temperature ${}_eT_g$. The glass transition zone in the T_gTP diagram contains three lines representing: the glass transition beginning ($_iT_g \approx T_g - 20°C$), glass transition ($T_g = T_c$) and its end ($_eT_g \approx T_g + 35°C$), respectively.

— *sol fluid* state ($T > T_g$ and $-45.6°C < T_g < 12.5°C$) of a viscous liquid material having a low value of the modulus (E″) which shows a small gradual increase in the neighbourhood of the gelation point [51, 83].

— *sol-gel rubber* state ($T > T_g$ and $12.5°C < T_g < 111.2°C$) of a gelled, not fully cured material, in which the modulus (E″) increases along with the cross-linking progressing.

Usefulness of the T_gTP diagram consists in that T_g values are there used as a measure of conversion progression, making this way that the critical points such as the maximum and minimum of the modulus are linearly located, approximately parallel to the glass transition line (T_g). It means that properties of chemically curing compounds in the glass transition state are mainly determined by the temperature range T_g—T of the material. Due to the fact that the relations between the critical points and temperature run linearly in the T_gTP diagram, to prepare it for various chemically curing materials is easy [83].

3.4. Summary

The cross-linking diagrams TTT (time—temperature—transition) and CTT ones (conversion—temperature—transition) as well as the complementary diagram T_gTP (glass transition temperature—temperature—property), prepared for the EPY compound may be a useful tool for analysing and designing its cross-linking cycles, because in the diagrams all the phenomenological changes which occur during the complex cross-linking process, are represented. In particular it concerns gelation and glass transition phases resulting from the chemical reaction which converts a viscous liquid into a solid material. Along with the progressing of chemical reaction (conversion), changes occur in the compound lossiness modulus, which show how far the occurring structural conversions (gelation and glass transition) are important for the creating of physical properties of cross-linking material.

By means of the cross-linking diagrams it is possible to achieve crucial data dealing with EPY composition processing. Therefore on the basis of the temperature-dependent gelation lines in the diagram TTT (Fig. 3.8), a time interval during which the composition remains in liquid state and is still fit for processing, can be determined. Beyond the gelation line,, a time point to solidification of resin compound, depending on cross-linking temperature, can be determined. And, from the CTT diagram (Fig. 3.10) information on cross-linking level of the compound can be gained, that makes it possible to determine final mechanical and thermal properties of the compound. Changes in the properties, which take place during cross-linking process, are illustrated in the T_gTP diagram (Fig. 3.11), in which the straight lines represent run of structural changes in the material: the glass transition (T_g), β-transiton ($T_β$) and gelation ($_{gel}T_g$). The lines delineates this way sub-zones in which the material exhibits different physical properties along with the conversion progressing (both before and after gelation).

All the cross-linking diagrams for the EPY compound enable to better understand the relation between its reagents, cross-linking path, structure, transformations, states and properties. Hence, they makes it possible to determine an optimum path between time and temperature of cross-linking process so as to put gelation and glass transition under control and — in consequence — to ensure that required usage properties are reached for a given application of the compound.

4 Design of machinery seating arrangements by using EPY compound chocks

4.1. Documentation of seating arrangement

The seating of machines and devices on shipboard foundations must be approved by a classification society supervising the construction or repair of ships. Documentation to be submitted to get approval of the seating project should contain, according to Germanischer Lloyd [96, 97], the following:

1. General information concerning the ship, device to be seated, classification society supervising the construction or repair of the ship as well as a shipyard in which the ship is built or repaired.
2. The drawing of the seating arrangement (Fig. 4.1a), showing the following data:
   - location, number and dimensions of all chocks;
   - location, number and dimensions of all stoppers (front and side);
   - location, number and dimensions of all foundation bolts (ordinary and fitted) as well as sleeves (if any);
   - name of the compound used for the chocks and material for foundation bolts, nuts, stoppers and sleeves.
3. Drawings of cross-sections of foundation bolt joints (Fig. 4.1b).
4. Information concerning:
   - load-carrying surface area of chocks;
   - pressure exerted on chocks, resulting from machinery weight, tension in foundation bolts and total pressure;
   - axial force and stress in foundation bolts as well as their elongation under tightening;
   - stretching moment for nuts of foundation bolts, or pressure in a hydraulic tightening device.

4.2. General information for the design of seating arrangement

1. Heights of foundation chocks:
   - minimum: 10 mm,
   - recommended: 20÷35 mm,
   - maximum: 50 mm (in one layer).

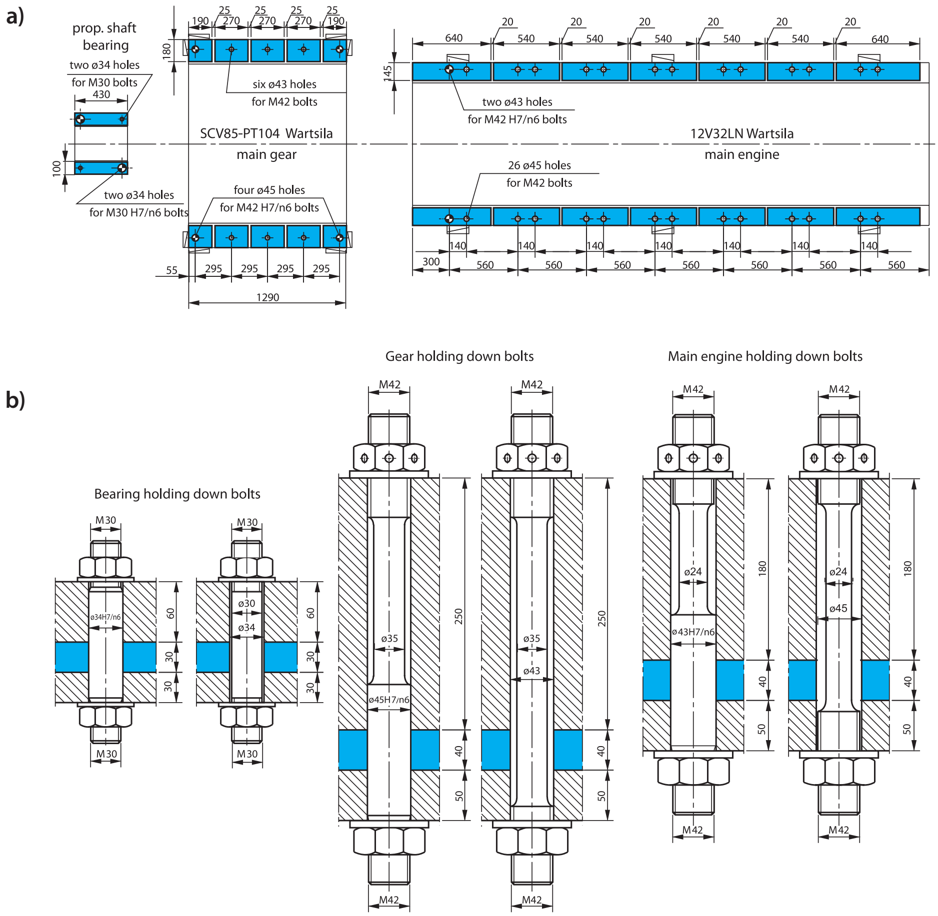


Fig. 4.1. Arrangement of EPY compound chocks (a) and cross-sections of foundation bolt joints of propulsion shaft bearing, main gear and main engine (b)

In case if chocks thinner or thicker than the above given are to be cast it is necessary to be in contact with MSJ company, in advance.

2. Casting moulds are made of foamed plastics (polypropylene, polyurethane, micro-rubber, foamed polystyrene) or metal sheets of 1÷2 mm in thickness.

3. Breadth of gate of the mould for the casting of a foundation compound chock should amount to 15÷30 mm, and the height of a front wall of the mould should be such as to ensure forming an overpour (sinkhead) of 15÷30 mm in height.

4. Mass of the compound to be used for casting the chocks is calculated from the formula:

$$m_t = \alpha \rho_t A_e H \tag{4.1}$$

where:

- m_t — mass of compound, kg
- α — a coefficient which takes into account volume of the gate, overpour and of losses, equal to 1.05÷1.20,
- ρ_t — EPY compound density equal to $1.59 \cdot 10^{-6}$ kg/mm^3,
- A_e — effective (total) load-carrying area of chock surface, mm^2,
- H — nominal chock height, mm.

4.3. Design calculations of the seating on EPY compound chocks

4.3.1. General remarks

The following denotations, units and quantity names shown in Tab. 4.1, have been assumed (acc. GL design guidelines [97]),:

4.3.2. Calculation of the minimum required load-carrying area of chock surface

$$A_m = \frac{W}{p_w} \tag{4.2}$$

where:

- W — weight of the object, N,
- p_w — pressure exerted on chocks by weight of the object, N/mm^2.

Limiting conditions:

- $p_w \le 0.7$ N/mm^2,
- $A_m \le A_e$,

where:

- A_e — total effective load-carrying area of chock surface.

4.3.3. Calculation of axial force in the tensioned holding down bolt

$$F_p = \frac{(p_t - p_w)\, A_e}{n} \tag{4.3}$$

where:

- p_t — total pressure on chocks, resulting from weight of the object and axial force in tensioned holding down bolts, N/mm^2,
- n — number of foundation bolts.

Limiting conditions:

- $p_t \le p_a$,
- $F_p > F_0$,

where:

- F_0 — axial force in bolt, resulting from external loads, N,

Table 4.1. Denotations, units and quantity names used in machinery seating calculations

Denotation	Unit	Name
A_e	mm^2	Effective (total) chock load-carrying surface area
A_m	mm^2	Minimum required chock load-carrying surface area
A_p	mm^2	Effective surface of a hydraulic bolt stretcher piston
D_m	mm	Minimum diameter of a holding down bolt shank
D_o	mm	External diameter of a holding down bolt thread
D_r	mm	Minor diameter of a holding down bolt thread
D_s	mm	Diameter of a holding down bolt shank
D_{s1}—D_{si}	mm	Successive diameters of a holding down bolt shank related to lengths L_1—L_i
F_o	N	Axial force in a bolt due to external load
F_p	N	Axial force in a tensioned bolt
k	—	Hydraulic coefficient for settling and elastic recovery
ΔL	mm	Theoretical bolt elongation
ΔL_m	mm	Required minimum theoretical bolt elongation
L_1—L_i	mm	Lengths of successive segments of a holding down bolt shank, related to diameters D_{s1}— D_{si}
n	—	Number of holding down bolts
p_a	N/mm^2	Permissible pressure for an applied compound
p_n	bar	Hydraulic pressure in a bolt stretcher
p_t	N/mm^2	Total surface pressure on chocks resulting from machine weight and pre-tension of the bolts
p_w	N/mm^2	Pressure on chocks exerted by machine weight
P	mm	Holding down bolt thread pitch
R_{eH}	N/mm^2	Minimum yield point of bolt material
T	Nm	Holding down bolt nut tightening torque
W	N	Machine weight
σ_e	N/mm^2	Reduced stress (accounting for tension and twist)
σ_t	N/mm^2	Tensile stress

p_a — permissible pressure for a compound to be used, N/mm^2,
$p_a = 5\ N/mm^2$ (MPa) in $T \le 80°C$ — for the seating of main engines, transmission gear etc. (acc. PRS, ABS*, GL, LRS, RMRS, BV, DNV),
$p_a = 15\ N/mm^2$ (MPa) — for the seating of mechanisms for which co-axiality is not required (acc. PRS),
$p_a = 30\ N/mm^2$ (MPa) — for the seating of windlasses and mooring winches, with taking into account pull force,
$p_a < 60\ N/mm^2$ at momentary loads (acc. PRS).

* Acc. ABS $p_a = 15\ N/mm^2$ valid since 21.06.2002

4.3.4. Calculation of stretching moment for nuts of holding down bolts

$$T = \frac{F_p D_o}{5000} \qquad (4.4)$$

where:

- T — nut stretching moment, Nm,
- D_0 — external diameter of holding down bolt thread, mm,
- F_p —initial (assembly) tension in holding down bolt, N.

Limiting condition:
The calculation method is applicable to steel holding down bolts of regular thread, when common oils free from special additives such as e.g. M_0S_2, are used for lubrication of the holding down bolt thread and friction surface of nuts.

4.3.5. Calculation of pressure in the hydraulic bolt stretcher

$$p_h = 10 \frac{F_p}{A_p k} \qquad (4.5)$$

where:

- F_p — axial force in tensioned bolt, N,
- A_p — effective surface area of the piston of the hydraulic bolt stretcher, mm^2,
- k — hydraulic coefficient for taking into account sagging in bolt joint.

Limiting conditions:
$k = 0.85$, in case if another value of the coefficient k is assumed, results of measurements of actual axial force in tensioned holding down bolts are to be submitted to the classification society (GL).

4.3.6. Calculation of bolt elongation resulting from assembly tension

$$\Delta L = F_p \left(\frac{L_1}{D_{s1}^2} + \frac{L_2}{D_{s2}^2} + \ldots + \frac{L_i}{D_{si}^2} \right) 618 \cdot 10^{-8} \qquad (4.6)$$

where:

- F_p — assembly (initial) tension force in holding down bolt, N,
- $L_1, \ldots, L_i$ — lengths of successive parts of shank of holding down bolt, corresponding to the diameters $D_{s1}, \ldots, D_{si}$, mm, respectively,
- $D_{s1}, \ldots, D_{si}$ — diameters of shank of holding down bolt, corresponding to the lengths $L_1, \ldots, L_i$, mm, respectively.

Limiting conditions:

- — $\Delta L \geq L_m = 0.0343 p_t$, mm,
- — $\Delta L_m = 0.12$ for $p_t < 3.5\ N/mm^2$.

4.3.7. Calculation of reduced stress or equivalent tensile stress related to diameter of foundation screw bolt with taking into account assembly tension

1. Holding down bolts stretched by means of a stretcher:

a) bolts of constant diameter shank ($D_m = D_r$):

$$\sigma_e = 1.5 \frac{F_p}{D_r^2} \tag{4.7}$$

where:

F_p — assembly tension force in bolt, N,
D_m — minimum diameter of foundation bolt shank, mm,
D_r — diameter of thread core of holding down bolt, mm.

b) bolts of changing diameter shank ($0.8\,D_r \le D_m < 1.0\,D_r$):

$$\sigma_e = 1.72 \frac{F_p}{D_m^2} \sqrt{0.6 + \frac{D_r}{D_m^2}\left(P + 0.2D_r\right)} \tag{4.8}$$

where:

P — pitch of thread of holding down bolt, mm.

Limiting condition: $\sigma_e \ge 0.9\,R_{eH}$ (where R_{eH} — minimum yield point of bolt material, N/mm^2).

2. Hydraulically tensioned bolts:

$$\sigma_t = 1.274 \frac{F_p}{D_m^2} \tag{4.9}$$

Limiting condition: $\sigma_e \le 0.8\,R_{eH}$ for $k = 0.85$.

4.3.8. Calculation of tensile stresses related to thread diameter of holding down bolt with taking into account assembly tension

$$\sigma_t = 1.274 \frac{F_p}{D_r^2} \tag{4.10}$$

In order to prevent nuts against self backing-off the following condition is to be satisfied: $\sigma_t < 150$ N/mm^2 (where: σ_t — tensile stress in holding down bolt bolt). For low-speed engines $\sigma_t < 100$ N/mm^2 is assumed.

4.4. Example design calculations of the seating arrangement

Design input data and results of design calculations for 6MU453C MaK main engine and G1VY Flender main transmission gear seated on EPY compound chocks are presented below. The design input data and calculation results as well as relevant drawings are presented in the form required for submitting to classification societies for approval.

Table 4.2. An example of a design documentation of a main engine seating arrangement with foundation chocks made of EPY compound (Fig. 4.2a, b)

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Szczecin, 14.04.2001 r.

OBLICZENIA POSADOWIENIA SILNIKA GŁÓWNEGO NA PODKŁADKACH Z TWORZYWA EPY
Calculation of chocking of main engine on EPY resin

Nazwa statku / Name of the vessel	M/v „Tejo Chemist"; GL-ID nr 33688
Maszyna, typ / Engine, type	Silnik główny MaK 6MU453C
Towarzystwo klasyfikacyjne / Classification society	Germanischer Lloyd; Certyfikat nr 17395-00HH
Stocznia / Shipyard	Gdańska Stocznia Remontowa S.A.

Opis Description	Symbol Symbol	Wartość Value	Jednostka Unit	Uwagi Remarks
Ciężar obiektu Engineweight	W	206010	N	
Efektywna powierzchnia nośna podkładek Effective total surface of cast resin chocks	A_e	471617	mm^2	rys. 1/2/P-08
Nacisk powierzchniowy od ciężaru obiektu Total surface pressure from engine weight	p_w	0.44	N/mm^2	$p_w < 0.7\ N/mm^2$
Średnica gwintu śruby fundamentowej zwykłej Outer diameter of thread of holding down bolt	D_{ohd}	24	mm	M24×2
Skok gwintu śruby fundamentowej zwykłej Pitch of holding down bolt thread	P_{hd}	2	mm	—
Liczba śrub fundamentowych zwykłych Number of holding down bolts	n_{hd}	24	szt. pcs	M24×2
Średnica gwintu śruby fundamentowej pasowanej Outer diameter of thread of fitted bolt	D_{of}	24	mm	—
Skok gwintu śruby fundamentowej pasowanej Pitch of fitted bolt thread	p_f	2	mm	—
Liczba śrub fundamentowych pasowanych Number of fitted bolts	n_f	4	szt. pcs	—
Liczba odlewanych podkładek fundamentowych Number of cast resin chocks	n_{ch}	14	szt. pcs	—
Całkowity nacisk powierzchniowy na podkładki Total surface pressure on the chocks	p_t	4.52	N/mm^2	$p_a = 5\ N/mm^2$
Nacisk powierzchniowy od napięcia śrub Total surface pressure from bolts tension	p_{t-w}	4.08	N/mm^2	$p_{t-w} = p_t - p_w$
Siła poosiowa w napiętej śrubie fundamentowej Preloading bolt force exerted by tightening	F_p	68775	N	$F_p = (p_t - p_w) A_e / /(n_{hd} + n_f)$
Obliczenia śrub fundamentowych zwykłych **Calculation of holding down bolt**				
Średnica rdzenia śruby fundamentowej zwykłej Thread root diameter of holding down bolt	D_r	21.55	mm	rys. 2/2/P-08

Opis Description	Symbol Symbol	Wartość Value	Jednostka Unit	Uwagi Remarks
Średnica trzpienia śruby fundamentowej Shank diameter of holding down bolt	D_{s1}	17.00	mm	—
Długość rozciągana gwintu śruby fundamentowej Stretched thread lenght of holding down bolt	L_r	25.00	mm	—
Długość trzpienia śruby fundamentowej Shank length of holding down bolt	L_1	180.00	mm	—
Naprężenie zredukowane w śrubie Holding down bolt equivalent tensile stress	σ_e	423	MPa	śruby klasy 8.8 $R_{eH} = 640$ N/mm^2
Minimalne wymagane wydłużenie śrub Req. min. theoretical elongation of bolts	ΔL_m	0.155	mm	$\Delta L_m = 0.0343\, p_t$
Teoretyczne wydłużenie śruby fundamentowej Theoretical elongation of holding down bolt	ΔL	0.288	mm	$\Delta L > \Delta L_m$
Moment dokręcający nakrętkę Tightening torque of holding down bolt	T_{hd}	330	Nm	$T = F_p D_{ohd}/5000$
Obliczenia śrub fundamentowych pasowanych w EPY **Calculation of fitted bolts of cast-in-EPY resin**				
Średnica rdzenia śruby fundamentowej pasowanej Thread root diameter of fitted bolt	D_r	21.55	mm	rys. 2/2/P-08
Średnica trzpienia śruby pasowanej Shank diameter of fitted bolt	D_{s1}	17.00	mm	—
Średnica trzpienia śruby pasowanej Shank diameter of fitted bolt	D_{s2}	24.00	mm	—
Średnica trzpienia śruby pasowanej Shank diameter of fitted bolt	D_{s3}	20.00	mm	—
Długość rozciągana gwintu śruby pasowanej Stretched thread length of fitted bolt	L_r	24.00	mm	—
Długość trzpienia śruby pasowanej Shank length of fitted bolt	L_1	120.00	mm	—
Długość trzpienia śruby pasowanej Shank length of fitted bolt	L_2	145.00	mm	—
Długość trzpienia śruby pasowanej Shank length of fitted bolt	L_3	10.00	mm	—
Naprężenie zredukowane w śrubie pasowanej Fitted bolt equivalent tensile stress	σ_e	423	MPa	śruby klasy 8.8 $R_{eH} = 640$ N/mm^2
Naprężenie w rdzeniu gwintu śruby pasowanej Tensile stress related to thread root diameter	σ_t	189	MPa	—
Teoretyczne wydłużenie śruby pasowanej Theoretical elongation of fitted bolt	ΔL	0.316	mm	$\Delta L > \Delta L_m$
Moment dokręcający nakrętkę śruby pasowanej Tightening torque of fitted bolt	T_f	330	Nm	$T = F_p D_{of}/5000$

Projektował	14.04.2001	D.J. Ratajczak
Sprawdził	14.04.2001	W. Jaroszewicz
Posadowienie SG MaK 6MU453AK na podkładkach z tworzywa EPY		

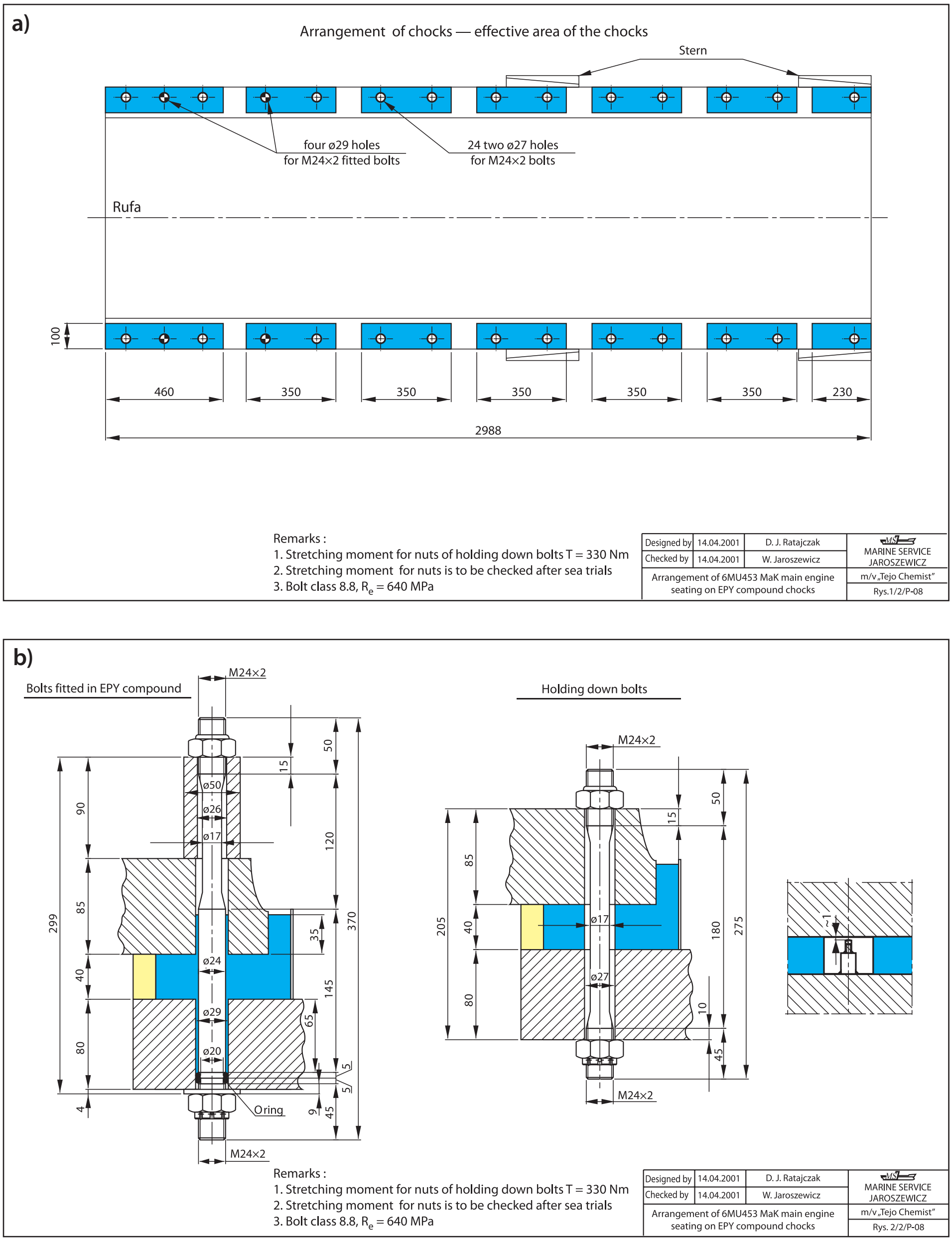

Fig. 4.2. Arrangement of EPY compound chocks (a) and cross-sections of foundation bolt joints of 6MU453 MaK main engine (b)

Table 4.3. An example of a design documentation of a main gear seating arrangement with foundation chocks made of EPY compound (Fig. 4.3a, b)

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Szczecin, 14.04.2001 r.

OBLICZENIA POSADOWIENIA PRZEKŁADNI GŁÓWNEJ NA PODKŁADKACH Z TWORZYWA EPY
Calculation of chocking of main gear on EPY resin

Nazwa statku / Name of the vessel	M/v „Tejo Chemist"; GL-ID nr 33688
Maszyna, typ / Engine, type	Przekładnia główna Flander G1VY
Towarzystwo klasyfikacyjne / Classification society	Germanischer Lloyd; Certyfikat nr 17395-00HH
Stocznia / Shipyard	Gdańska Stocznia Remontowa S.A.

Opis Description	Symbol Symbol	Wartość Value	Jednostka Unit	Uwagi Remarks
Ciężar obiektu Engineweight	W	120663	N	—
Efektywna powierzchnia nośna podkładek Effective total surface of cast resin chocks	A_e	301268	mm^2	rys. 1/2/P-08
Nacisk powierzchniowy od ciężaru obiektu Total surface pressure from engineweight	p_w	0.40	N/mm^2	$p_w < 0.7$ N/mm^2
Średnica gwintu śruby fundamentowej zwykłej Outer diameter of thread of holding down bolt	D_{ohd}	36	mm	M36×4
Skok gwintu śruby fundamentowej zwykłej Pitch of holding down bolt thread	P_{hd}	4	mm	—
Liczba śrub fundamentowych zwykłych Number of holding down bolts	n_{hd}	8	szt. pcs	—
Średnica gwintu śruby fundamentowej pasowanej Outer diameter of thread of fitted bolt	D_{of}	36	mm	M36×4
Skok gwintu śruby fundamentowej pasowanej Pitch of fitted bolt thread	p_f	4	mm	—
Liczba śrub fundamentowych pasowanych Number of fitted bolts	n_f	4	szt. pcs	—
Liczba odlewanych podkładek fundamentowych Number of cast resin chocks	n_{ch}	8	szt. pcs	—
Całkowity nacisk powierzchniowy na podkładki Total surface pressure on the chocks	p_t	4.99	N/mm^2	$p_a = 5$ N/mm^2
Nacisk powierzchniowy od napięcia śrub Total surface pressure from bolts tension	$p_{t\text{-}w}$	4.59	N/mm^2	$p_{t\text{-}w} = p_t - p_w$
Siła poosiowa w napiętej śrubie fundamentowej Preloading bolt force exerted by tightening	F_p	115222	N	$F_p = (p_t - p_w)A_e / (n_{hd} + n_f)$
Obliczenia śrub fundamentowych zwykłych Calculation of holding down bolts				
Średnica rdzenia śruby fundamentowej zwykłej Thread root diameter of holding down bolt	D_r	31.09	mm	rys. 2/2/P-08
Średnica trzpienia śruby fundamentowej Shank diameter of holding down bolt	D_{s1}	25.00	mm	—

Opis Description	Symbol Symbol	Wartość Value	Jednostka Unit	Uwagi Remarks
Długość rozciągana gwintu śruby fundamentowej Stretched thread lenght of holding down bolt	L_r	25.00	mm	—
Długość trzpienia śruby fundamentowej Shank length of holding down bolt	L_1	135.00	mm	—
Naprężenie zredukowane w śrubie Holding down bolt equivalent tensile stress	σ_e	334	MPa	śruby klasy 6.8 $R_{eH} = 480\ N/mm^2$
Minimalne wymagane wydłużenie śrub Req. min. theoretical elongation of bolts	ΔL_m	0.171	mm	$\Delta L_m = 0.0343\ p_t$
Teoretyczne wydłużenie śruby fundamentowej Theoretical elongation of holding down bolt	ΔL	0.172	mm	$\Delta L > \Delta L_m$
Moment dokręcający nakrętkę Tightening torque of holding down bolt	T_{hd}	830	Nm	$T = F_p D_{ohd}/5000$

Projektował	14.04.2001	D.J. Ratajczak
Sprawdził	14.04.2001	W. Jaroszewicz
Posadowienie przekładni głównej Flander G1VY na podkładkach z tworzywa EPY		

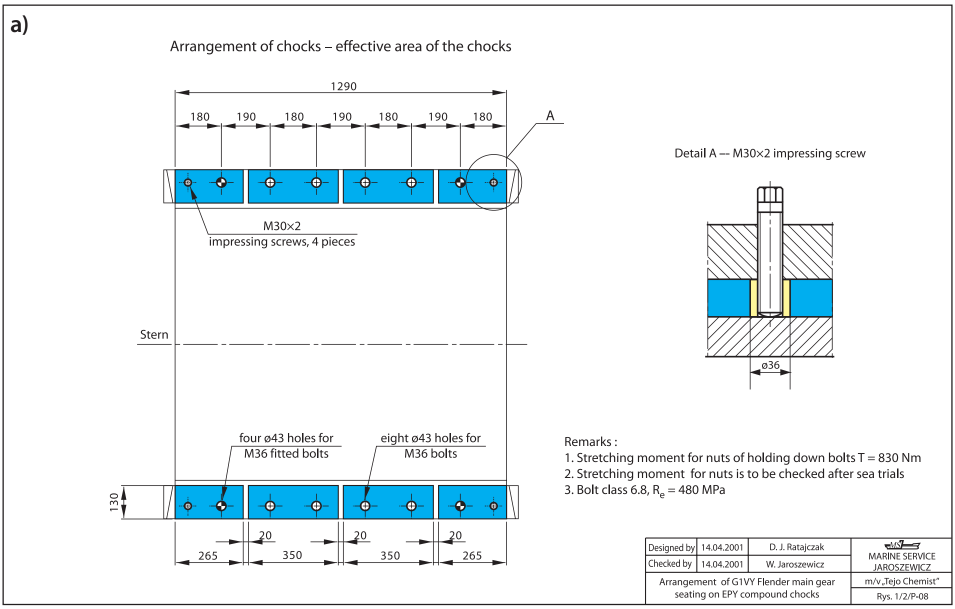


Fig. 4.3a. Arrangement of EPY compound chocks for G1VY Flender main gear

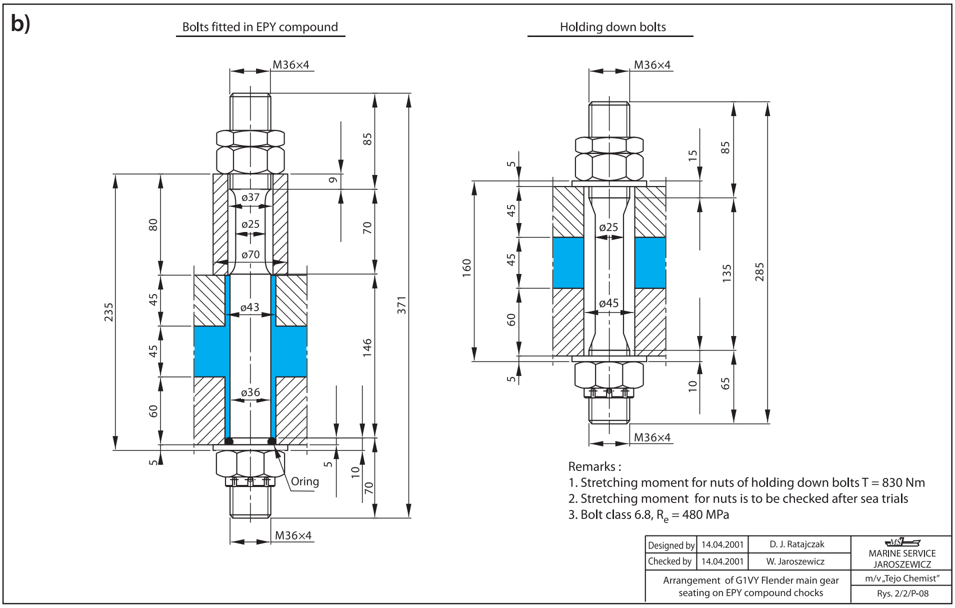


Fig. 4.3b. Cross-sections of foundation bolt joints of G1VY Flender main gear

5 The technology of the ship machinery seating with the use of EPY compound

5.1. The technology of the ship machinery seating on chocks cast of EPY compound

The ship machinery seating technology on chocks cast of EPY compound will be discussed on the example of ship main propulsion engine as in this case the requirements are especially strict and the technology of its seating is precisely laid down in relevant procedures used by the shipyard building the ship and also by MSJ Co carrying out seating operations [98].

The basis for starting the seating work is the documentation of a main engine (ME) seating arrangement, agreed with its producer, ship owner and the shipyard, and approved by the classification society supervising the construction of the ship. The seating operations with the use of EPY compound may be carried out only by employees of MSJ Co or another personnel properly trained and authorized by this company.

The execution of the seating process of a main engine consists in positioning it on the foundation, then proper aligning by means of adjusting screws or wedges, in accordance with the principles and procedures being in force in the shipyard. The engine should be placed somewhat over its final position, by 0.001÷0.002 part of chock height, to compensate for shrinkage of the compound in curing and the deformations resulting from weight of the engine and the pre-tension of holding down bolts. When the appropriate positioning of the main engine on its foundation is completed, holes for holding down bolts are drilled in the foundation plate; in case if fitted bolts are applied the holes should be also bored. All these operations are carried out by yard personnel in compliance with relevant procedures.

The load-bearing surfaces of the main engine and its foundation are not required to be especially machined, but only cleaned to remove mechanical contaminations and oil lubricants. Some classification societies allow to leave a thin, good quality paint coat on the load-bearing surfaces.

In places where the chocks have to be installed, moulds of foamed polyurethane or foamed polypropylene, of 20÷30 mm thick walls, are made (Fig. 5.1). Their internal dimensions (L and B — Fig. 5.1b) are to correspond to the chock dimensions given in the seating arrangement documentation for the object in question. The front dam of the mould (Fig. 5.1a, b) are made of a steel sheet 1÷2 mm thick, which is joined with the foundation by spot welding. The gap between the steel sheet and the foundation is sealed with a gap filling adhesive.

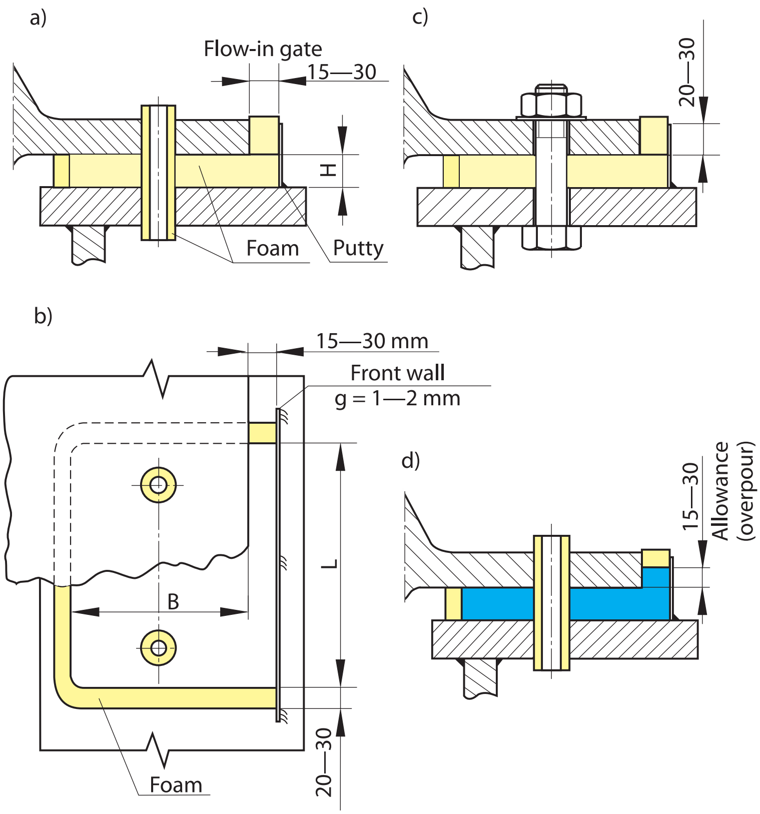


Fig. 5.1. Preparation of casting mould for the foundation chock: a—b) with holes sealed by pipes of soft rubber or foam; c) with pre-inserted holding down bolt; d) mould filled with resin compound

The casting moulds have to extend by 15÷30 mm over the actual chock area so as to form a pouring space (ingate) for filling the chocks with liquid composition (Fig. 5.1).

The ingate has to be so arranged as to prevent against trapping the air inside the mould, that would make its complete filling not possible. In the vicinity of the ingate the mould walls should be higher by 20÷30 mm (Fig. 5.1c) in order to obtain an extra volume for the composition, the so called overpour (shinkhead) which is necessary to account for shrinkage and to ensure proper filling of the mould. In practice, the shrinkhead (of 15÷30 mm in breadth) is formed along the whole chock length L (Fig. 5.1b).

In order to make disassembling possible, the surfaces contacting the compound should be sprayed with an adhesive (release) agent-silicone oil (e.g. Silikone Spray Lubricant, Release Agent PR-225 lub WD-40), before the front dam closes the mould.

Into the holes for holding down bolts pipes made of soft rubber or foamed resin (Fig. 5.1a, b) are pushed throughout by using only a small force, or alternatively, the holding down bolts with only slightly tightened nuts (Fig. 5.1c) may be inserted. The surfaces of the bolts which will be in contact with the compound should be covered with the release agent (solid grease).

After placing and sealing the casting moulds for all chocks, the main engine alignment is checked again (acc. a relevant technological procedure used in the shipyard).

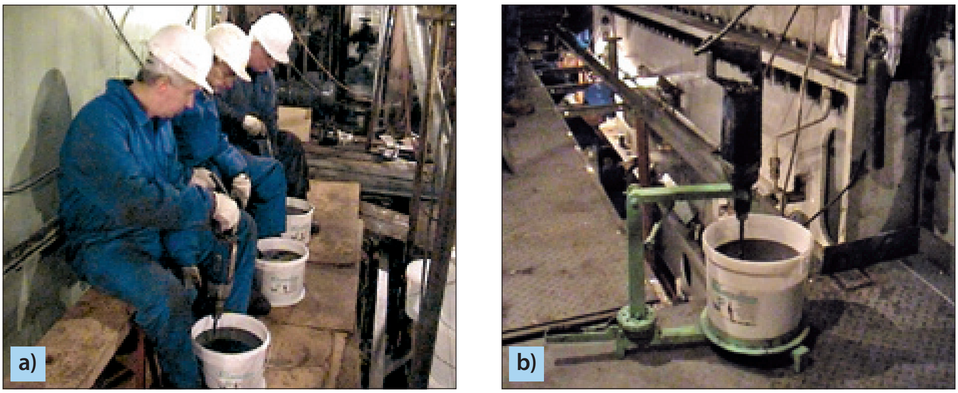


Fig. 5.2. Composition mixing: a) manual, by using a driller; b) in a mechanized way

EPY compound consists of two components. It is delivered in steel sheet containers of 1, 3 or 6 kg capacity of the compound pre-mixed with fillers. In separate containers appropriate amounts of hardener are delivered. All the preparatory operations should be completed in advance before mixing the two components together and their careful stirring because after starting the mixing only 10÷20 min are left to gelation of the formed composition. The stirring takes 4÷6 min and is performed manually (with the use of a driller fitted with a special stirrer of MSJ design, at the rotational speed n = 600÷800 rpm — Fig. 5.2a), or in a mechanized way (Fig. 5.2b). The temperature of the mixed components should amount to 15÷25°C, and the ambient temperature around the chocks — at least 10°C.

During long storage of the liquid compound, fillers tend to sediment, especially in elevated temperatures. Hence it is recommended to stir preliminarily the compound (i.e. the resin with fillers) inside the container before the hardener is added. After the hardener is added and carefully mixed with the resin it is recommended to leave the liquid composition undisturbed for about 5÷10 min so as to allow the air contained in it to escape.

The moulds should be filled slowly and in a continuous way (Fig. 5.3), avoiding any interruptions in flow of the liquid composition so as to make it possible to remove residual air from it and to prevent against "capturing" a new portion of air. The filling should be performed continuously until the mould and the sinkhead is entirely filled up (to at least 15 mm above the highest point of the chock — Fig. 5.3a). The sinkhead of the liquid composition (15÷30 mm) generates the necessary pressure and ensures certain reserve of the compound for a whole chock; it also guarantees good contact between the cast chock and the machine bed plate load-bearing surface. It

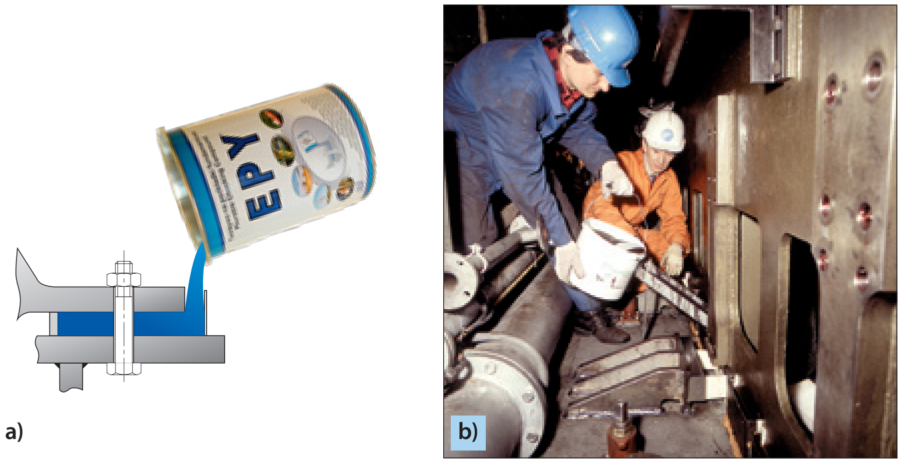


Fig. 5.3. Mould filling with liquid composition: a) schematic illustration; b) on board a ship

is assumed that the chock sinkhead should contain at least 1% of the whole volume of the cast. In other cases, e.g. stern bearings in which sinkhead does not cover all length of compound cast, higher sinkheads containing abt. 1% of the whole cast volume should be applied, otherwise the casting should be carried out layer by layer.

Fig. 5.4 shows various examples of foundation chocks cast from EPY compound. Fig. 5.4a presents a standard main engine holding down bolt joint with the foundation chock cast of EPY compound. Its characteristic features are: that the bolt is loosely inserted throughout common hole in foundation plate, washer and engine bed plate, and that the whole chock with its sinkhead is cast together in the mould. One of the ways to avoid serious technological difficulties in casting high chocks (H > 50 mm) and shortening the time of their casting on board a ship is casting the chocks with the prefabricated elements marked 9 in Fig. 5.4b [50]). The elements are cast from EPY compound in advance, curing in optimum workshop conditions and then inserted into the casting moulds in such a way that they form middle layers of cast chocks after filling the remaining free space (30÷40%) of the mould with liquid compound.

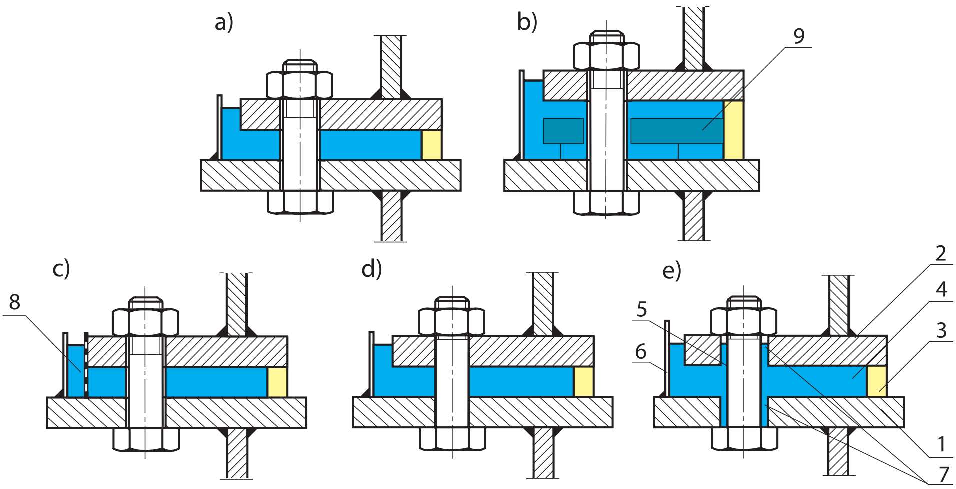


Fig. 5.4. Examples of foundation chocks: a) with a common holding down bolt; b) with prefabricated EPY compound insert; c) with perforated element; d) with a bolt fitted to metal elements and compound; e) with a bolt fitted to EPY compound; 1 — foundation plate, 2 — machine bed plate, 3 — foam mould, 4 — EPY compound chock, 5 — holding down bolt, 6 — flat bar, 7 — EPY compound sleeve (pipe), 8 — perforated element, 9 — prefabricated EPY compound element

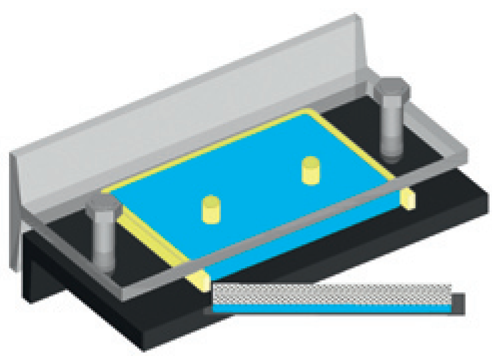


Fig. 5.5. Removal of an allowance (overpour) together with front wall and perforated element

For many foundation bolt joints, especially for MEs with side stoppers, there is a need to remove chock sinkheads which have only an auxiliary role during chock casting and do not bear any operational load. Their removal is troublesome provided that in the casting moulds perforated elements are fitted, marked 8 in Fig. 5.4c [99]. The elements can be removed together with the sinkheads after the gelation of cast chocks (Fig. 5.5).

For main engine (ME) foundation joints, some number of fitted bolts (Fig. 5.4d, e), are often applied whose task is to exactly position the engine against its foundation. Fitting the bolts in the traditional way which consists in bolt shank grinding and hole boring (Fig. 5.4d), is labour and cost consuming and troublesome for execution on board the ship. The bolts fitted in EPY compound can fulfil the same task (Fig. 5.4e; [49]). Fitting the bolts in the compound consists in inserting them with some clearance into the common holes in foundation plate and ME bed plate and filling the casting mould with the compound up to the ME bed plate upper plane.

The duration time for chock curing depends on ambient temperature and amounts to:

— 72 h at 10°C,
— 48 h at 15°C,
— 24 h at 20°C.

During chock curing period the principles concerning ME alignment process should be also obeyed, i.e. any ship ballasting, work in engine room and weight handling on the ship etc are not allowed. The chemical processes which occur during the composition curing, are very complex and their run depends on temperature. The cross-linking of the composition requires some time and the cross-linking progression actually achieved depends on temperature of the composition in curing. As the curing reaction is exothermal the temperature of curing composition rises up to its maximum value and then drops. From the results of the recording of the composition's temperature versus curing time a curve called *exotherme* can be plotted (Fig. 5.6).

In practice, it has been used to treat the maximum temperature value recorded in curing as exotherme. With a large mass of compound and high ambient temperature, the temperature of the material may be too high and lead to destruction of the chocks. If, on the other hand, the temperature of the compound in curing is too low, it only cures partially and does not fully reach its required hardness and strength. It is then required to additionally heat the curing chocks from outside. The casting and curing processes should be so selected as to reach the maximum temperature (exotherme) of the composition in the range of 80÷90°C. Therefore, it is very important to select appropriate curing conditions and take into account many factors, first of all the height of chocks and the temperature of the foundation. According to the conditions, an appropriate amount of hardener should be dosed, Fig. 5.7. In case ambient temperature is lower than 10°C heating the chocks from outside should be provided by means of hot air blowing or heat radiators.

After the chocks are cured, the front sheet dams should be removed from the moulds (Fig. 5.1, 5.5), hardness of the cured compound should be measured, sharp edges of the chocks-removed by grinding, the ME alignment-checked again. Hardness of the cured compound measured by means of Barcol hardness tester should

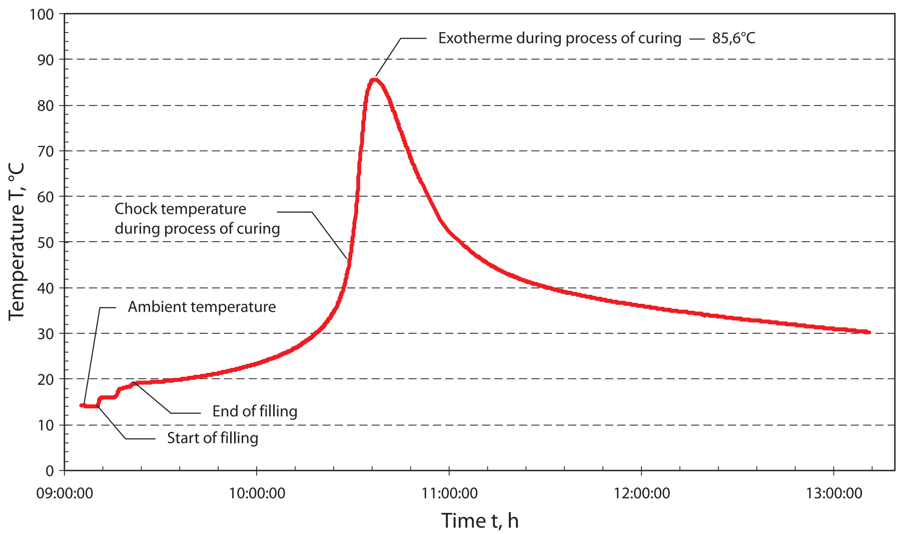


Fig. 5.6. Exemplary diagram of composition temperature versus foundation chock curing time

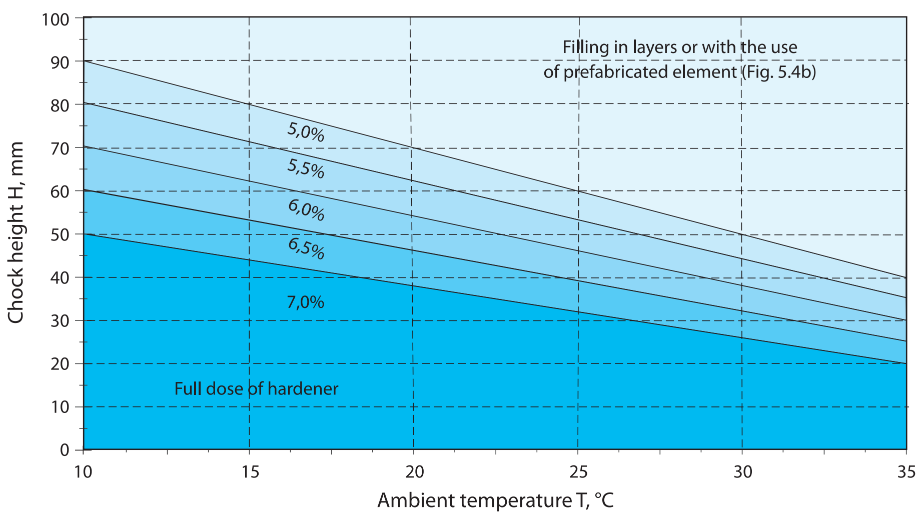


Fig. 5.7. Demanded dose of hardener versus foundation temperature and chock height

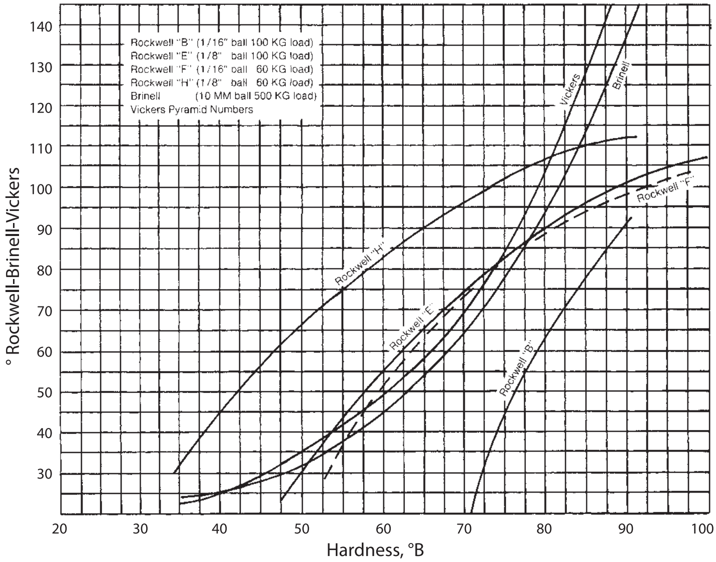


Fig. 5.8. Hardness diagrams (in various scales) versus Barcol hardness measured in °B units [100]

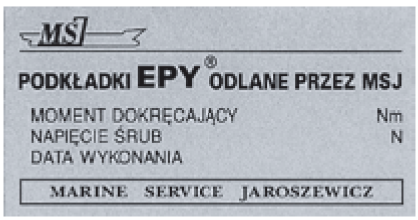


Fig. 5.9. Identification plate

be at least 40°B. The comparative hardness curves are presented in various scales in Fig. 5.8 [100].

Then the adjusting screws should be unscrewed (or the alignment wedges - removed), the nuts of foundation bolts should be tightened (in accordance with shipyard's instruction) and after that the alignment of ME should be checked again. Finally, a designation plate is fitted (Fig. 5.9) and a protocol (formal report) is written.

Cast and cured chocks, together with correctly tensioned holding down bolts, ensure an exact and reliable alignment of the engine throughout multi-year service of the ship.

Temperature is the most important factor in seating the machines and devices on foundations with the use of cast compound chocks. It concerns the temperatures in all phases of this process, namely : temperature of components before their mixing, temperature of chock casting and forming during exothermal process of curing, temperature rise rate up to the service conditions and temperature of chocks in service. The temperature range of 0÷80°C may be considered the possible to occur ambient temperature range. In this range the difference of 10 degrees may be a difference between a success and a failure in the resin compound application. For instance, if the temperature of a composition is too high, it may cure so fast that the mould will not be fully filled. Too low temperatures may result in a not fully cured compound.

5.2. The technology of seating stern tubes and liners of shaft line bearings

5.2.1. Traditional versus modern method of stern tube seating

EPY compound may be applied not only to casting the foundation chocks for main engines and gears, electric generating sets, pumps and other auxiliary devices, but also to seating stern tubes, liners of shaft line transverse (radial) bearings, liners of rudders, permanent and removable pins, which are usually under large transverse and axial loads.

Traditional method of stern tube assembling on sea-going ship consisted in bushing it (pushing in) [103]. It was associated with necessity of application a special portable boring machine to machining the hole in ship's stern frame (at maintaining proper clearance for interference fit) and a hydraulic press of high pushing force (up to 1000 kN). It was a very troublesome, labour and cost consuming method; moreover it was very difficult to mend any error which was easy to make during this process.

In contrast to that, the modern method of stern tube seating with the use of chemically curing compound (Fig. 5.10), is relatively not complicated, exact and fast. In this case the hole in the bush of ship's stern frame, which constitutes the socket for seating stern tube, should be greater by 20÷40 mm than the outer diameter of the tube. The stern tube is introduced into the hole and aligned by using the adjusting screws (Fig. 5.10). It provides in effect a ring gap of 10÷20 mm mean dimension. Such gap dimension is recommended as it ensures a wide range of possible correction in position of the stern tube against the hole in case when a misalignment between the hole and the stern tube takes place, and allows to obtain sufficiently thick wall of compound cast. Minimum distance between the surfaces should be equal to 8 mm at least. Next, the pouring space, after its appropriate sealing (both on front and back side), is filled with liquid epoxy resin mixed with hardener.

The hole where stern tube has to be installed needs not be exactly machined as no its dismantling is usually foreseen. In case of such a need the hole should be machined before stern boss or stern journals are welded to stern frame. However its diameter should be somewhat greater than outer diameter of the stern tube in order to obtain after its installation mean radial clearance in the range of 10÷20 mm.

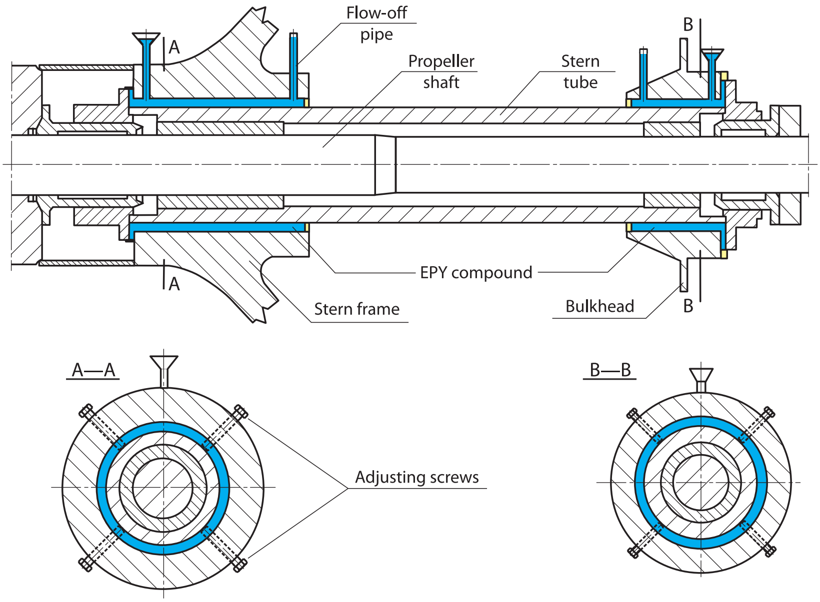


Fig. 5.10. Stern tube seated in liners cast of EPY compound

Before installation of stern tube or shaft line bearing liner is started, surfaces of the hole and elements to be introduced, which will be in contact with liquid compound, should be cleaned up from any solid oils, paints, rust and other mechanical contaminations, and then degreased. After the stern tube is inserted sufficiently deep into the hole, it requires to be appropriately aligned (centred). It is usually performed by using as a rule four (sometimes three) radial adjusting screws located in two planes of its cross-section, respectively, on both sides, possibly close to their ends (Fig. 5.10).

Holes for the adjusting screws are usually drilled and threaded in ship stern boss or stern journals, and the adjusting screws are screwed in from outside (Fig. 5.11a). It is not always possible or needed to drill through the stern journal from outside, e.g. in case its wall is very thick or a suitable place is not accessible. In some cases adjusting screws screwed in from the inside may be used (Fig. 5.11b) or external screws acting on stern tube flange (Fig. 5.11c) applied. In the latter case the screws are screwed in to the plates welded to front surface of stern journal, in place of stern tube installation work, and removed after its completion.

The adjusting screws should be uniformly distributed along circumference as shown in Fig. 5.11a, b, c. However sometimes certain limitations take place and the screws may be distributed otherwise. Fig. 5.11d shows such practical case. The stern tube which has two bearings (front and rear one) may constitute a constructional

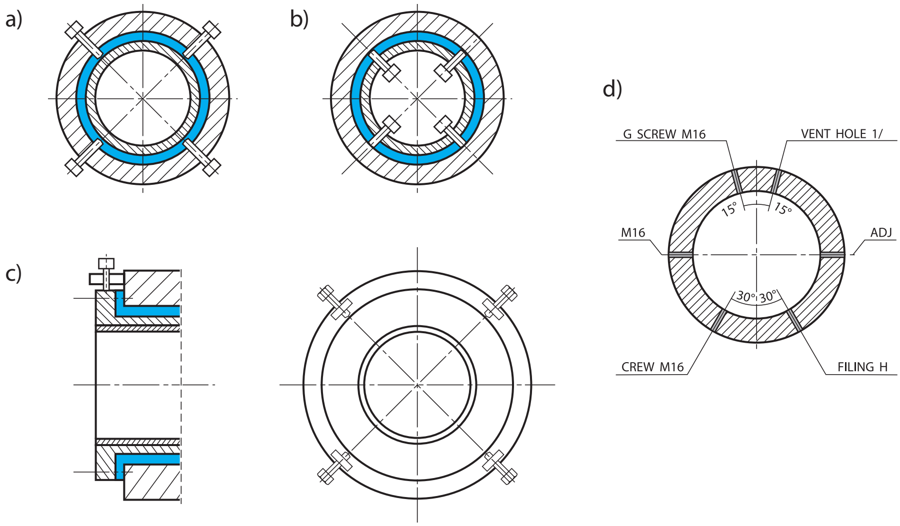


Fig. 5.11. Screws for adjusting stern tube position in stern boss or stern journal: a) adjusting screws screwed in from outside of stern tube; b) screws screwed into stern tube wall from inside; c) screws screwed into welded plates and acting on stern tube flange; d) an example of untypical arrangement of adjusting screws (taken from practice)

element manufactured (turned) from one tubular segment (Fig. 5.10) or a structure welded from a few tubular segments. The welded stern tubes are usually applied when their lengths are greater (in the range of 3÷5 m).

Propeller shaft bearings, instead to be installed in one stern tube, are sometimes mounted in two separate bearing journals. Each of them is separately positioned and aligned in stern frame bush by using adjusting screws placed in two sides (front and rear) An example of such solution is schematically shown in Fig. 5.12.

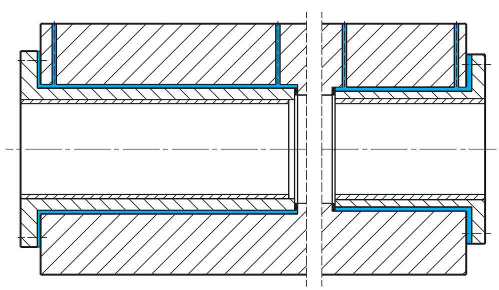


Fig. 5.12. Propeller shaft bearing liners separately assembled in ship stern bush

Exactness of machining the outer surface of stern tube or bearing journal is of a low importance as they are usually not intended for dismantling. The poured and hardened compound guarantees to keep the stern tube in firm position against the hole. However if the dismantling of journal or stern tube is taken into account, its outer surface is to be machined according to N9 class (R_a = 6.3 μm) or even more exactly, and to be covered with an anti-adhesive agent layer. In such cases it should be properly protected against possible change of its position in service. Stern tube is usually fitted with a flange which is fastened to the front of stern frame bush with screws and ensures its stable position. (Fig. 5.13a). Otherwise it should be appropriately secured by using screw bolts (Fig. 5.13b), or by cutting longitudinal grooves in elements to be connected, which, when the stern tube is already filled with the compound, will ensure its stable position (Fig. 5.13c).

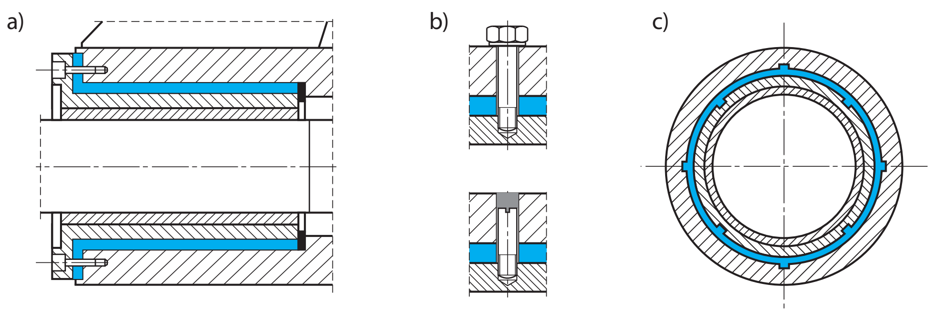


Fig. 5.13. Exemplary stern tube protection against change in its position: a) by means of a flange fastened with screws; b) by means of screws; c) by means of longitudinal grooves cut in joint elements

When the compound is cured, the adjusting screws should be removed and their holes plugged with screw bolts, or their protruding parts should be cut away and the places sealed by means of an epoxy sealing compound.

5.2.2. Sealing of pouring space

The proper sealing (packing) of pouring space (from both sides) before filling it with liquid compound, constitutes an important problem in the assembling process of stern tube or propeller shaft bearing journal.

There is no problem with the sealing of the rear, easily accessible end of pouring space because to this operation carried out on flange of the stern tube a metal ring (screwed or welded) and epoxy sealing compound is used (Fig. 5.14, detail A).

To the sealing of the other side of pouring space, located rather far from the rear end of stern frame bush, polyurethane foams or soft rubbers are usually applied

(Fig. 5.14, detail B). The foam may serve either as a permanent sealing element or temporary one used only during stern tube seating operation. In case the foam is the permanent sealing element it should have a closed-cell structure, but if the foam seal has to be removed and a permanent foam seal be used instead (in order to protect the connection against sea water or oil), it should be of open-cell structure which makes additional venting of pouring space possible.

To seal the pouring space at the front end of the stern tube, accessible from the inside of ship, metal rings should be applied, fitted with a rubber seal (e.g. rubber ring gasket or foam) fastened to the front surface of stern frame bush by means of screw bolts. (Fig. 5.14, detail C).

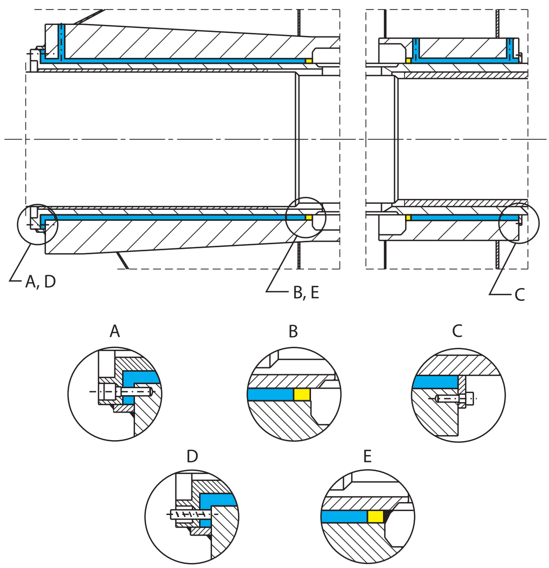


Fig. 5.14. Various versions of the stern tube sealing (packing) in easily accessible places

In the internal part of the pouring space (hard accessible) foam strips having breadth and thickness sufficiently greater than the pouring gap height, are used. In case there is an access to this part the foam strip should be pushed in to the gap circumferentially, when the stern tube is already installed (Fig. 5.14, detail B). The seal is often additionally strengthened and secured by means of an elastic epoxy compound which provides reliable tightness for a given connection Fig. 5.14, detail E). Sometimes, when the compound is completely cured, the sealing foam is removed and reliable tightness of the connection is ensured by means of a special elastic epoxy paste.

Flange of stern tube or bearing journal is, together with the compound cast and cured under it, fastened to the stern frame bush by using bolts. In case the holes for the bolts fastening stern tube flange or stern journal are drilled and threaded in advance, the bolts should be secured by an anti-adhesive agent, then loosely screwed in and properly sealed before the pouring space is filled with the compound. In case the holes have been drilled in advance only in the flange, wooden pins should be put in them instead of the bolts (Fig. 5.14, detail D) and then sealed by using putty or epoxy paste. It is not recommended to drill holes in the compound as it contains ceramic components which blunt cutting tools.

In case the access to the pouring space is possible from only one side and the other end is not accessible when the stern tube or stern bearing journal is already introduced, then the sealing process of this end is difficult and requires high attention. Various solutions may be applied to this case and necessary sealing elements are to be mounted in advance before the stern tube or bearing journal is introduced into their respective holes. A few methods of doing such sealing, which are most commonly applied in practice, are presented in Fig. 5.15. Figure 5.15a shows the internal sealing made with the use of foam or soft rubber gasket which is supported on an offset specially machined in stern frame bush hole for this purpose. The sealing is made on the front surface of the mounted journal, and properly pressed to it. In case of a longer stern tube, special stopper rings for polyurethane foam seals should be fastened by screws or welding in appropriate places (Fig. 5.15b). Good results have been obtained in practice by applying the authors' original solution consisting in that a strip of sealing foam is fastened circumferentially to the stern tube and then its part is flanged out during introduction of stern tube to its respective hole. In this case the foam strip, on a part of its breadth, is glued first to the stern tube (by using butadien glue) and then pressed to it by means of a tense tape or wire. Such sealing is shown schematically in Fig. 5.15c, and its practical application is exemplified on a stern tube model under testing, which is described in Chapter 8 (p. 8.5.5, Fig. 8.29).

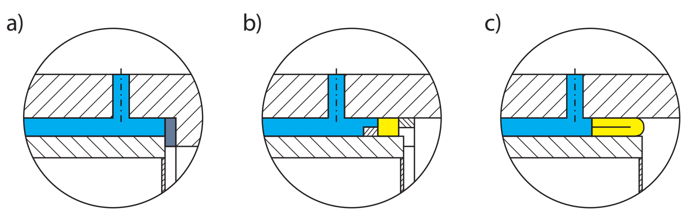


Fig. 5.15. Exemplary sealing the pouring space of stern tube inside stern boss (in places not accessible after inserting the stern tube)

In the case of application of any internal sealing very high caution should be paid during process of introduction of stern tube into hole because it is then easy to damage the prior-mounted sealing, that may result in serious complications.

5.2.3. Filling the pouring space with the resin compound and its curing

The pouring space filling with liquid composition may be performed twofold: by pouring it from the top, or by pumping from the bottom. In practice the pouring from the top has been found much more convenient as the filling from the bottom requires a special (expensive) pump and installation as well as its troublesome cleaning each time after ending the pumping operation. Moreover, in the pouring space an uncontrolled excessive pressure may occur from the side of the pumped compound, which may damage the sealing.

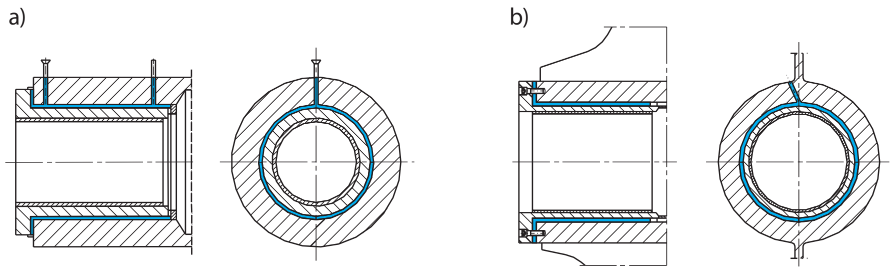


Fig. 5.16. Compound pouring into stern tube

For filling the pouring space from the top, an appropriate flow-in and a flow--off devices (the latter serves also as a de-aerator) should be provided. In practice, these are special holes drilled close to the utmost cross sections of the pouring space to be filled (Fig. 5.16). To the holes which are threaded in a part of their length, special flow-in and flow-off pipes are screwed in. The ingate pipe should be vertically located, have its internal diameter in the range of 20÷36 mm (depending on a size of stern tube and amount of the compound to be filled) and be ended with a funnel to make the filling easier. Length of the flow-in and flow-off pipes should be 250 mm at least so as to produce necessary hydrostatic pressure and provide an excess amount of the compound to account for shrinkage (thermal and chemical) which occurs in curing process of the compound, as well as possible leakage through non-tight spots. In case when to drill vertical flow-in and flow-off holes is not possible they should be done with a small angle of inclination from perpendicular (Fig. 5.16b).

Sometimes some difficulties occur in drilling flow-in and flow-off holes in stern boss or stern journal, in such case the pouring is performed through a ring gap at

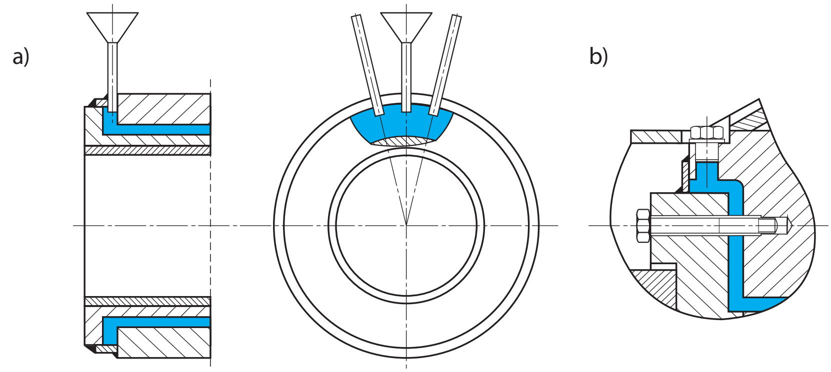


Fig. 5.17. Compound pouring through a gap close to flange

the flange. To this end holes should be made in the sealing strip on the flange and relevant flow-in and flow-off pipes should be inserted (Fig. 5.17a). Various special solutions for stern tube pouring may be also applied. An example of such solution is presented in Fig. 5.17b. In this case the compound is poured through a special hole made at a stern tube outlet which is properly shaped. The compound flows through the gap at the flange and then fills the whole stern tube pouring space. When the pouring process is ended the flow-in hole is plugged by means of a threaded stud.

The pouring should be carried out in a continuous way, maintaining a sufficiently high head of the compound in the pouring gate as it prevents against entrapping the air into the flow-in pipe.

On account of compound shrinkage (both thermal and chemical) which occurs in curing process, the pouring into large spaces is usually performed in two stages: at first about ⅔ of compound mass is poured and then, after its gelation, the remaining ⅓. Proper overpours (sinkheads) located in the highest points of the pouring space ensure its correct filling and good adhesive contact between the compound and surfaces of stern tube and hole for it. When the pouring space is already filled, levels of the compound both in the flow-in and flow-off pipe should be observed because to pour an additional portion of the compound before its gelation is sometimes necessary.

After gelation of the compound, the flow-in and flow-off pipes are removed and, when the compound is fully cured, their holes are plugged by means of bolts or a special plastic sealing composition. The adjusting screws are removed and their holes are plugged by means of bolts, cut away and secured by a sealing paste.

In the case when shaft line axis is deflected from horizontal plane the flow-in pipe should be joined with the top of the lower end of stern tube and the hole

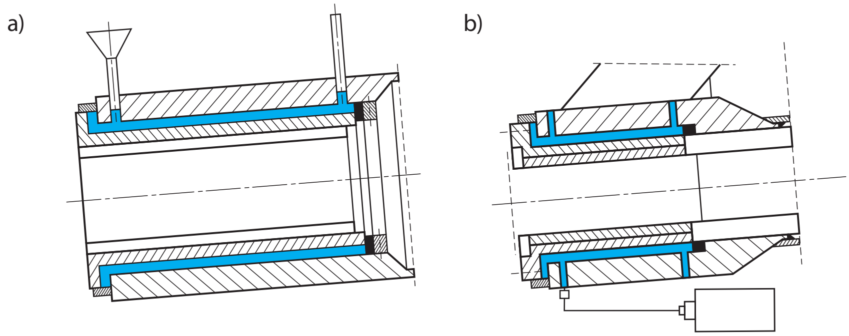


Fig. 5.18. Filling the pouring space with compound in case when shaft line is deflected from horizontal plane: a) by pouring from top; b) by pumping from bottom

with flow-off pipe should be located in the highest point of the upper end of stern tube (Fig. 5.18a).

Pumping the liquid compound into pouring space is usually executed from the bottom through a hole made in the possibly lowest point of the space. (Fig. 5.18b). The air-escape and flow-off must be located in the top of the upper end of stern tube. Pipe installation through which the compound has to be pumped (Fig. 5.18b), should be fitted with a cut-off valve. When the pouring space is completely filled the valve should be closed and the compound delivering pipe - disconnected. In case the pump would not be immediately used again, it should be carefully cleaned.

Note:
During filling the free space between stern tube and its seat in stern journal large buoyance forces acting on the stern tube occur in compliance with Archimedes principle. In the case of large tubes the forces may significantly exceed their weight and exert very high pressure force onto adjusting screws located in the upper part of stern tube. As a result, loss of contact with the adjusting screws located in the lower part of the stern tube and a disturbance of its position may happen. Therefore the adjusting screws should be properly strained in order to ensure stable position of the stern tube during process of pouring the liquid compound to it. However the straining cannot be too high to avoid any deformation of stern tube.

The poured compound should be properly cured. Curing time of EPY compound should be equal at least to:

72 h — in temperature range of 10÷13°C,
48 h — in temperature range of 14÷20°C,
24 h — in temperature > 20°C.

Fig. 5.19. Stern tube assembling in winter conditions with the help of a special booth heated with warm air (Onega Shipyard, Petrozavodsk, Karelia)

When the site where installation operations are carried out, is directly exposed to weather conditions, appropriate sheltering measures (umbrella roof or tent) should be applied. In case the ambient temperature drops below 13°C the site should be heated by warm air blowing for 24 h at least. In cold climate zones at air temperature below zero various ways of sheltering and heating the stern tube assembling site are used. For instance, in Onega Shipyard, Petrozavodsk (Carelia), an ingenious, warm-air-heated booth was applied (Fig. 5.19). The stern tube assembly work in question was carried out in winter (March 2008). The booth has been found very comfortable and useful in practice. It may be easily moved and used for stern tube installation on various ships.

5.2.4. Protection of the connection against influence of external factors

In spite of that poured compound well adheres after curing to the surface of the hole and the surface of stern tube or stern journal installed in it and ensures that they are exactly positioned, it not always provides perfect tightness of the connection. It results from temperature change which occurs in practice and significant difference between thermal expansion coefficients of the compound and metal. For this reason independent protective means against influence of external factors (sea water and oil) should be designed and applied to this system, such as it is used

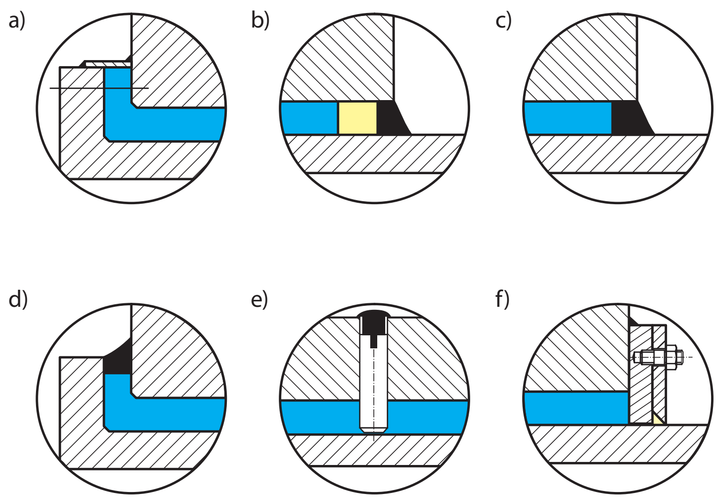


Fig. 5.20. Various ways of protection against impact of external factors (sea water, oil) used in seating stern tubes and shaft bearing liners: a) metal ring welded to flange; b), c) sealing made of elastic epoxy resin (at maintaining or removing the foam sealing, respectively); d) sealing made of elastic epoxy resin placed on flange; e) plugging the adjusting screw hole with a bolt and sealing it by using plastic epoxy resin; f) sealing with the use of a screwed-in ring disc and rubber O-ring

in traditional design solutions, i.e. stern tubes assembled with force fit on sea-going ships. A few such protective means used in seating stern tubes on sea-going ships are shown in Fig. 5.20. Apart from the methods shown in this figure there are also other solutions for the protection.

5.3. Health and fire safety issues

EPY compound is based on epoxy resins. In liquid state they are to some extent aggressive and may cause rash or eczema in allergic persons. Due to this fact utmost care should be given to avoidance of any liquid resin getting into skin and eyes contact and even more so for the very aggressive hardener. To use protective clothing is necessary. Vapours of liquid compound may cause irritation of respiration tracts and eyes, hence ventilation should be used in closed spaces. In case of skin contamination it should be wiped clean with a tampon wetted with acetone, and then washed with lukewarm soaped water, neutralized with acetic or citric acid washed with water again and greased with protective cream.

Eating and smoking are prohibited during work with hardener. Hardeners are flammable liquids which may be extinguished by using water, fire extinguishing powders, carbon dioxide. Detailed information on these issues is contained in the relevant hazardous chemical substance characteristics cards [101, 192].

In the curing process of the compound exothermal chemical reaction takes place, during which no volatile by-products are emitted. EPY compound, in solid state after curing, is not harmful to health, that is confirmed by Sanitary certificate no. 172/779/190/2009 issued by Polish Institute of Maritime and Tropical Medicine in Gdynia.

6 Practical examples of applications of EPY compound chocks for the seating of machinery

6.1. General remarks

Practical use of foundation chocks of chemically curing compounds for the seating of ships machinery dates back to the mid 1960s, when it was initiated in the United States with the compound Chockfast Orange. Polish resin compound for foundation chocks, developed at the Technical University of Szczecin in the years 1970÷1973, was first time used in 1974 on the training motor ship ”Kapitan Ledóchowski” built by Szczecin Shipyard.

Chemically curing compounds with exactly defined properties, improved as time progressed, have proved to be an almost ideal material for machinery foundation chocks. Their application in industrial practice was decided first of all by the following factors:

1. The possibility to mix the composition and easily cast the foundation chocks of any required dimensions and shapes in site of their installation.
2. Good strength properties of cured compound.
3. Relatively low value of elasticity modulus and very good natural fitting over a wide area of contact with high coefficient of friction; the factors ensure a reliable installation without any fretting and wear of contact surfaces.
4. Significant shortening of the duration time of machinery seating on foundations, and lowering cost of the operations.
5. Better, in comparison with steel, mechanical vibration damping properties and better isolation properties against structural sound.

Compound chocks are convenient for use not only in the seating of new machinery, but also in the repair operations carried out away from repair workshops. Apart from rough cleaning and degreasing of foundation surface no special surface preparation is needed.

Any roughness, corrosion pits and non-parallelism of surfaces, which make use of traditional metal chocks difficult or impossible, do not constitute any obstacle in case cast compound chocks are used instead. Significant technical and economic benefits and also operational advantages resulting from the modern seating technology and its new materials have proved themselves in practice, and consequently a new standard for ship machinery seating has been established. The technology is also used more and more for the seating of various important land-based objects.

6.2. Examples of the seating of ship machines and devices

6.2.1. Main propulsion engines and gears

6.2.1.1. General remarks

Ship machines and devices may be seated on their foundations in a stiff or elastic way. Large main propulsion engines and gears are as a rule inflexibly fastened to their foundations, which ensures their proper installation and stable position in service. Metal chocks have been traditionally used in such seating arrangements, and presently chocks made of polymer resin compounds specially developed for this purpose are applied. It should be distinctly stressed that application of the compounds has been conditioned upon that they would be capable of ensuring the inflexible fastening of an object in a way not worse than that based on traditional metal chocks. The compounds in question do not belong to the group of compounds (elastomers) used for elastic pads. They are of a relatively high stiffness, intended (acc. GL rules [43]) for foundation chocks used for the inflexible seating of ship machines and devices.

The compounds in question have also found application in the elastic seating of ship engines. In such cases they are used for foundation chocks placed under shock absorbers on which the engine is elastically seated. An example of such seating arrangement is discussed below (in p. 6.2.1.3).

6.2.1.2. Rigid seating arrangement

Compounds for foundation chocks have been developed firstly in order to simplify the seating of ship main propulsion engines and gears and shorten time of their installation. The traditional way of seating the machines (by using metal chocks) had many substantial drawbacks, including: the necessity to machine the foundation plate and metal chocks, the necessity to fit the chocks manually and many other troublesome and time-consuming operations. The requirements which apply to the main engine seating (Fig. 6.1) are very high, hence the operations on the chocks went on for a very long time (1÷3 weeks), were troublesome and their labour costs were significant.

Application of compound chocks cast in site under the properly aligned engine, has simplified seating operations, shortened installation time and lowered costs of the work. Moreover, it gave many technical and operational benefits.

Ship main propulsion engines are the largest group of objects seated on compound chocks. The numbers of engines seated this way are presented in Tab. 6.1, depending on their producers.

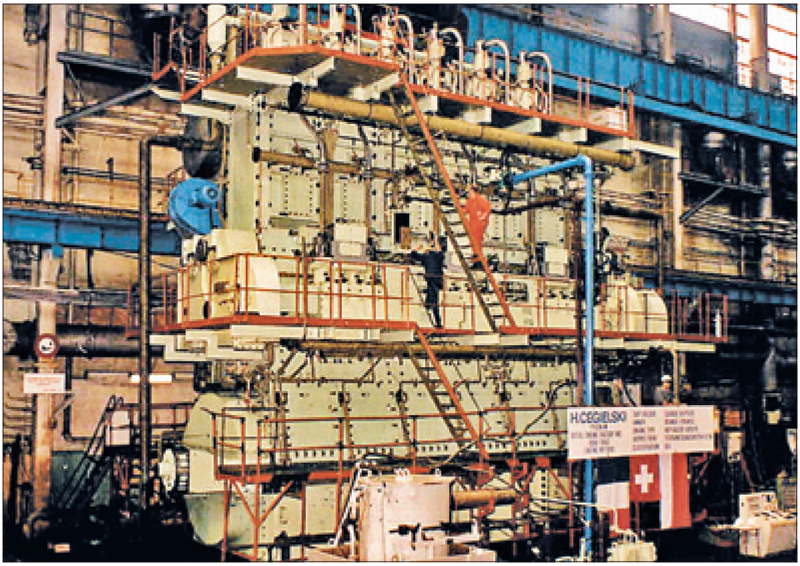


Fig. 6.1. 6RTA76 HCP-Sulzer main propulsion engine (on test stand)

Table 6.1. List of main engines seated on resin compound chocks in the years 1974÷2014

Type of engine	Number of engines
Caterpillar	79
Deutz	106
HCP-Fiat	19
HCP-MAN	85
HCP-Sulzer	356
MAN-B&W	80
MaK	129
Puck	231
SKL	225
Wärtsilä	115
Wola	158
Inne	653
In total	**2236**

An example of the engine seated on EPY compound chocks is shown in Fig. 6.2a. The engine is mounted on 20 chocks whose arrangement is shown in Fig. 6.2b. Fig. 6.3 shows the main propulsion gear of a ship, also seated on EPY compound chocks.

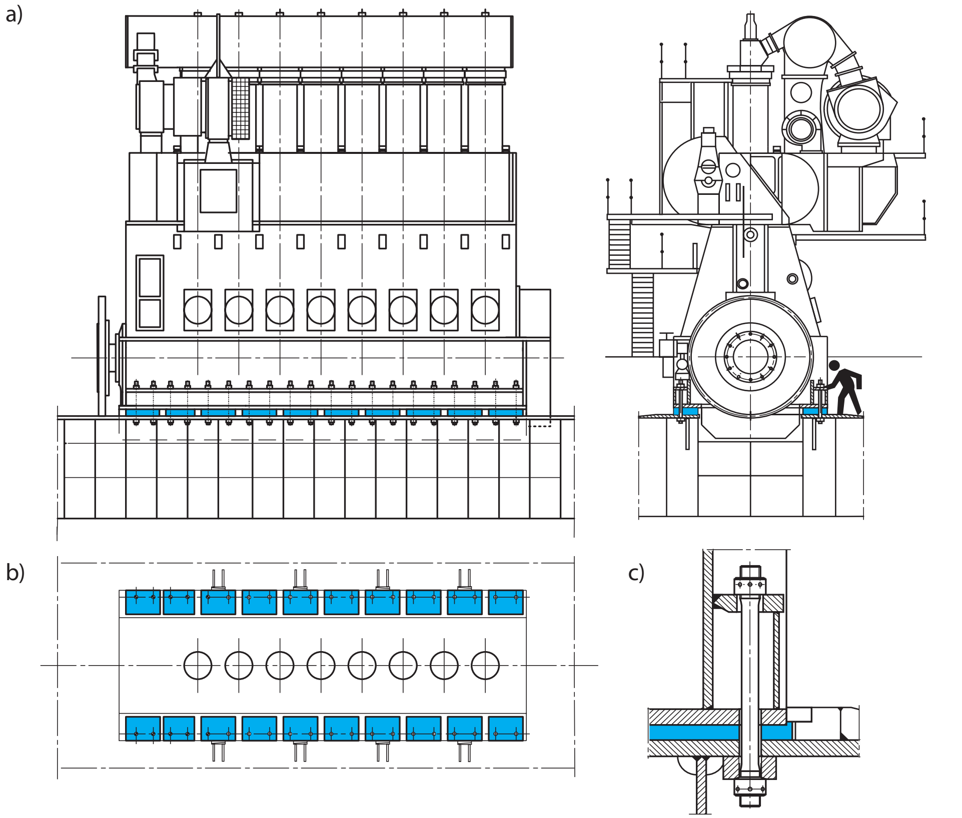


Fig. 6.2. 8RTA68T-B Sulzer main propulsion engine seated on EPY compound chocks: a) overall view; b) arrangement plan of foundation chocks; c) cross-section of a foundation bolt joint

Holding down bolts fastening the main engine or gear may be inserted with some clearance (Fig. 6.4a, b) or fitted in their holes (Fig. 6.4c, d, e). The fitting may be to metal (Fig. 6.4c) or in compound (Fig. 6.4d, e). In case of loosely inserted bolts, elastic pipes made of rubber or foamed polyurethane are pushed into their respective holes before the chock is cast (Fig. 5.1d). In case of bolts fitted to metal (Fig. 6.4c) at first the holes are drilled and bored, then the fitted bolts are inserted and only after that the mould is filled with compound. Such procedure is very troublesome and time-consuming especially in case of large holes (40÷60 mm diameter). Bolts

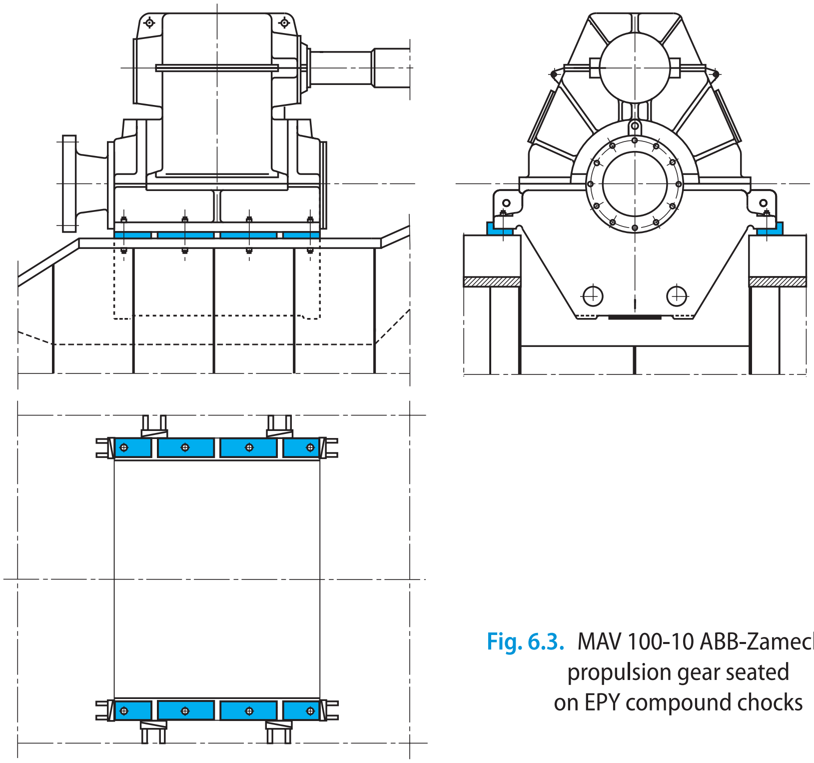


Fig. 6.3. MAV 100-10 ABB-Zamech ship propulsion gear seated on EPY compound chocks

fitted in compound material (Fig. 6.4d, e) are inserted before casting and the chocks (including the piping) are then cast around them. Fitting of holding down bolts in compound is an original solution which was patented [49] and approved by classification societies. The compound piping of wall thickness in the range of 2÷10 mm is cast together with the foundation chock, which eliminates the necessity to fit the bolts to the holes (of 20÷60 mm diameter) in foundation plate and engine bed plate. As a result, duration time of the operation is significantly shortened and its cost is reduced as well. Bolts fitted in compound may safely transfer very large static and dynamic loads in directions tangent to supporting surface. As EPY compound contains ceramic components any machining (drilling and boring) of the holes should be avoided after the chocks are cast and cured.

6.2.1.3. Elastic seating arrangement with the use of compound chocks

Foundation compound chocks are used not only for the so called stiff seating of ship main propulsion engines but also in elastic seating arrangements of such objects for foundation chocks placed under shock absorbers on which the engine is elastically seated. An example of the engine elastically supported on shock absorbers which are seated on EPY compound chocks, is presented in Fig. 6.5÷6.7. It is ME MaK 8 M32C

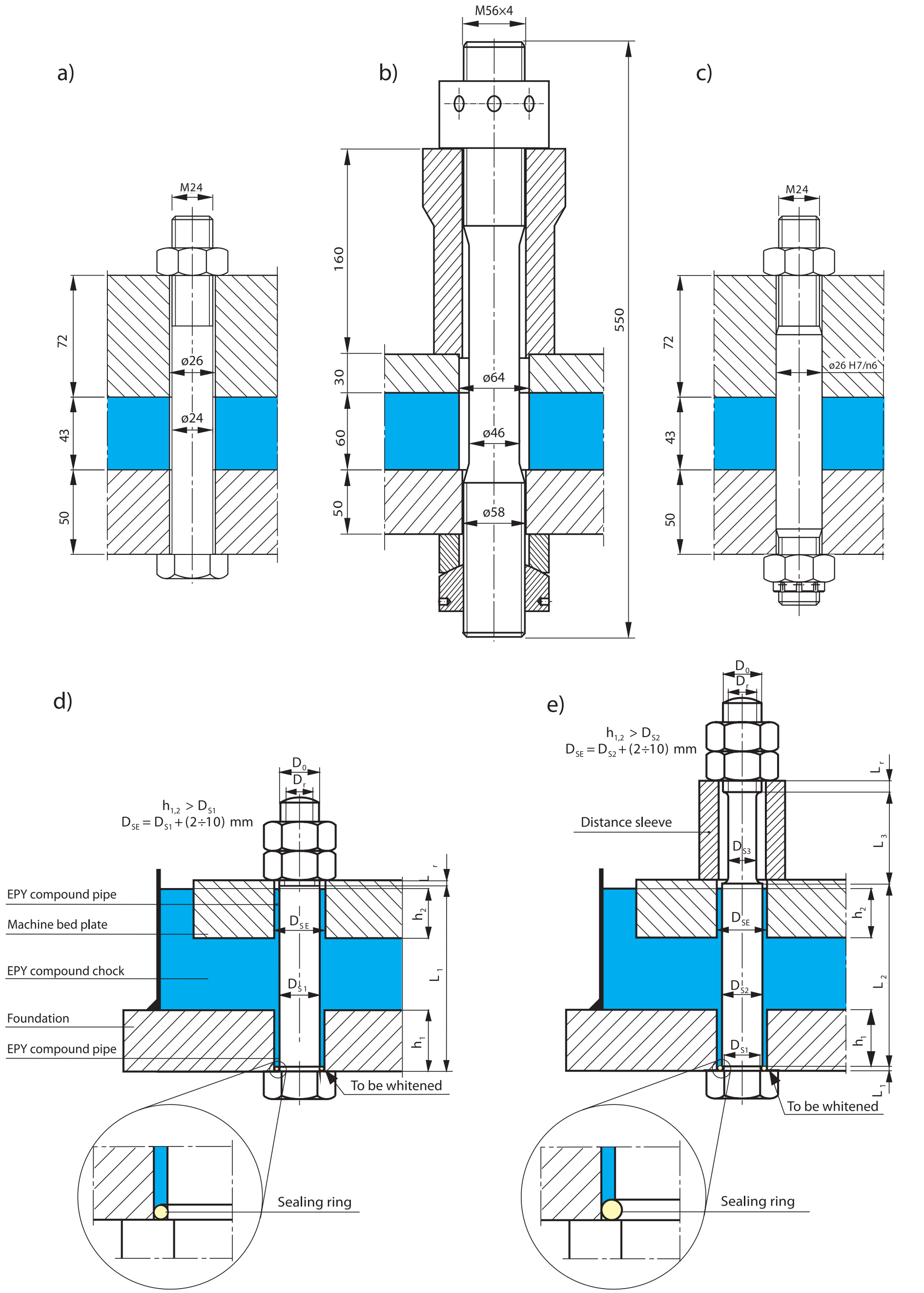


Fig. 6.4. Exemplary cross-sections of ship machinery foundation bolt joints: a), b) with loosely inserted bolt to hole; c) with a traditionally fitted bolt to machine foundation and bed plate; d), e) with foundation bolt fitted to compound pipe cast together with a whole chock

main engine installed on the m/t NORDERVON, deep-sea fishing trawler. The seating operation of the engine on compound chocks was performed, on order of NSS Ltd Co in Szczecin, by MSJ Co in January 2010, under supervision of Det Norske Veritas.

Schematic arrangement and dimensions of the compound foundation chocks are presented in Fig. 6.6a. Fig. 6.6b shows schematic drawing of the shock absorber seated on the compound chock. Eight shock absorbers were fastened to the engine bed plate with the use of bolts, four on each side (Fig. 6.6a). The engine was properly

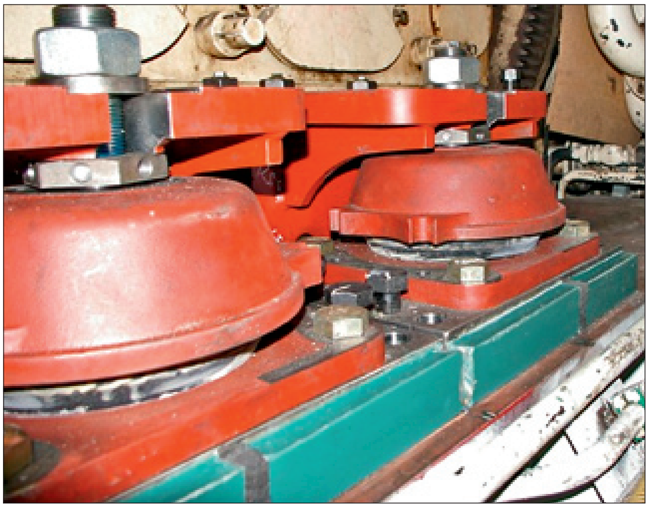


Fig. 6.5. Fragment of a flexible support of ship engine on shock absorbers seated on foundation chocks cast of EPY compound

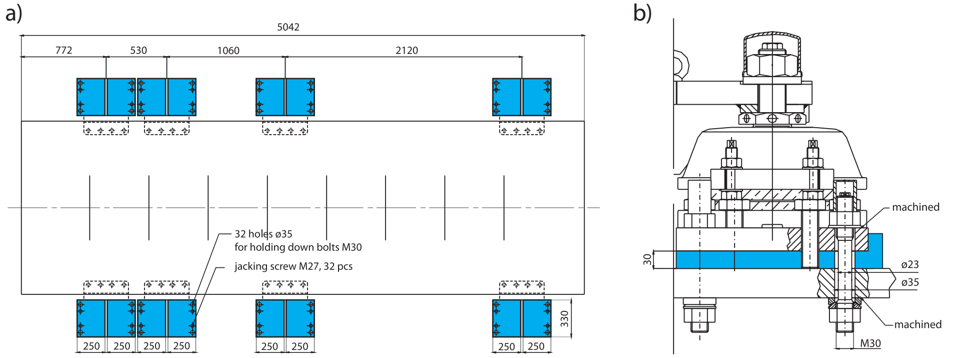


Fig. 6.6. Schematic arrangement plan and dimensions of foundation chocks (a) and the seating of shock absorber on EPY compound chock (b)

positioned on its foundation by using adjusting screws placed in base plates of the absorbers (Fig. 6.7). On the foundation casting moulds of steel sheets were then prepared and firmly sealed by means of a putty (Fig. 6.7a, b). Polyurethane foam pipes were installed in the places where the holes for the bolts should be formed in the

Fig. 6.7. EPY compound foundation chocks under shock absorbers supporting main engine of sea-going ship: a) filling the casting mould; b) the mould after filling with compound; c) ready-to-use chocks after removing the mould

cast chocks. After checking if the engine is properly aligned the moulds were filled with liquid resin compound mixed in advance with hardener. When the compound has been fully cured, the moulds were removed to get ready to use chocks. They had smooth side surfaces and exactly fit to load bearing surfaces of the foundation and the shock absorbers fastened to it (Fig. 6.7c). Next, the adjusting screws were loosened and the holding down bolts joining all the foundation system together were properly tensioned. The seating arrangement prepared this way ensures high exactness, stability and reliability. It is resistant to action of water, oils and chemical agents.

6.2.2. Stern tubes, shaft line bearing liners and rudder arrangement liners

The use of EPY compound in liquid state to the casting of the seating of stern tubes, shaft line bearing liners and rudder arrangement liners, applied since 1979, is a technique thoroughly proved in practice. The seating technology of stern tubes and stern bearing journals was discussed in detail in p. 5.2 of this book. Due to its many advantages the technology presently has become a standard in shipbuilding and ship repair work. In the period between 1979 and the end of 2013 the total number of seating operations with the use of the compound, completed on stern tubes and journals of various ships, reached 886. Three exemplary practical applications of EPY compound for this purpose are presented in Fig. 6.8, 6.9 and 6.10.

Figure 6.8 shows a typical project of the seating arrangement of a large stern tube on sea-going ship. Fig. 6.9 presents an example of application of EPY compound to seating the main propulsion shaft line elements on a twin-screw ship, and Fig. 6.10 — its application to seating the shaft line and ruder arrangement elements on a sea-going ship.

The assembling of stern tube and elements of shaft line and ruder arrangement is relatively simple, easy, very exact and fast. There is no need of the centering and exact machining of large diameter holes.

6.2.3. Application of the resin compound to the seating of bearing liner on ship shaft line

6.2.3.1. Introductory remarks

The process of seating stern tubes and rudder bearing liners discussed in p. 6.2.2 was carried out with regard to holes in relevant structural elements of ships. The technology has been already well mastered and proved in practice. It has become presently a standard in shipbuilding practice.

In this point the following issue is presented: the process of the seating of a large bearing liner (of 1055 mm outer diameter and 4860 mm length) onto ship propulsion shaft. This is a novel, original solution which has not been applied so far in practice. For this reason it is discussed in some detail.

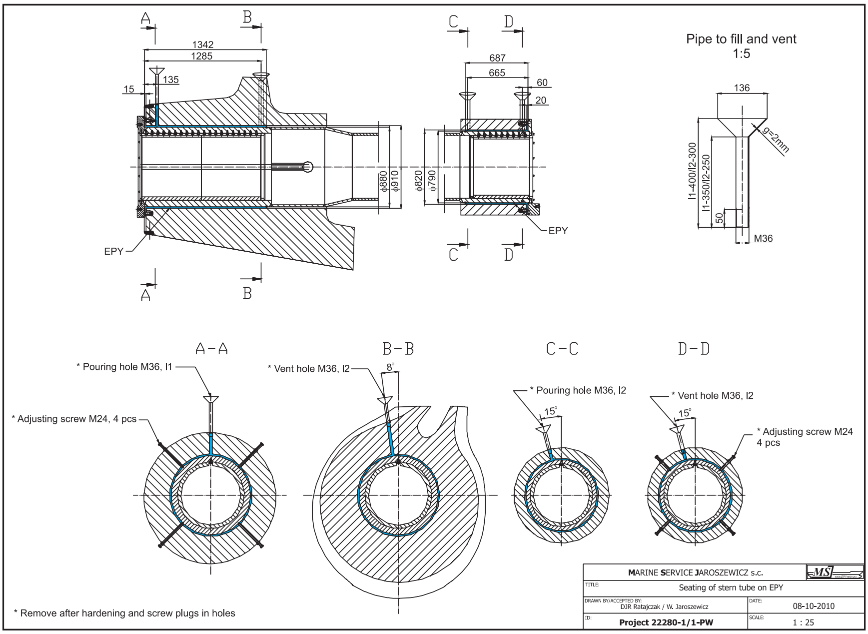


Fig. 6.8. Exemplary design project of the seating of stern tube on sea-going ship

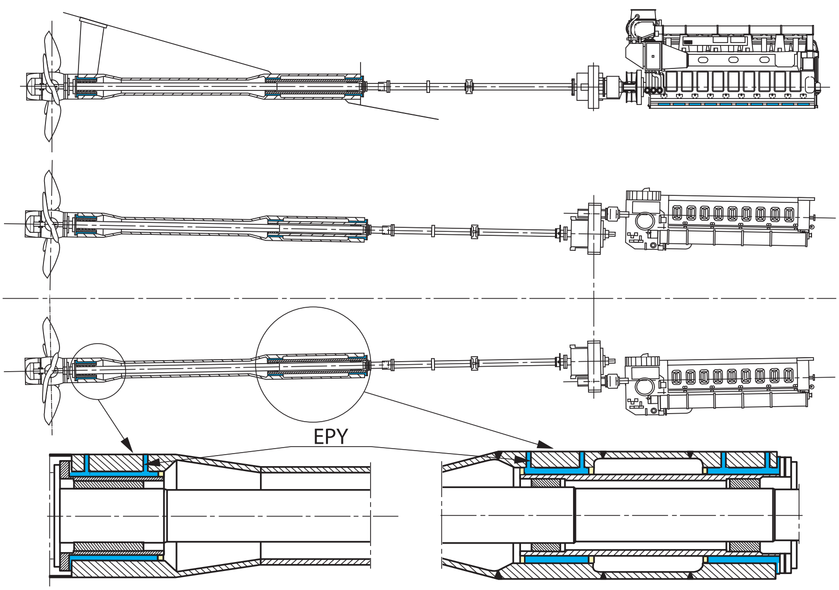


Fig. 6.9. The exemplary application of EPY compound to the seating of shaft line elements of main propulsion system on a twin-propeller ship

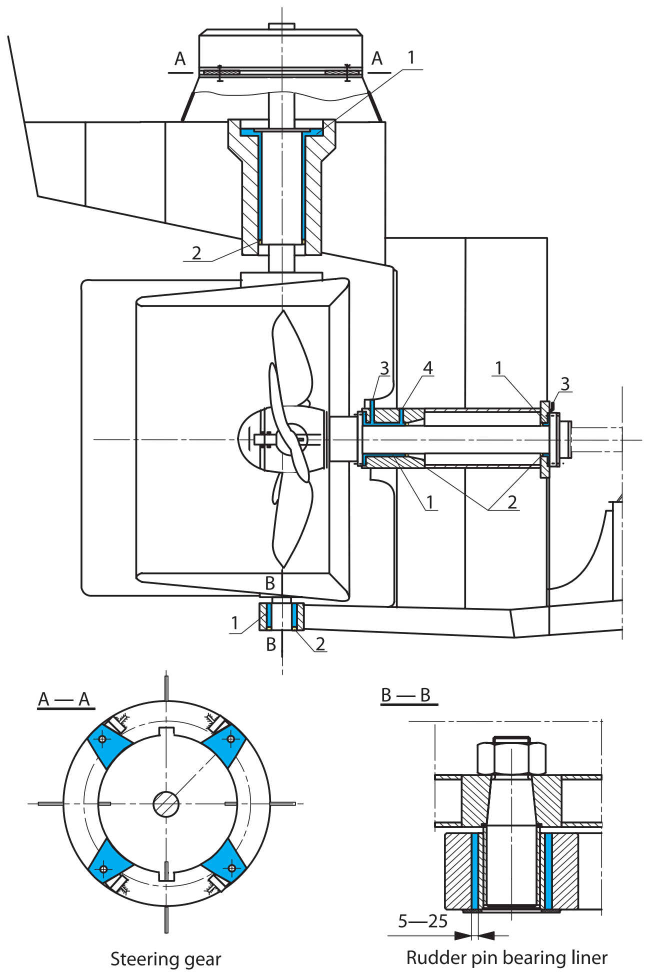


Fig. 6.10. The exemplary application of EPY compound to the seating of elements of shaft line and rudder arrangement on sea-going ship: 1 — EPY compound, 2 — sealing foam, 3 — flow-in holes, 4 — flow-off holes

In hitherto practice, the bearing liners made of bonze have been usually seated on shaft lines of ships by using thermo-compression bonding. Their assembling process consists in proper heating the liner and free inserting it onto shaft and then letting it to cool down to ambient temperature. Such solution was used also in the case of the shaft in question (Fig. 6.11) during process of building the ship. Two bearing liners were inserted onto the shaft by means of the thermo-compression method. During general overhaul of the ship it was revealed that to remove one of them and replace it by another, is necessary. The new liner to be inserted onto the left part of

Fig. 6.11. A fragment of ship propulsion shaft line, prepared for seating a new bearing liner

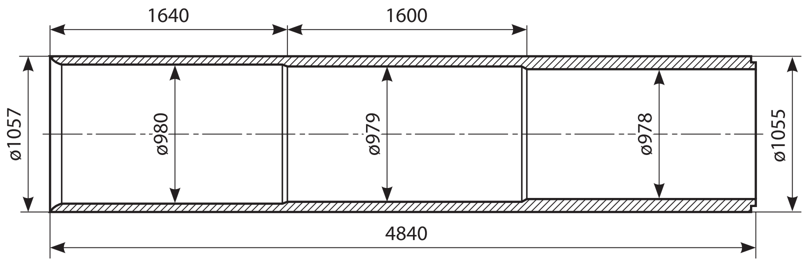


Fig. 6.12. Shape and dimensions of a new bearing liner intended for the seating with the use of EPY compound

the shaft, ended with the large flange (Fig. 6.11), had much greater dimensions than the other one which was in a good state and had to remain on the shaft. Shape and dimensions of the new liner are shown in Fig. 6.12.

The overhaul of the "Arkhangelsk", a ship operating in Arctic waters, was carried out by an Estonian firm (OÜ Wärtsilä BLRT) of Tallin, in a Chinese shipyard (Yiu Lian Dock Yard Ltd, Shenzhan), under supervision of Russian Maritime Register of Shipping. The shipyard in which the ship had to be repaired, was of no practical possibilities to seat the so big liner onto shaft by using the traditional, thermo-compression method. In this situation it was decided to make use of a special polymer compound widely applied in present to seating many ship machines and devices. The firm which was repairing the ship, applied to many specialty firms engaged in seating ship machinery with the use of resin compound, located in that region. However none of them was ready to execute this novel and risky task. Only Marine Service Jaroszewicz Company of Szczecin decided to cope with the challenge.

Scope of the work contained: elaboration of a detailed design project of seating the liner onto shaft, relevant assembling technology and its execution in the Chinese ship repair yard.

6.2.3.2. Design project of the seating of bearing liner onto shaft

The design project of the seating arrangement of bearing liner onto ship propulsion shaft with the use of EPY compound is presented in Fig. 6.13. The shaft is hollow inside and its outer diameter in the place of seating the liner somewhat varies and has subsequent values of 968, 967 and 966 mm, over three shaft segments of 1640, 1600 and 1600 mm in length, respectively. In a similar way values the internal diameter of the liner are also differentiated. (Fig. 6.12); they are equal to 980, 979 and 978 mm, respectively. The difference in diameters of the shaft and liner is kept constant at the value of 12 mm. It provides as a result the compound pouring gap of 6 mm in its nominal height over the entire length of the seating. This is a relatively low height

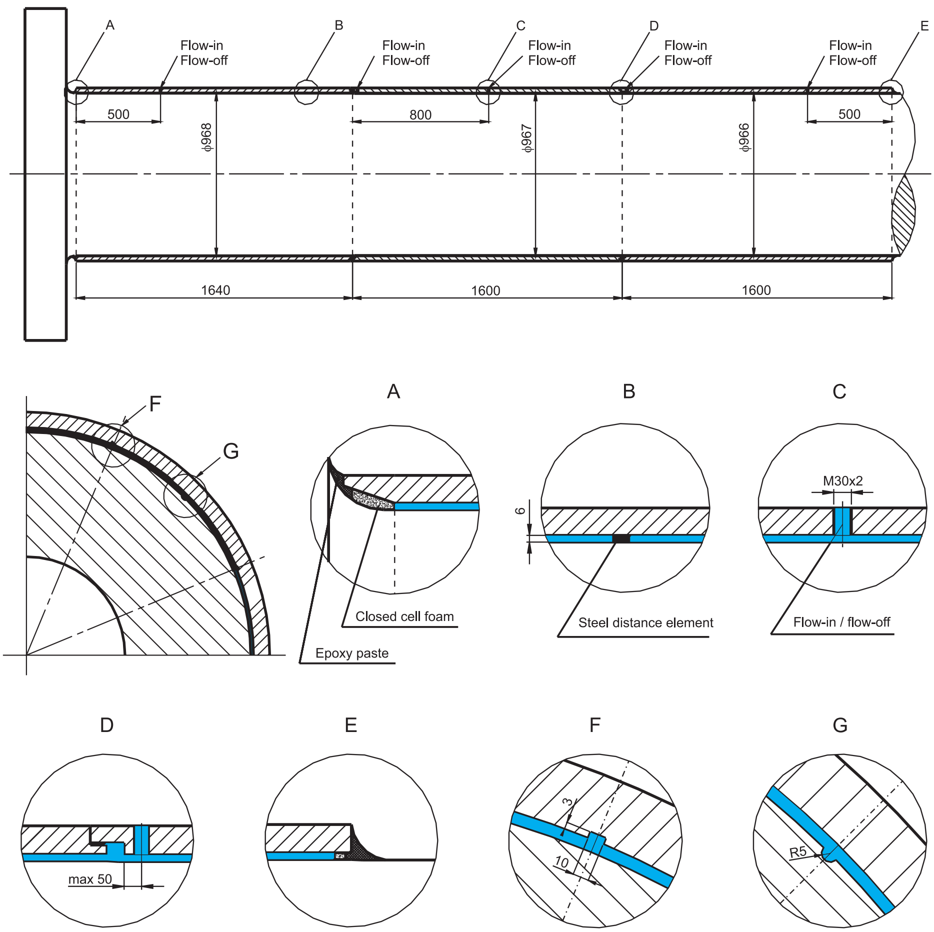


Fig. 6.13. Design project of the bearing liner seating onto ship propulsion shaft with the use of EPY compound

(in comparison to large remaining dimensions of the gap), which is associated with many problems not been investigated so far. They concern proper filling the pouring space in order to obtain a correct cast — of a small thickness and very large remaining dimensions. As results from the hitherto gained experience, in this case, to obtain a good effect is very hard and associated with a significant risk. It is worth mentioning that in the case of seating the stern tube into stern frame bush of ship, of similar or even significantly smaller dimensions, the applied height of pouring gap usually is equal to 15÷20 mm, that is an important, but not only difference in comparison to the solution presented in the design project in question.

The total length of the bearing liner (Fig. 6.12) amounts to 4840 mm, and its outer diameter is constant and equal to 1055 mm. As internal diameters of the liner somewhat differ to each other, its thickness stepwise changes and has a little different values, namely: 37.5, 38.0 and 38.5 mm.

It was decided, in view of manufacturing difficulties, to prepare three separate component liners instead one, which should be next, after inserting them onto the shaft, properly connected together by using lap joints (Fig. 6.13, detail D) to fulfil their function as correctly as a uniform liner could do. In order to ensure coaxiality of the liner and shaft and a constant height of the pouring gap as well, 24 distance elements of 6 mm in height were welded on to the shaft surface (Fig. 6.13, detail B). The elements welded to the shaft can be seen in Fig. 6.15.

Along the upper generating line of the bearing liner, (before its mounting) five holes (M30) were drilled and threaded in order to place flow-in and flow-off pipes in them (Fig. 6.13, details C and D). At both ends of the liner, seals were provided (Fig. 6.13, details A and E): internal one made of polyurethane foam (for the compound) and external, permanent one to protect the joints against exposure to sea water action. The latter seal was decided to be made with the use of a special epoxy sealing paste (Phillybond Orange Sealant Resin, ITW Philadelphia Resins). In the seals four control venting holes were provided (in the bottom, mid height and in the top), which should be properly sealed when the liquid compound is seen in them during pouring. The lap joints of particular component parts of the liner should be circumferentially sealed by means of a self-adhesive tape. Also in these seals the control venting holes were provided, to be sealed when the liquid compound is seen in them during pouring.

The fully cured compound which fills the whole pouring space, should ensure not only reliability of the connection but also safe transferring the torque exerted onto the bearing liner. It was assumed that the circumferential forces acting on the connection should be transferred entirely by integral keys of the compound, formed in longitudinal key grooves which are machined in internal surface of the liner and external surface of the shaft. To this end, eight longitudinal grooves located in 45° angular distances to each other, were designed. Their shape and dimensions are shown in Fig. 6.13, details F and G. They should be entirely filled with the liquid compound, to form, after curing, a properly fit, splined connection between the compound, shaft and bearing liner.

The compound integral keys located in the grooves are first of all exposed to shearing forces and surface pressure. In view of that, relevant control calculations were performed. The following input data were assumed:

Maximum shaft power	$P = 15{,}400$ kW
Shaft rotational speed	$n_w = 120$ mm^{-1}
Radius of action of circumferential force applied on shaft-compound connection surface	$R = 483$ mm
Total length of key (groove)	$L = 4840$ mm
Breadth of integral key	$B = 10$ mm
Depth of key (groove in shaft)	$H_w = 3$ mm
Depth of key (groove in liner)	$H_t = 5$ mm
Number of circumferential keys (grooves)	$n_r = 8$
Shear strength of the compound	$R_t = 59.1$ MPa
Compression strength of the compound	$R_c = 169$ MPa

Shaft torque

$$M_o = 9550 \cdot 10^3 \frac{P}{n_w} = 1225583\,\text{Nm} \tag{6.1}$$

Total circumferential force on shaft-compound connection surface

$$F_T = \frac{M_o}{R} = 2537438\,\text{N} \tag{6.2}$$

Shear stresses

$$\tau = \frac{F_T}{n_r B L_T} = \frac{2537438}{8 \cdot 10 \cdot 4840} = 6.55\,\text{MPa} \tag{6.3}$$

Surface compression forces

$$p = \frac{F_T}{A_p} = \frac{2537438}{8 \cdot 3 \cdot 4840} = 21.84\,\text{MPa} \tag{6.4}$$

Shearing safety factor

$$n_\tau = R_t / \tau = 8.95 \tag{6.5}$$

Surface compression safety factor

$$n_p = R_c / p = 7.74 \tag{6.6}$$

As results from the above presented calculations, the safety factors in shearing and surface compression at the ultimate load (shaft torque) exerted on the bearing liner, are sufficiently high.

It should be noticed that in the calculations extremely unfavourable conditions were assumed, as neither adhesion nor friction forces of the compound on contact surfaces with shaft and liner, were taken into account, which really occur increasing safety of the connection. For the calculations it was assumed that the connection between the compound, shaft and liner is loaded with the torque of the most possible value resulting from power of the engine. In usual ship's service conditions the shaft transfers the torque from the engine to screw propeller and only a small part of it is lost to overcome friction which occurs in the bearing. Only this small part of the torque is really exerted to the splined connection between the compound, shaft and bearing liner. As a result, the real safety factors in shearing and surface compression for the compound in usual ship's service conditions are of values many times higher than the above calculated *de facto* for failure state of the bearing when rotations of the shaft are completely blocked in the bearing. Such situations has not been reported so far in practice.

Therefore it may be concluded that the designed shaft-liner connection with the use of EPY compound fulfils safety conditions for its strength, with a very large margin.

6.2.3.3. Model testing

In spite of 30-year experience gained in seating the ship machines and devices with the use of the compound, it was decided that some model tests should be performed in advance in view of a specificity and great responsibility of the undertaking. The tests were aimed at practical checking the feasibility of the proposed solution and elaboration of many details dealing with the technology of its implementation.

The model of the seating of the liner on the shaft with the use of EPY compound is shown in Fig. 6.14. Its diameter amounted to 1000 mm, and its length — 2000 mm. The gap height was 4 mm, that was ensured by properly located distance elements. The conditions assumed for the model were more unfavourable than in the real object. First of all it concerned the pouring gap height which was smaller by 2 mm than that in the real object.

The model was made of wood (model plywood wrapped around circular disks and properly stiffened by ribs). The outer liner was made of plexiglass to make observing the process of filling the pouring space with liquid compound, possible. Two holes were drilled along the generating line of the plexiglass liner. Into the holes, pipes ended with funnels were inserted. They had to serve as the flow-in and flow-off ways for liquid compound. The distances of the flow-in and flow-off holes to each other and from the ends were the same as those in the real object. Lengths

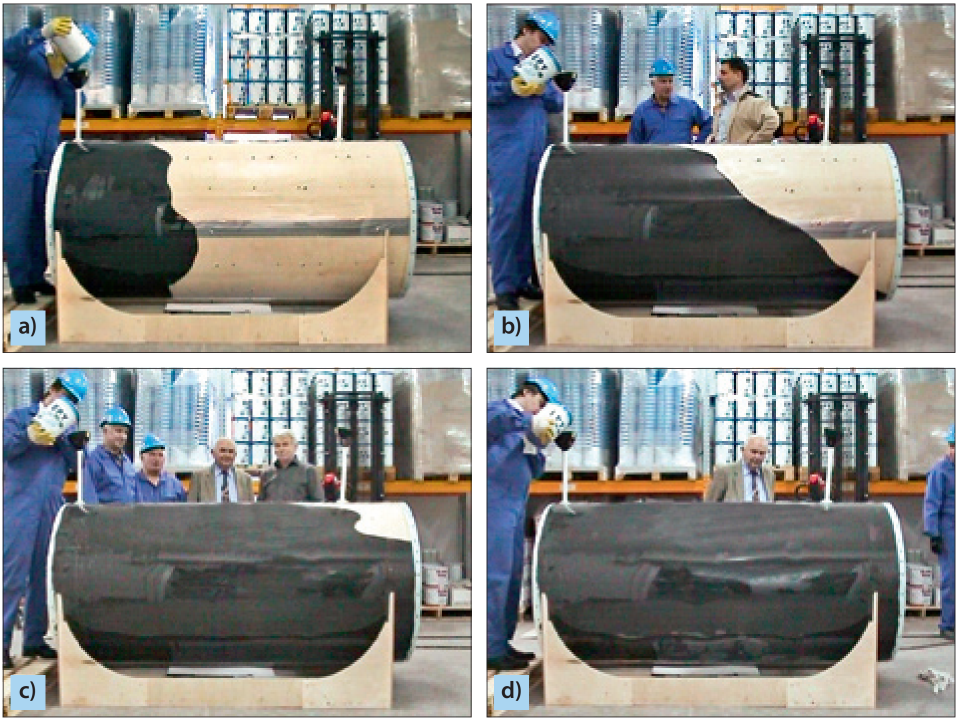


Fig. 6.14. Model tests on run and time of filling the pouring gap between shaft and liner with liquid EPY compound

of the pipes, equal to 500 mm, had to provide a proper value of hydrostatic pressure for the compound filling the pouring space and to contain a sufficient amount of the compound for supplementing its lacking portions inside the pouring space till the instance of its complete curing. The important thing in the experiment was to practically prove the pouring process through one hole and a mode and speed of spreading the compound as well as possibly correct filling the whole pouring space before the commencement of its gelation process. It was also important to assess a real duration time necessary for execution of the operation in given temperature conditions.

The sealing of pouring space at its boundary was made with open-cell polyurethane foam. It formed an additional way for air escape during filling the space. In the experiment in question it was important to check the way of spreading the compound over the pouring space as well as quality of the produced cast after its curing in ambient conditions.

Results of the experiment turned out to be very useful in elaborating many details of assembling technology of real liners onto ship shaft line. In the seating technology of constructional elements with the use of the compound there are many important details which may decide on ending either with success or failure in practical application of such solutions.

6.2.3.4. Preparation of elements and run of their assembling

The bearing liner segments properly prepared according to the design shown in Fig. 6.13, as well as a fragment of the shaft on which they have to be installed, are presented in Fig. 6.15. Eight longitudinal grooves of shape and dimensions shown in Fig. 6.13 (details F and G) were cut on both the inner surface of the liner and the outer surface of the shaft. 24 distance elements were welded onto the shaft's surface, in appropriate locations. Their height was equal to 6 mm in order to ensure proper position of the liner against the shaft and uniform height of pouring gap. The distance elements were properly tapered (Fig. 6.15d) to facilitate the process of inserting the liner onto the shaft and shifting along it.

Fig. 6.15. Segments of the bearing liner and shaft with cut grooves and welded distance elements

The inner surfaces of the liner were properly machined by using a boring machine. The shaft surface was carefully cleaned with the use of glass-paper. Just before the assembling of the liner onto the shaft their surfaces were carefully degreased by using acetone. The overall view of the shaft and the first segment of the bearing liner (hanging on the traverse) are shown in Fig. 6.16a. The liner was inserted onto the free (thinner) end of the shaft which was in this time placed on the roller support located in some distance from the end of the shaft (Fig. 6.16b). Next, after proper fixing the shaft end and shifting off the support rolls (Fig. 6.16b), the liner was shifted by means of the traverse along the axis of the shaft up to vicinity of its flange. The next two segments of the bearing liner, mutually connected with lap joint, were in a similar way inserted onto the shaft and shifted along it. The assembling operation of the third segment of the liner is shown in Fig. 6.16c.

The distance elements welded to the shaft ensured proper centering the liner and proper pouring gap height (Fig. 6.15d). Some minimum clearance was maintained

Fig. 6.16. Run of the inserting operation of particular segments of bearing liner onto shaft

to make shifting the liner segments possible. Certain margin was provided to the outer diameter of the liner for finishing its surface after completing its mounting. When the particular segments of the liner have been already connected to each other, the steel flow-in and flow-off pipes together with cones welded to their upper ends were screwed into it. Finally, the pouring space was sealed at its ends and the liner lap joints, in compliance with the above discussed design project (Fig. 6.13). The unit composed of the shaft and liner, prepared for filling it with the compound, is shown in Fig. 6.17a. The length of the flow-in and flow-off pipes amounting to about 650 mm, including cones, was so selected as to generate and maintain an appropriate hydrostatic pressure for filling the entire pouring space. Also, it was an important thing to obtain an appropriate volume of the flow-in and flow-off system and the compound contained in it after the filling of the entire pouring space. It was necessary for supplementary filling the additional volumes formed as a result of some sealing-foam susceptibility to compression, shrinkage of the compound during its curing, and other factors.

Fig. 6.17. The assembled unit prepared for filling with the compound (a) and a way of filling operation (b)

Ambient temperature in the workshop, when the seating operations were under way, amounted to 20÷24°C. It was decided to heat the system up to about 30°C before its filling with the compound, in order to reach effect of better and faster filling the pouring space. The system (Fig. 6.17a), while covered with a sheltering canvas cover, was heated by using three small electric heaters for about 24 h. In the instant of start of the pouring the liner's temperature was equal to 27°C and the temperature of the pouring compound — to 30°C. The pouring of the compound was executed simultaneously through three holes: two extreme and one middle (Fig. 6.17a). The manner of pouring the compound is shown in Fig. 6.17b. It was run in a continuous and uniform way.

The necessary amount of the compound was calculated in advance. In the time of pouring, the control points located at the end seals and lap joints of the liner, which served as additional venting ducts, were observed. After the compound was seen in them, the points were properly sealed. The pouring time reached 3 h. When the pouring space is completely filled the flow-ins and flow-offs were observed for 2 h and the compound was poured again to supplement the lacking amounts and keep proper level of hydrostatic pressure. The total amount of the poured compound was 98.6 l. The process of dropping the compound level in the flow-ins and flow-offs was ended after 2 h. And, after the next 12 h the flow-in and flow-off pipes and sealing tapes on lap joints of the liner were removed. The holes in the liner, which remained in the spots where the pipes were installed, were finally blanked off with threaded stoppers made of the same bronze material as that of the liner.

During the pouring and curing of the compound no temperature rise was observed in the liner. The curing was carried out in the ambient temperature (in the range of 20÷24°C) and lasted 36 h. Hardness of the compound, measured on special cast samples was 42÷46°B. Control on whether the pouring space is completely filled, was conducted simply by "knocking", and, in dubious places indicated by surveyor, by control drilling. No such place was found where the compound was lacking. After completion of the assembling work the liner's surface was mechanically finished to remove the remaining small margin of the material.

6.2.3.5. Final remarks and conclusions

The presented novel project of the seating of large bearing liner onto ship propulsion shaft with the use of the special epoxy compound (EPY compound) and the technology developed for its execution and implemented in practice, was a success. The applied solution passed a practical exam, that was confirmed in writing by the ship's operator who reported correct performance of the liner seated on the propulsion shaft, and the stern bearing as well. No failure has been claimed so far (for more than four years after introducing the repaired ship into operation).

Results of the project show one of the possible practical applications of EPY compound to solving difficult and complex assembling questions which may appear in the building and repairing of sea-going ships.

Owing to the development and implementation of special polymer compounds it has been possible to solve so far many difficult and complex problems associated with construction and technology of assembling and repair of many machines and devices, which later generated many troubles for designers, manufacturers and operators of such objects. In some cases such solutions are the only practically feasible in a given situation.

6.2.4. Deck equipment

The cast compound foundation chocks are used not only for the seating of machines and devices located in closed under-deck accommodations but also for seating various devices installed on ship's open decks. EPY compound is fully long-term weather resistant. It is especially applicable to the seating of various winches: windlasses, towing, mooring and trawl winches. Fig. 6.18 presents the cruise ship "Fantasy" whose 101V14725FW Pusnes mooring winch was seated on the chocks made of Polish EPAX compound.

Fig. 6.19 shows the seating arrangement of a trawl winch. Number of chocks used for seating the winches may be various, depending on the type of winch and its size, and may range from a few to a few dozens.

Fig. 6.20a presents a sea-going ship with slewing cranes installed on the columns, and Fig. 6.20b — a simplified schematic diagram of such crane. The crane was installed on a large-size ball bearing (D = 2500 mm).

Fig. 6.20c illustrates a traditional seating method for the bearings, which consists in exact fitting (by using reddle) the surfaces to be connected, and Fig. 6.20d — the seating of the same bearing on a thin layer of EPY compound (1÷3 mm thick). A manner of seating the bearing is shown in Fig. 6.21. Due to use of liquid compound for the seating process, whose excess is pressed out aside, a very good fit between the contact surfaces was obtained after curing without any need of using the troublesome, costly and time-consuming machining operations on the column and crane contact surfaces. This way, the assembling work takes less time and is cheaper, while the so seated bearing operates perfectly and is fully reliable.

6.2.5. Tanks installed on the deck and inside the ship

Polymer compounds have turned out very useful for seating various tanks installed on ship's decks or also inside ship's hull spaces. Below, a few characteristic, practically proved examples of such application of the compound are described to illustrate many possible variants and ways of its execution.

Fig. 6.22 shows the "Odyssey", the world-first floating rocket launch platform "Sea Launch" for launching communication satellites to their orbits. It was built within the framework of an international project whose participants were: USA (Boeing), Russia (Energya), Ukraine (Yuzhnoye) and Norway (Kvaerner). The platform, built in Vyborg Shipyard (Russia) in 1998, is equipped with two cylindrical rocket fuel tanks of 40 m length and 80 t mass each. The tanks were seated on foundation chocks cast of EPY compound. Each of the tanks was supported in four points on foundations prepared for them. In the support points of the tanks special side arms were welded. The seating surfaces of the foundations and arms were in advance machined to be flat, however as a result of welding operations they become greatly deformed. It caused that correct mounting the tanks was found not possible even with the use of traditional, metal adjustment chocks. It was practically impossible

Fig. 6.18. The cruise ship "Fantasy" with a mooring winch seated on EPAX compound chocks in 1988

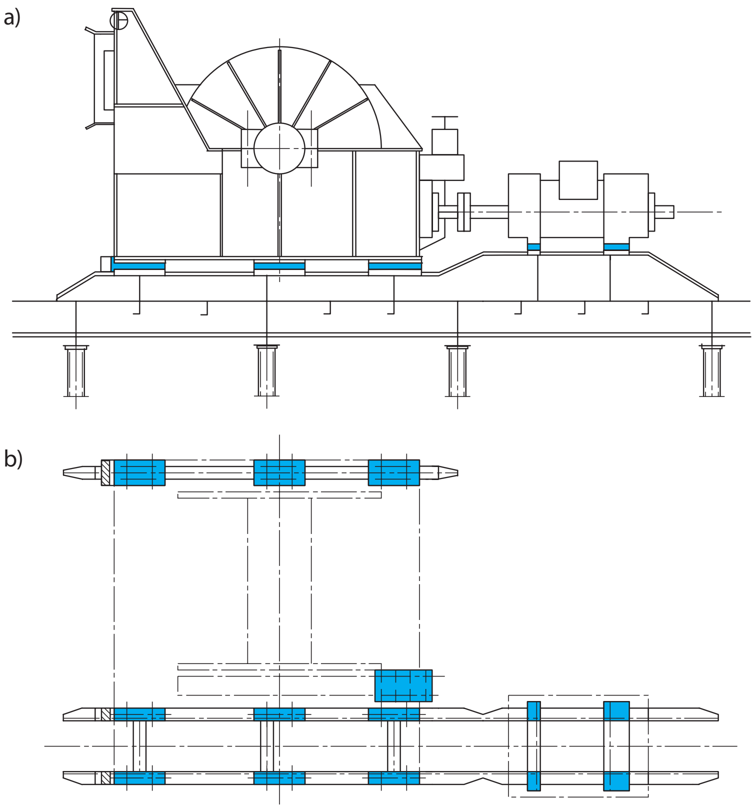


Fig. 6.19. An examplary seating of trawl winch on EPY compound chocks: a) scheme of seating the winch on foundation; b) arrangement plan of foundation chocks

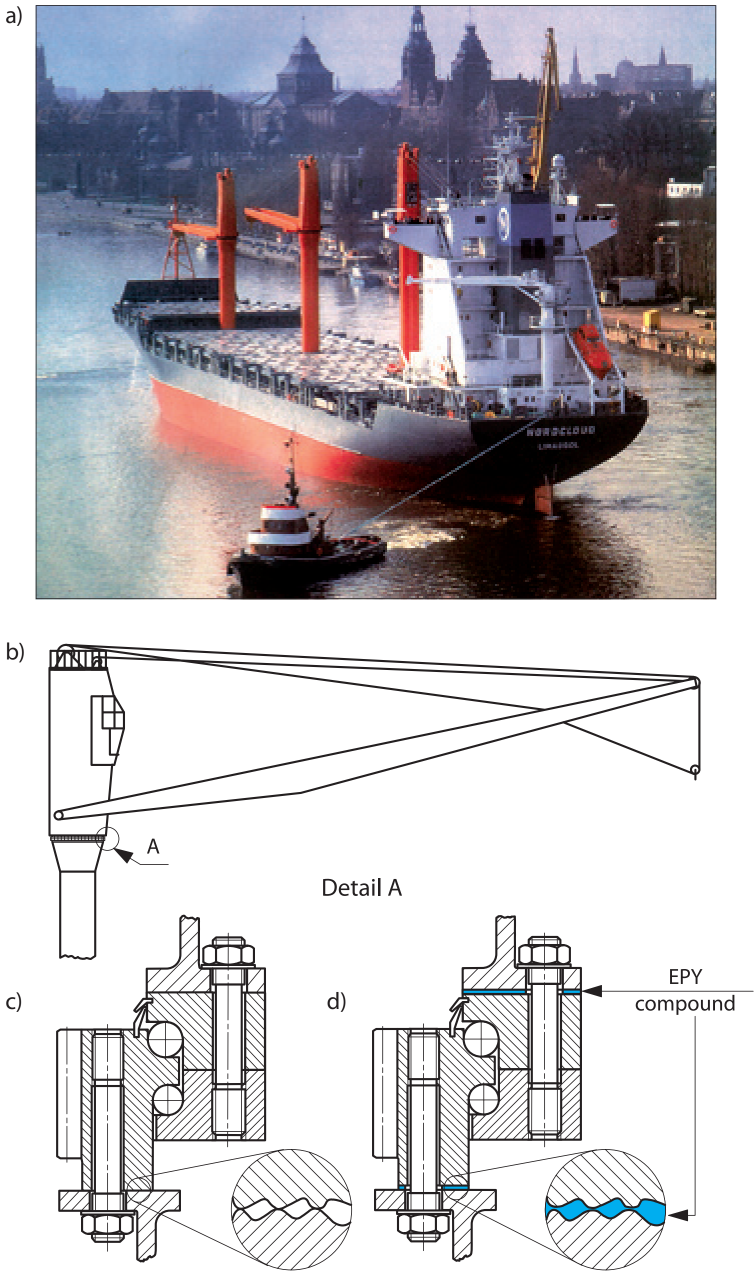


Fig. 6.20. Application of EPY compound for the seating of slewing cranes on shipboard columns: a) a view of a B567 ship built in Szczecin Shipyard Co.; b) simplified drawing of the crane; c) traditional method of seating the slewing bearing (D = 2500 mm); d) a novel method for seating the bearing with the use of a thin layer of EPY compound

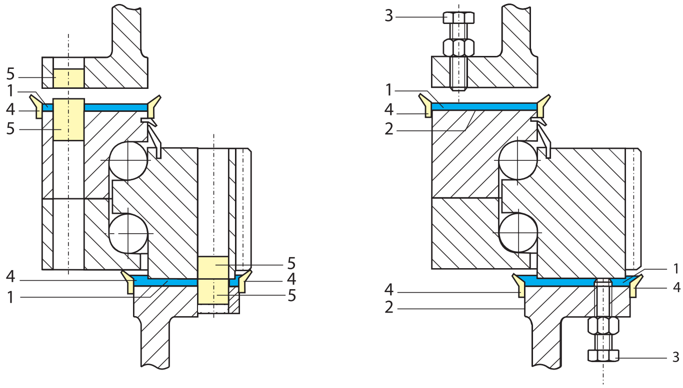


Fig. 6.21. The seating of a large rolling bearing on EPY compound layer: a) cross-section showing a way of prevention against leakage of the compound; b) cross-section showing screws for bearing position adjustment; 1 — EPY compound layer; 2 — bearing contact surface; 3 —adjustment screw; 4 — edge sealing; 5 — foam compound plugs

Fig. 6.22. The floating rocket launch platform "Sea Launch" with rocket fuel tanks seated on EPY compound chocks

to fit properly the metal chocks to a large area (of abt. 1 m^2) of deformed surfaces of the foundation and arms. In this situation, to use EPY compound foundation chocks cast directly under properly positioned tanks, was urgently decided. The solution turned out to be very fast, simple, effective to execute and also very stable and reliable in service. It guaranteed to obtain simultaneously an ideal fit between all contact surfaces.

EPY compound turned out to be very useful also in seating the cylindrical tanks on the deck of chemical tankers, special sea-going ships. The ships which have double bottoms and sides, are intended for the shipping of acids, alcohols, vegetable oils, animal fats, molasses, petrochemicals etc. In the years 2001÷2007 Szczecin Shipyard built eight B 588 chemical tankers (Fig. 6.23). They were then the largest and most modern ships of the kind in the world and fitted with the newest navigation and safety systems. Their length was equal to 183 m and breadth — 32 m. The ship of the kind had 40 tanks with total capacity of 52,000 m^3, made of duplex stainless steel; 34 of them were located inside the ship and 6 — on its deck. (Fig. 6.23).

The first ship of the series, named "Bow Sun", put into service in 2003, achieved very good opinions from the side of shipbuilding industry experts. The Royal Institution of Naval Architects in London awarded the title of "Ship of the year 2003" to this chemical tanker, that has been the most prestigious recognition in shipbuilding industry [104]. Odfjell-Seachem company, Bergen (Norway), is the owner of these ships.

The tanks located on the decks of the ships were seated with the use of EPY compound. The tank is of cylindrical form with 5.3 m diameter and 17.12 m length.

Fig. 6.23. A chemical tanker of B 588 series with tanks seated on the deck by using EPY compound EPY

Its weight is equal to 422,760 N, its capacity — 377.7 m^3, and its total weight with cargo — 4,199,746 N. Each of the tanks was seated on two semicircular supports (beds) with the use of EPY compound layer in compliance with the schematic diagram shown in Fig. 6.24a. One of the supports is fixed. The other, movable, makes its free expanding and contracting in changeable temperature conditions, possible (Fig. 6.24b). The tanks are fastened to the supports in four points by using four screw bolts (M56×5.5), but the fastening is unyielding only on one side, on the other side it allows for some shift. The shift is possible due to oval holes for the fastening screw bolts, made in the tank arms.

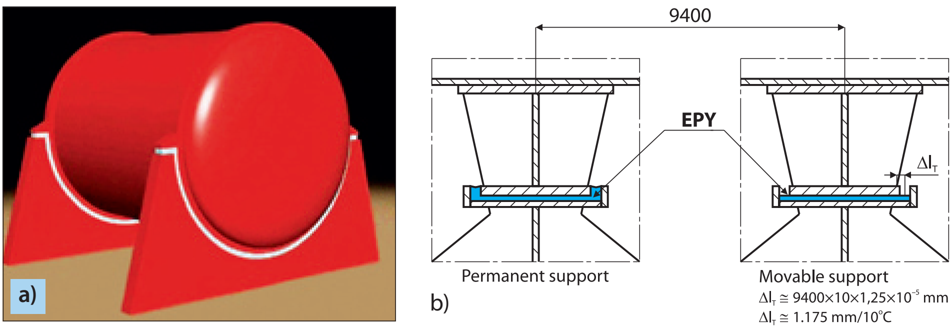


Fig. 6.24. Overall scheme of seating the tank on ship's deck (a) and schematic drawings of the permanent (left) and movable support (right) (b)

Assembling operation of the tank on the ship's deck is shown in Fig. 6.25. After proper positioning of the tank and sealing the pouring spaces between the tank and its beds (Fig. 6.25a), the spaces were filled with liquid compound properly mixed with hardener. The pouring was carried out from the top through the gap at the flat support (Fig. 6.25c). Fig. 6.25d shows the tank arm with the chock cast underneath.

In the years 2001÷2008 48 tanks of the kind were seated on the chemical tankers of B 588 series. It is worth to mention that also all main propulsion engines and stern tubes on these ships were seated with the use of EPZ compound. The ships were equipped with NSD6RTA58TB Cegielski-Wärtsilä engines of 12,750 kW rated power each, 11 m in height, 8 m in length and its breadth at the base was equal to 4 m. Mass of the engine was 322 t. In total, 64 various objects were seated by using EPY compound on the chemical tankers in question. All the work which was carried out under supervision of DNV surveyors, successfully passed its practical exam.

Fig. 6.26 shows installation of other tanks on a ship with the use of resin compound. It was very large tanks for carrying LNG/LPG liquefied gas, of 3700 m^3 capacity and

Fig. 6.25. Installation of the tank on the ship: a) and b) overall picture of the tank during installation; c) filling the pouring space with the compound; d) tank arm seated on EPY compound chock cast on upper flat surface of the bed

Fig. 6.26. Tanks for shipping the liquefied gas LNG/LPG, installed onboard a sea-going ship

mass of over 300 t, each. They had diameters of about 12 m and 36 m length. The tanks were seated inside a LNG/LPG gas tanker of 7500 m^3 capacity, built by Gdańsk Ship Repair Yard Company.

The tanks were inserted into the ship's hull by means of two floating cranes of total hoisting capacity of over 5000 kN (500 t) (Fig. 6.26). MSJ Company in Szczecin is presently the only firm in Poland, which has at its disposal professional personnel and experience as well as necessary authorization for carrying out seating operations with the use of resin compound on sea-going ships.

Each of the tanks was seated on two suitably profiled beds with the use of Epocast 36P compound which had consistency of a putty. The seating process consisted of a few phases. First, a necessary thickness of compound layer was determined in particular areas of the beds where a given tank had to be seated. To this end, in certain points on the beds some portion of a putty was placed. Its thickness was greater than that of the assumed compound layer. Then, the tank was lowered down to its proper position. This way the coated putty was compressed to an appropriate thickness in all the points. Next, the tank was lifted up to some height to measure values of the thickness (Fig. 6.27a) and remove the putty. On the basis of the measurements was determined a necessary thickness of the compound layer to be put on a given place, in order to ensure proper support over the entire assumed area and protect against pressing out an excessive amount of the compound aside. Excess of the pressed out compound results in unwanted loss of material and spoils aesthetic view of the seating. Next, to the elevated part of the bed some number of flat bars was transversely welded (Fig. 6.27b), to stop possible flowing out the compound

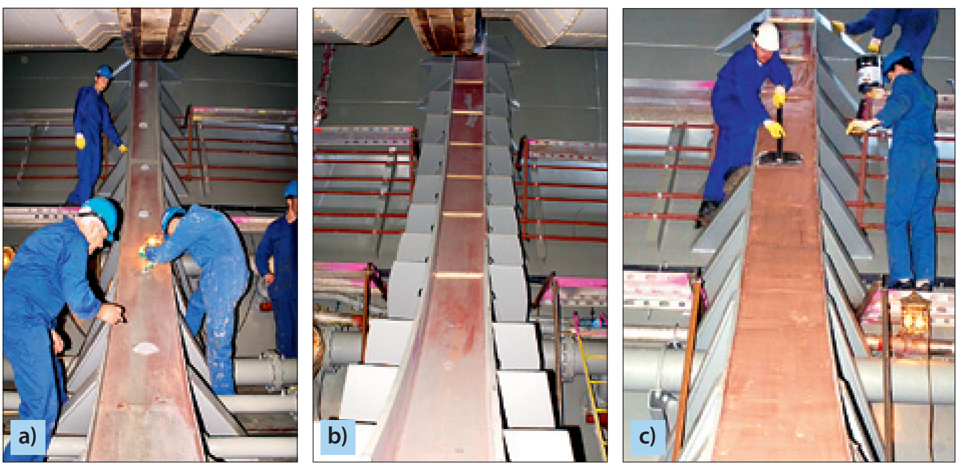


Fig. 6.27. Preparation of the bed for seating the tank on it

during its putting on. Fig. 6.27c shows the operation of putting Epocast 36P compound layer on the properly prepared bed.

On completion of the operation on both beds, carried out in accordance with the values of the compound layer thickness determined in advance for each of the places, the tank was finally lowered and seated on the compound layer (Fig. 6.28a). The small amount of the pressed out compound and its uniform distribution (Fig. 6.28b) proved that the thickness of the introduced compound layer was correct.

Fig. 6.28. Operation of letting down the tank up to its final seating on the beds covered with a compound layer (a) and a fragment of the seating arrangement with a side-squeezed portion of the compound (b)

The putting-on of the compound and the final seating of the tank had to be performed within an appropriately planned time interval during which the compound still maintains its plastic features. Therefore the operation required engaging and training an appropriate number of workers for mixing and putting-on the compound simultaneously in many places as well as to properly synchronize all the work. The operations were carried out by a multi-member team under supervision of Jędrzej Ratajczak, D.Sc., Eng. Fig. 6.29 shows employees of: the Gdańsk Ship Repair Yard "Remontowa" Co., Northern Shipyard Co. in Gdańsk, and MSJ Co. in Szczecin, who actively took part in the seating of the tanks on the ship NB 604/1.

In the opinion of all interested parts the seating operations were conducted perfectly. High quality and reliability of the seating arrangement in question was confirmed in multi-year service of the ship.

Later, in 2013, two even larger tanks were seated this way on B787 gas tanker of 9000 m^3 capacity (Fig. 6.30a). The ship, g/t "Syn Antares", was built by Gdańsk

Fig. 6.29. Employees of the shipyard and MSJ company, which took actively part in seating the tanks onboard the ship NB 604/1 at Northern Shipyard in Gdańsk (June 2008)

Fig. 6.30. The tank of 500 t mass (a) introduced to the hold on the ship "Syn Antares" (b)

Shipyard Co. for Cantiere Navale di Pesaro, Italian ship owner. Two large tanks of 500 t mass each were seated in the holds of the ship (Fig. 6.30b). Their diameter reached 12,140 mm and their total lengths differed a little to each other: for the fore tank it was 42,525 mm, and for the aft tank — 42,000 mm. The tanks were manufactured by Gas and Heat, an Italian firm.

As the outfitting of Gdańsk Shipyard's quay with hoisting facilities was insufficient it was decided to carry out the seating operations of the tanks on B787 ship in the dry dock No. SD2 located in the terrain of the former Gdynia Shipyard Co. To this end it was necessary at first to tow the ship and load the tanks onto pontoons and move them into assembling site.

The tanks were placed in two holds of the ship, as shown in Fig. 6.30b. Each of them was seated (acc. the seating arrangement design) onto two properly profiled beds by using TG7B Phillymasic compound (manufactured by ITW Polymer Technologies, USA). The run of the seating work was generally similar to that above described in the case of the tanks seated on Epocast36P compound. However some, rather important differences took place. The seating operations on the latter tanks were carried out in June in temperature conditions favourable for the compound whereas the seating of the tanks in question was conducted on 25 and 26 January in the ambient temperature equal to –10°C. The low temperature caused many various difficulties. It was necessary to elevate the temperature and maintain it for many hours as the compound requires to have positive temperature both during its putting –on and spreading over the bed's seating area and its proper curing as well. The problem was solved by the shipyard itself. The temperature conditions caused that the installation work lasted for two days.

Fig. 6.31a and b illustrate certain fragments of the performed assembling operations. They show: the spreading of the compound over the tank support and the covering of the compound surface, after spreading, with Teflon film, respectively. By means of the film a sliding support is formed; it protects the ship's structure and the tanks against occurrence of large longitudinal forces resulting from temperature changes.

Fig. 6.31. Fragments of the performed assembling operations showing the spreading of compound over the tank support (a) and the covering of compound surface with Teflon film, after the spreading (b)

Fig. 6.32. MODU "Petrobaltic" and "Balic Beta"; on the first drilling unit a windlass (in 1984) and electric generator (in 1994) was seated; the operations were performed in the Ship Repair Yard "Radunia"; on the second unit three WAB 1240 D6 electric generating sets and three supporting bearings were seated; the operations were performed in sea conditions (2004÷2005)

Fig. 6.33. MODU "Bredford Dolphin"; main propeller electric motor was seated under supervision of DNV; the work was performed in Gdansk Ship Repair Yard (2007)

Fig. 6.34. MODU "Polarnaja Zviezda" (Polar Star); 61 various pumps and other auxiliary devices were seated; the work was performed in Vyborg Shipyard (Russia, 2009)

Fig. 6.35. MODU "Polarnoe Sijanie" (Aurora Polaris); 61 various pumps and other auxiliary devices were seated; the work was performed in Vyborg Shipyard (Russia, 2010)

Installation of the tanks was completed successfully and on schedule – in spite of the unfavourable weather conditions. The proper planning and execution of the task constituted a huge technical and organizational undertaking which required a significant commitment and strict cooperation from the side of many responsible and qualified persons both from Gdańsk Shipyard Co and Marine Service Jaroszewicz Co. (specialized in seating operations with the use of the compound). The fact that in conducting the task as many as 32 employees from the shipyard and 22 employees from MSJ Company were engaged, may illustrate the scale of the undertaking. After completion of the seating operations on the tanks the ship was towed back to Gdańsk Shipyard in order to continue outfitting work.

6.2.6. Application of the resin compound on marine floating drilling units (platforms)

EPY compound has found extensive application not only in shipbuilding and ship repair industry but also for the seating of many machines and devices on marine floating drilling units. In total, 143 different objects have been seated by using the cast compound chocks on the floating drilling units. It was: winches, electric motors and generating sets, pumps, bearings, tanks and other auxiliary devices. The units on which the seating operations in question were performed, are shown in the photos Fig. 6.32 through 6.35. The names of the drilling units and certain information on the objects seated on them are given in the captions of the photos.

6.2.7. The seating of rail track of rotational drum and basket axle spider on the ship intended for laying the cable on sea bed

One of the original applications of EPY compound in practice has been the seating of rail track of rotational drum on deck of the sea-going ship intended for the power cable laying on sea bed. Overall view of the ship is shown in Fig. 6.36.

The ship was built by STX South Korean shipyard in 2011. It was originally intended for dumping stones and crumble aggregate onto sea bed to cover cables and pipelines. Its conversion from stone dumping to cable laying function and general overhaul was performed by the "Energomontaż—Północ—Gdynia" Company in 2013. During the conversion work all obsolete devices were removed and the ship was outfitted with full set of new equipment for cable transporting and laying onto sea bed. Among other things, the rotational drum of 28 m diameter which accommodates 5400 t of power cable, was installed on the ship. The drum was manufactured by Caley Ocean Systems, a Scottish firm, and shipped on board a pontoon barge to a dry dock of the former Gdynia Shipyard where it was installed on the deck of the ship in question.

Installation of the drum on the ship's deck required a. o. to prepare a rail track which enables the drum to rotate around its vertical axis. The track was made in the form of five concentrically — located, separate steel rings of double T section (Fig. 6.37). On the rail track was located and fixed a large number of bearing — supported

Fig. 6.36. The cable layer "Willem de Vlamingh"

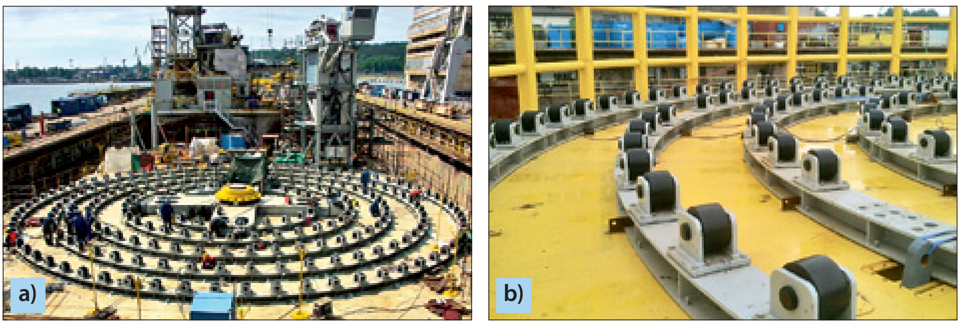


Fig. 6.37. Rail track fitted with rollers for supporting the rotational drum which accommodates winded power cable: a) overall view; b) fragment

rollers capable of transferring the weight of the drum and the cable reeled around it, and making its rotation possible. The whole rail track, after the exact leveling of the support plane for all rollers with the use of geodesic instruments and adjusting screws, was finally seated on the ship's deck by using the foundation chocks cast of EPY compound. It should be also mentioned that all the operations aimed at proper location of the track were executed by the personnel of the firm which carried out conversion work on the ship in question. Whereas preparation of chock moulds and casting the chocks was performed by employees of MSJ company under supervision of Bureau Veritas surveyors.

The whole weight of the drum and the cable reeled on it was estimated equal to 80,380 kN. 236 rollers and the same number of foundation chocks cast of EPY compound were used in order to distribute uniformly the weight over the ship's deck surface. The chocks of 500 × 500 mm support surface area were located in the places where the rollers were installed (Fig. 6.38). Because of significant unevenness of the deck the cast chocks had to have different heights contained in the range of 5÷45 mm.

It should be also added that on the ship, apart from the rail track, the cable basket axle spider was seated by using EPY compound (Fig. 6.37a). The manufacturing of 236 chocks under the rail track was executed on 16÷18 June 2013, and the seating of the cable basket axle spider — on 9 July 2013.

It is worth to mentioned that structural elements supported in many points (more than three) constitute multifold statically indeterminate systems which cause many computational and manufacturing problems, particularly in using the traditional metal foundation chocks. It is hard to imagine that in the case in question metal foundation chocks would be individually fitted at so large unevenness of deck surface. Application of the chocks cast *in situ* is favourable not only that it facilitates operation and shortens time of their manufacturing. Its main advantage is that they automatically match up with all uneven areas of contact surface of ship's deck and steel rail track to be seated on it. As a result, it brings in the seating arrangement

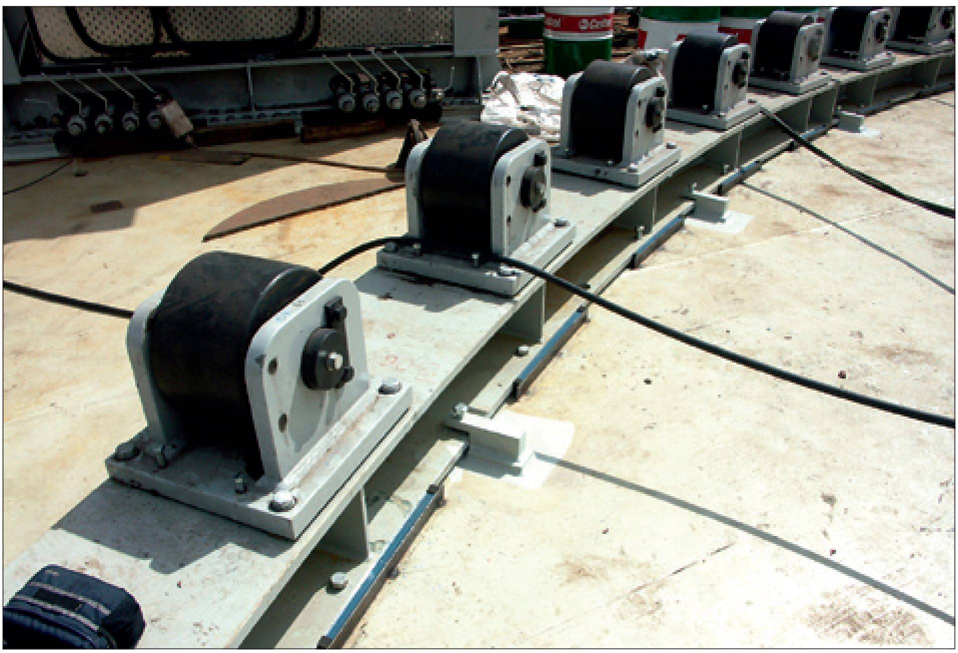


Fig. 6.38. A fragment of the rail track with rollers and foundation chocks cast of EPY compound

of a high technical quality which guarrantees uniform load distribution over all the chocks and entire area of their contact surface, without introduction of unexpected assembling stresses and deformations to the system, that often happens in statically indeterminate systems in case of using metal chocks for their seating.

6.2.8. Application of EPY compound for the seating of oarlocks on an ocean-going row boat

EPY compound has found practical use not only for the seating of large main propulsion engines and gears as well as many other auxiliary devices and large structural elements (stern tubes, rudder arrangement journals etc) but often also for the seating of various minor structural elements requiring high reliability and durability. A peculiar, worth mentioning case in this range is the use of EPY compound in building "propulsion system" for a single-handed, ocean-going row boat intended for doing "Trans Pacyfik Solo" voyage. The boat is shown in Fig. 6.39 and a detail description of the boat and its voyage are contained in the book titled "Ocean Niespokojny", written by its hero, Romuald Koperski [164].

On the boat EPY compound was applied to fastening the oarlocks which constitute supporting nodes for the oars. An overall view of the oarlock is presented in Fig. 6.40a, and a way of EPY compound application to its fastening onto the boat is illustrated in Fig. 6.40b. For this work the use was made of experience gained from research and practical application of thin layers of the compound to structural element joints as well as bolts fitted in the compound, that was discussed in detail in p. 8.1 and 8.2 of this book.

Fig. 6.39. The single-handed row boat "Pianist" intended for doing cross-Pacific voyage, at the moment of starting from the port of Choshi, Japan

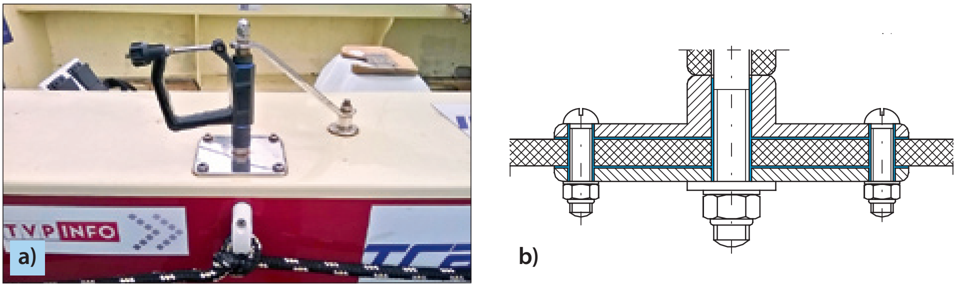


Fig. 6.40. The oarlock of the single-handed, ocean-going row boat "Pianist": a) overall view; b) a way of EPY compound use for fastening the oarlock onto the boat

Contact surfaces of the structural elements are not ideally smooth. Deviations from an ideal state which occur on them (roughness, waviness, shape errors) make that they contact to each other only in separate points (micro-zones) and their real contact surfaces constitute usually a very small percentage of their nominal contact surface. In such joints take place unfavourable contact phenomena which often lead to their fast wear and failure situations. The thin compound layer fills all micro and macro-gaps occurring between the surfaces joined to each other. After curing the compound, applied external load is correctly transferred by the whole nominal contact surface, avoiding this way occurrence of unfavourable contact phenomena of a local character. EPY compound is resistant to long-lasting action of sea water and prevents joined surfaces against destruction. As a result, high reliability and durability is ensured for the described structural joint which is a crucial element of the "main propulsion system" of this boat.

6.3. Examples of the seating of land-based machinery with the use of resin compound

6.3.1. Application of resin compound for repair and modernization of the seating of large piston (reciprocating) compressors

6.3.1.1. General characteristics of large piston compressors and problems associated with them

Large low-speed piston compressors of rated power ranging from a few hundred up to a few thousand kW belong to technical devices which generate large dynamic forces, mechanical vibration and noise strongly affecting their foundations and environment. They are installed in chemical industry enterprises, natural gas compression stations and many other industrial works. Majority of the compressors installed in Polish chemical industry and gas compression stations are now in the age of 20, 30 or even more years. The compressors were seated in a traditional way, on reinforced concrete foundation blocks and rigidly fastened with them by means of foundation bolts either going through holes or anchored in the concrete, in compliance with recommendations of their manufacturers. Fig. 6.41 exemplifies such a compressor mounted in the traditional way, which has been used since 1966.

As results from information obtained from the user of the compressors, that already after a short time of their operation some problems appeared and that they caused many troubles which mainly consisted in:

— occurrence of excessive vibrations;
— loosening screw joints and breaking foundation bolts;
— crushing and cracking concrete foundation (e.g. breaking off a corner);
— cracking elements of compressor body, including crankcase;
— high failure frequency resulting in significant economical and financial losses and large costs of repair work.

Correct operation, reliability and long service life of large piston compressors depend not only on their design and workmanship but also — to a large extent — on how they are seated on foundation. High repair costs and large production and economical losses resulting from non-scheduled shutdowns made it necessary to seriously attempt to the problem not only from technical side but also scientific one. The problem has been first perceived and then undertaken in an organized manner in USA where since long time ago many piston compressors have been in use. In the 1990s many interesting elaborations and reports on the theme were prepared within the activity framework of Gas Machinery Research Council (GMRC) [105÷109]. They have resulted from joint effort of research institutes and engineers practically engaged in these issues. The efforts have been aimed at finding causes of excessive

Fig. 6.41. Overall view of a reciprocating synthesis gas compressor (of 6HGP/4 type) traditionally seated on concrete foundation

vibrations, high failure frequency of compressors, and many technical problems and economic losses (counted in millions of US dollars) associated with the above mentioned problems. It was stated that the main cause of such situation was low quality and high unreliability of the traditional methods of seating the objects on foundations, used during their installation work. For this reason, the recommendations were prepared for engineers responsible for installation and repair of foundations of piston compressors [108, 109]. The guidelines may be useful in improving reliability and service life of the machines without any greater troubles in their servicing.

Similar problems concerning piston compressors have occurred and still occur in EU countries. In 1999 European Forum Reciprocating Compressors (EFRC) which associated research institutes, designers, producers and users of the machines as well as the firms engaged in their installation and repair in European countries, was established. The forum has been established in order to form a platform for mutual exchange of scientific and technical experience between users and producers as well as assemblers and researchers of the machines in question, in order to elaborate unified procedures and guidelines for the measuring and classification of vibration of piston compressor units, and to analyze causes of generation of the vibrations and to search for ways leading to their mitigation [110].

The problems of excessive vibrations and high failure frequency of piston compressors are also well known in Poland. It concerns particularly compressors used in chemical industry (e.g. in ZAP) and natural gas compression stations located in various places over this country. As unambiguously results from the investigations performed in this field [111], most of the troubles which occurred in the compressor units, were caused by a low quality and high unreliability of the traditional arrangement of the seating of the machines on concrete foundations, made during their installation work. Therefore, since a certain time ago also in this country (like in other, more economically developed countries) systematic, repair and modernization projects concerning foundation work for such objects, have been carried out. To this end, use is properly made of modern scientific and practical knowledge in this field as well as new materials, including polymer compounds especially developed for such application.

In a contemporary approach, compressor units should be taken as integral dynamic systems which comprise three basic components [105÷110]:

— machines (compressors and engine);
— reinforced concrete foundation;
— fastening system which contains holding down bolts, supporting plates sunk in concrete or plastic compound, adjusting chocks made of metal or plastic compound, as well as steel structures (frames) if they are placed between machine and concrete foundation.

In such integral system the compressor is taken as a vibration generator which acts on to concrete foundation through the fastening system of determined elastic and damping properties. It should be taken into account the fact that in reality the so called rigid fastening is not ideally rigid. Stresses and deformations and contact phenomena which occur in its elements, have substantial effect on operational quality of the compressor and reliability and service life of the whole system.

6.3.1.2. Comparative analysis of the traditional and modern seating arrangements

On the basis of the literature sources [105÷109] and these authors' investigations [33, 111] it was definitely stated that occurrence of large vibrations and many troubles associated with them results mainly from substantial drawbacks of the traditional method of seating such units on concrete foundations. They were caused due to application of steel support plates sunk in concrete as well as steel washers and packages of thin sheets (0.1÷1 mm thick) used for proper positioning and leveling the particular elements of compressor unit to eliminate gaps in the support places (Fig. 6.42).

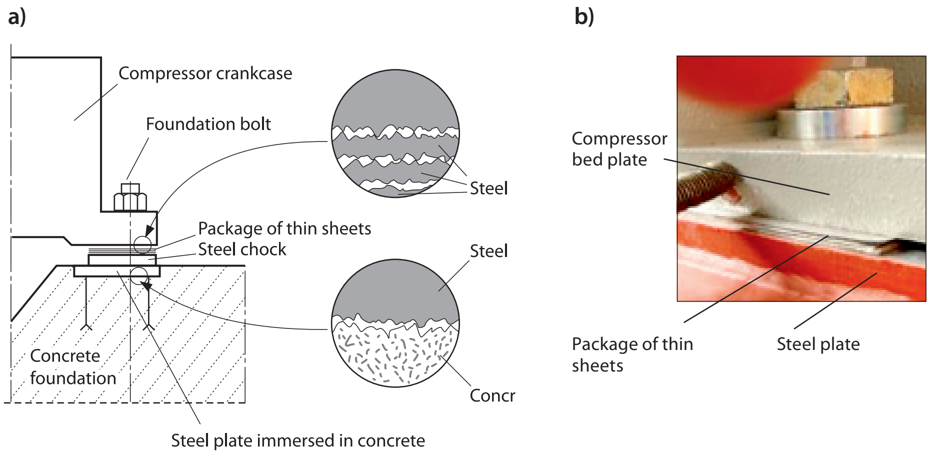


Fig. 6.42. Schematic drawing of traditional seating arrangement of compressor crankcase on concrete foundation with the use of plates, steel chocks and a package of thin steel sheets (a) and exemplary practical application of a package of thin sheets (b)

Such method of the seating of heavy piston compressors is very obsolete and unreliable in practice as it has two significant technical drawbacks, namely:

— it is usually very hard to properly match all chocks (washers) up with support surfaces of the foundation itself and bed plate of an object to be seated;

— it is not possible to ensure correct contact between surfaces of concrete and steel plate or chock and two metal surfaces.

The application of steel plates sunk in concrete and adjusting chocks in the traditional method of the seating of piston compressors (Fig. 6.42) results from difficulties in mutual fitting of large areas of support surfaces of foundations and bed plates of objects to be installed, and first of all from the need of exact alignment of mutually co-working elements of the unit (e.g. electric motor and piston compressor). Application of foundation chocks results in replacement of continuous (surface) support with a discrete one in the form of a definite number of "points". In case if such "points" are three or more in number the system becomes statically indeterminate. It is then very hard to properly fit all chocks and to determine forces of mutual interaction of machine and its foundation. In seating arrangements of heavy compressors and co-working devices number of foundation chocks is much greater than three. Such systems are multifold statically indeterminate that greatly complicates a way for their proper seating. Even if the metal chocks and the co-working elements of the compressor unit are only slightly unfit, because of their large rigidity, large unexpected assembling stresses usually occur in the system during its installation. Consequences of occurrence of the stresses in combination with thermal and operational stresses usually appear as late as during service of the machines, leading often to various failures.

Moreover, as results from the performed investigations, even if particular foundation chocks are nominally well fitted, macro- and micro-uneven areas happening on their surfaces cause that contact between co-working surfaces is of a discrete character and really takes place only on the tops of the highest of them (Fig. 6.42a). Real area of contact surface between an object and its foundation is very small in comparison with their nominal area. Moreover, adhesion forces on metal-to-concrete contact surface as well as metal-to-metal one, do not exist. As a result of dynamic forces micro-chipping very fast occurs under steel plate and upper layer of concrete is converted into tiny dust particles. In effect it leads to loosening the joint and rise of vibrations and often also to occurrence of macro-cracks and damage of concrete in upper layer of foundation. Fig. 6.43 shows an example of serious damages caused this way in practice. A separate problem is corrosion which occurs on the contact between steel and concrete, as well as a low resistance of concrete to action of various chemical factors.

The method of leveling the machines and eliminating the gaps by using packages of thin sheets (Fig. 6.42) in application to the exact seating of heavy machines on their foundations (either concrete or steel one), has many substantial drawbacks and is presently considered improper from the technical point of view because of high elastic-plastic susceptibility of numerous metal contact surfaces which mutually interact to each other. This leads to the so called sagging and knocking-out of supporting surfaces of chocks and foundation and loosening of screw joints. As a result, such traditional way of fastening the crankcase as well as other elements of the system, as shown in Fig. 6.42, does not properly fulfill its function and in many cases is the main cause of many troubles which occur and grow along with time of compressor service.

Some progress has been observed in this field when special polymer compounds were developed and applied to foundation chocks. The compound chocks cast directly

Fig. 6.43. An example of complete damage of the upper part of foundation of a reciprocating compressor with visible package of loosened sheets close to foundation bolts (a) and deep cracks in concrete and oil leakages (b, c)

in situ under properly aligned compressor, to a large extent simplified installation work and ensured a higher quality of the seating.

The modern method of the seating of machinery on steel or concrete foundations with the use of the special polymer compound is illustrated in Fig. 6. 44a. In short, it consists in exact positioning of an object to be seated on its foundation (in service position) by using adjusting screws or taper keys, building suitable cast moulds of polyurethane foam and steel sheet between foundation and bed plate of the object and then filling the moulds with liquid compound composition mixed of resin and hardener (Fig. 6. 44b).

After curing the composition in appropriate thermal conditions the ready-to-use foundation chocks are obtained. The chocks formed this way, due to application of some technological sinkheads which produce hydrostatic pressure, perfectly adhered

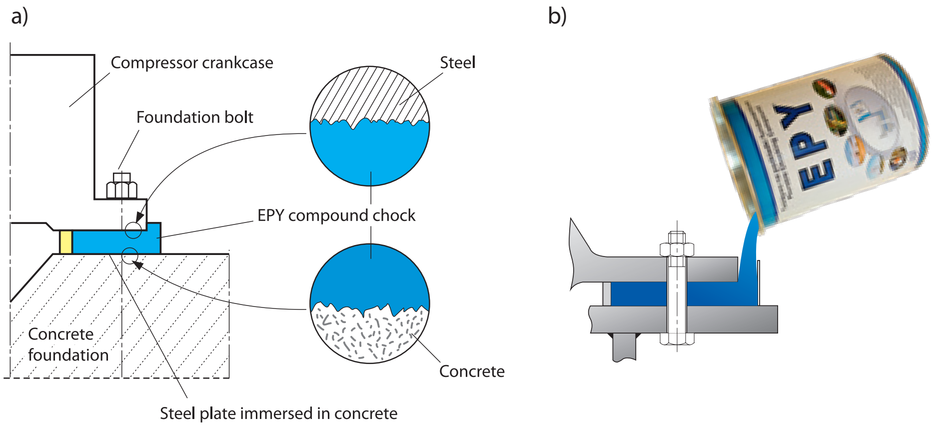


Fig. 6.44. Schematic drawing of the seating of compressor crankcase on concrete foundation by using chocks cast of EPY compound (a) and a way of casting the foundation chock (b)

to all macro- and micro-irregularities of surfaces of concrete foundation and machine bed plate. The chocks ensured much better matching up the bearing surfaces of machine and foundation than steel chocks (Fig. 6.44). Also, a good adhesion of the chocks to concrete was obtained, that prevents it against crushing. As a result, a more uniform distribution of assembling stresses in the system, its more stable work and a lower level of mechanical vibrations and noise, were achieved.

6.3.1.3. Modernization of seating arrangements of piston compressors

The above presented repair method of compressor's seating arrangement which consists in replacement of used up (loosened) metal chocks with polymer compound chocks cast *in situ*, is beyond doubt favourable and provides in effect a substantial improvement. However it does not remove all problems associated with the seating of the compressors on concrete foundation, especially those dealing with their service life. Better operational effects and longer service life of the seating may be reached by application of a steel structure (frame) inserted between the concrete foundation and the compressor unit to be seated on it.

The first, original modernization of such a seating arrangement (designed and executed by TECHMARIN Company of Świnoujście in 1993) was applied to GMVH12 engine-driven compressor (of 85,000 kg mass and 2026 kW rated power), installed in KRIO Gas Denitrification Plant in Odolanów, Poland. The seating arrangements of the compressor, both original and modernized one, are shown in Fig. 6.45a and 6.45b and c, respectively.

After installation of the compressors, the following problems have been identified (and have worsened in time) during many years of their service:

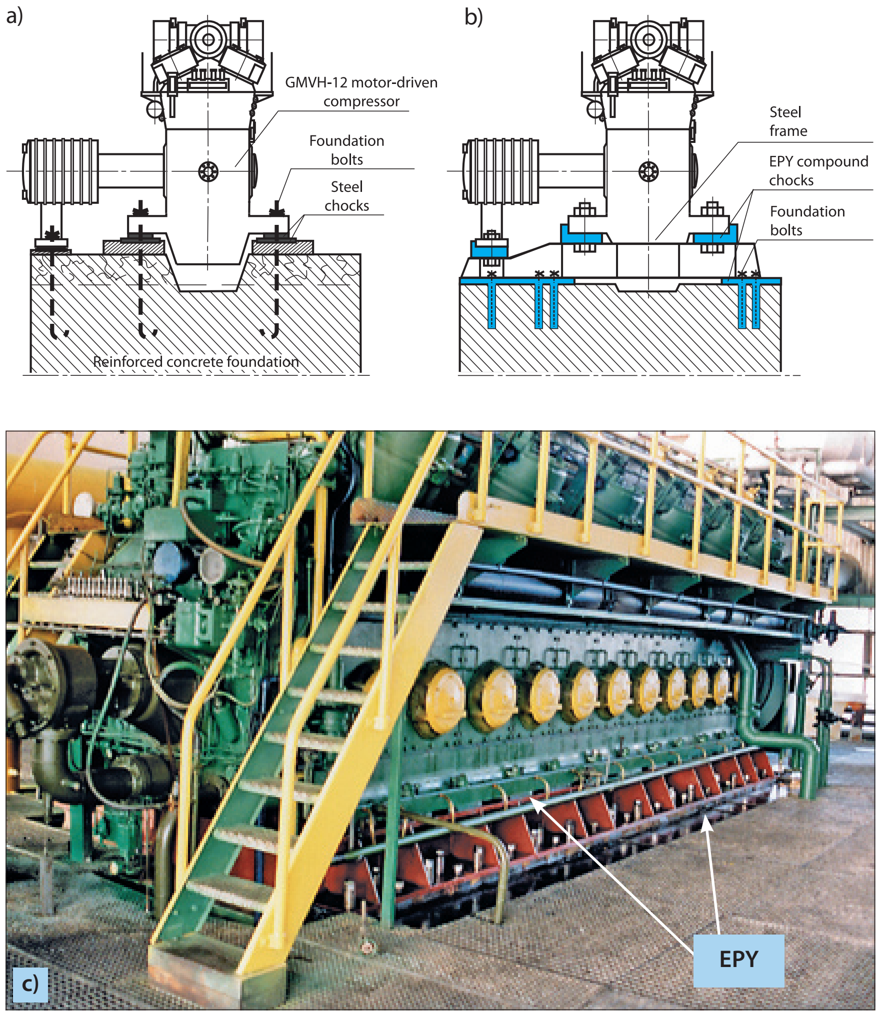


Fig. 6.45. Seating arrangement of GMVH-12 motor-driven compressor on concrete foundation: a) before modernization (seated on steel chocks); b) and c) after modernization (seated on a steel structure and chocks cast of EPY compound)

— cracking of the reinforced concrete foundation block in its upper part;
— ruptures of holding down bolts anchored in the reinforced concrete block;
— rise of mechanical vibration amplitude and noise intensity;
— increasing difficulties in maintaining specified clearances in the compressor crankshaft system;
— cracks in engine blocks and heads as well as anti-pulsation cylinders;
— high failure rate of the machines.

It was established beyond doubt that the main cause of these problems were some drawbacks of the seating arrangement of the compressor units by using metal chocks. The repair and modernization of the foundation consisted in:

— cutting off the cracked, upper layer of the reinforced concrete block (some 440 mm in height);

— preparing a special steel foundation frame;

— drilling 62 holes of 62 mm diameter and 600 mm deep for M40 bolts used for fastening the metal frame to foundation;

— pouring the compound around the holding down bolts;

— seating the steel frame on foundation block by means of cast compound chocks (Fig. 6.45b);

— tightening the nuts on the bolts fastening the frame to foundation block (after the compound had cured);

— positioning the compressor unit by using adjusting screws on the metal foundation frame in its service position;

— casting EPY compound chocks between the compressor unit bed plate and the metal foundation frame;

— tightening the nuts on the bolts fastening the compressor unit to the metal frame (after the compound had cured).

Detail information on this modernization work is presented in the paper [29]. The same solution was applied to all five compressor units installed in the KRIO plant and then also in many other plants of the kind in Poland. Expected merits of such solutions have been confirmed during multi-year, trouble-free operation of GMVH12 compressor units. In particular, as results from measurements carried out by various institutions as well as opinions expressed by users of the machines, the following advantages have been obtained:

— much lower level of mechanical vibrations (a dozen or so times lower),

— significantly lower intensity of noise,

— very distinct rise of reliability of the machines.

Modernization of seating arrangements similar to those shown in Fig. 6.45 was later performed for 1HB 5K400/250 Halberstadt compressors (Fig. 6.46). They were installed, in natural gas compression stations, on reinforced concrete foundations in the traditional manner according to the design and guidelines of their manufacturer. The seating arrangement of such compressor is schematically shown in Fig. 6.46a. The compressors in question which have been operated in the gas compression stations since 1992, practically just after a short time suffered intensive and fast amplifying vibrations which propagated over a large distance (even to distant office accommodations). Failures and shutdowns frequently happened and many repairs were necessary. In view of the excessive vibrations which exceeded permissible sanitary levels and were also hazardous for technical objects and buildings, Polish State Labour Inspection stopped further operation of the compressors at a certain moment. The main cause of the excessive vibrations and in consequence many troubles (analogue to those in the case of GMVH12 engine-driven compressors [29]) was the traditional — very unreliable also in this case — method of seating the compressors on reinforced concrete foundations with the use of steel plates sunk in concrete and adjusting chocks, as shown in Fig. 6.42. The loosening of the nuts or also cracking and chipping of concrete in the area of strong impact of the bolts and steel plates sunk in concrete, occurred relatively soon.

In the situation it was decided to thoroughly modernize the seating arrangement of the compressor units. The modernization consisted in the designing and manufacturing of a suitable steel structure to be seated on the existing reinforced concrete foundation with the use of some number of adjusting chocks cast of polymer resin compound and bolts anchored in the foundation by means of the same compound (Fig. 6. 46b).

In view of a cantilever ("gallery") form of the foundation (Fig. 6.46), only concrete elements crushed out off its upper layer were removed leaving all the not cracked part of the foundation in its place as otherwise a given foundation block would be

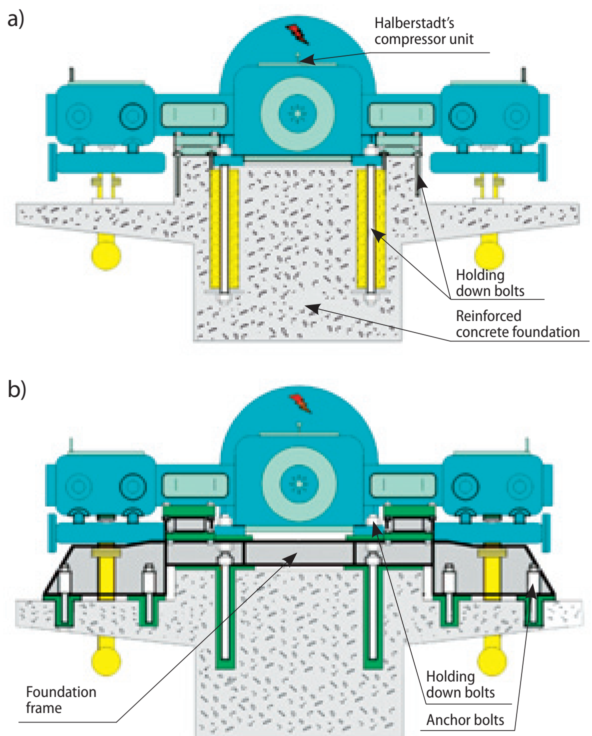


Fig. 6.46. Seating arrangement of 1HB 5K–400/250 Halberstadt compressors on concrete foundation: a) before modernization (seated on steel chocks); b) after modernization (seated on a steel structure and chocks cast of EPY compound)

weakened. The steel structure which was fit into the existing foundation and seated on the cast polymer compound chocks, effectively strengthened the foundation; it especially concerns its cantilevers which considerably protrude beyond the main block (Fig. 6.46b). The application of the steel structure without removing the thick concrete layer (as it was in the case of GMVH12 engine-driven compressors, Fig. 6.45) resulted in some increase, by about 400 mm, in the level of the fastening of compressor and engine.

The modernization of the seating of the first 1HB 5K400/250 Halberstadt compressor unit was made in 1995. In the next year the analogous conversion of the seating arrangements of the remaining compressor units installed in the same gas compression station, was performed. The generated vibrations significantly dropped to their permissible level (acc. ISO). The units have operated till now without any claims. The positive effects of the modernization caused that this method has started to be successively applied also in other natural gas compression stations in Poland.

Fig. 6.47 shows installation of structural elements of one of such compressors on to the steel frame which has been in advance seated on concrete foundation by using the cast compound chocks and bolts anchored in the compound. Particular components of the compressor unit are aligned on the frame by means of adjusting screws and taper keys. Only after checking if all elements and working units are correctly aligned, the polyurethane foam moulds were prepared for the chocks in their proper places. This operation is illustrated in Fig. 6.47. The moulds, after closing them by using smooth steel sheet along accessible edges, were filled with liquid

Fig. 6.47. The aligning of particular compressor components by means of adjusting screws and wedges

compound. Due to application of technological overpours (sinkheads) the moulds became completely filled with the compound and the chocks simultaneously perfectly matched up with bearing surfaces of the foundation and bed plate of the machine. After curing the compound, ready-to-use chocks were obtained without any need of their machining (Fig. 6.48). The technological overpours along the accessible edges of chocks are usually left on their places. In case of a need they may be so prepared as to be easily removed (see Fig. 5.5).

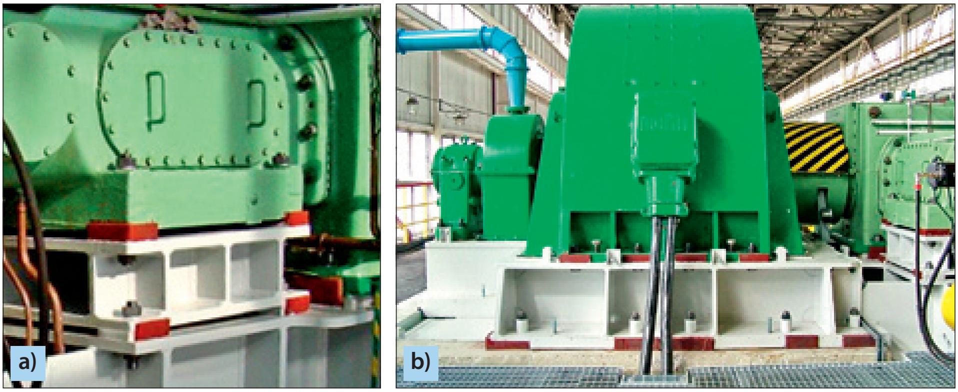


Fig. 6.48. Component elements of a compressor unit seated on foundation chocks cast of EPY compound: a) crosshead casing; b) driving motor

As all the chocks perfectly fit, the stresses involved by tensioning the holding down bolts are of only local character and does not deform the whole system. The thing looks different in the case of application of the traditional assembling method where getting the so exact fitting of all foundation chocks is practically impossible. In this case during tensioning the holding down bolts large undesirable assembling stresses occur in the machine body system, which may have a substantial effect on its deformation and cause the worsening of mutual alignment of particular working elements and units as well as the centring of crankshaft.

Overall views of the discussed compressor units before and after modernization of their seating arrangements are presented in Fig. 6.49. Some additional effects of the modernization are aesthetically designed landings arranged around the compressors, which facilitate access to their upper parts. Such landings were formerly not necessary as the compressor unit was installed a little lower (by about 400 mm), without any steel frame. Fig. 6.50 shows 6HGP/4 synthesized gas piston compressor before and after modernization of its seating arrangement, which consisted in application of a steel frame, holding down bolts sunk in the compound as well as cast compound foundation chocks.

Fig. 6.49. Overall view of 1HB 5K-400/250 reciprocating compressors operating in natural gas pressing plants: a) before modernization; b) after modernization of their seating arrangements

In closing, it should be distinctly mentioned that all the above discussed operations concerning repair and modernization of piston compressors were carried out by TECHMARIN Company, Świnoujście. The work performed by this enterprise has been characterized by a highly professional approach and workmanship quality together with adequate use of up-to-date scientific and practical knowledge in the area of seating methods and materials (resin compounds) intended for this purpose. The applied modernizing solutions are to a large extent original and novel.

The solutions have been proved in practice and obtained very good opinions from the side of users of the machines in question. For instance, let's refer to only one of

Fig. 6.50. Overall view of a 6HGP/4 reciprocating synthesis gas compressor: a) before modernization; b) after modernization of its seating arrangement

the opinions concerning the 6HGP/4 synthesis compressors: *The applied solutions have led to correct foundation of the machines, lowered vibrations and noise emission and have significantly reduced their failure rate and shutdowns, which consequently resulted in countable positive effects in production and economy.*

6.3.2. Modern seating arrangements for NEUMAN ESSER piston compressors

Fig. 6.51 illustrates the seating arrangement of one of the two 1TZL300 NEUMAN & ESSER piston compressor units, made under supervision of Marine Service Jaroszewicz Co. and commisioned by Koch-Glitsch Schweiz GmbH, a Swiss firm. The seating work dealt with a new investment and was performed at Pavlodar (Kazachstan) in 2008 in compliance with the design project and guidelines obtained from the provider of the machines.

On request of the commissioner, Chockfast Red S.G. compound (made in USA) was used for the seating. This is three-component, high-strength polymer mortar applicable to seating heavy machinery on concrete foundations. In comparison with concrete the compound has a high compression strength (125 N/mm^2), short curing time up to full strength, high adhesion to metal and concrete, significant resistance to weather factors, oils and various aggressive agents, low shrinkage and long service life.

The compound is intended for covering (pouring on) the upper surface of concrete foundation after proper alignment of the object on it by using adjusting screws. The recommended thickness of the compound layer is 25÷100 mm.

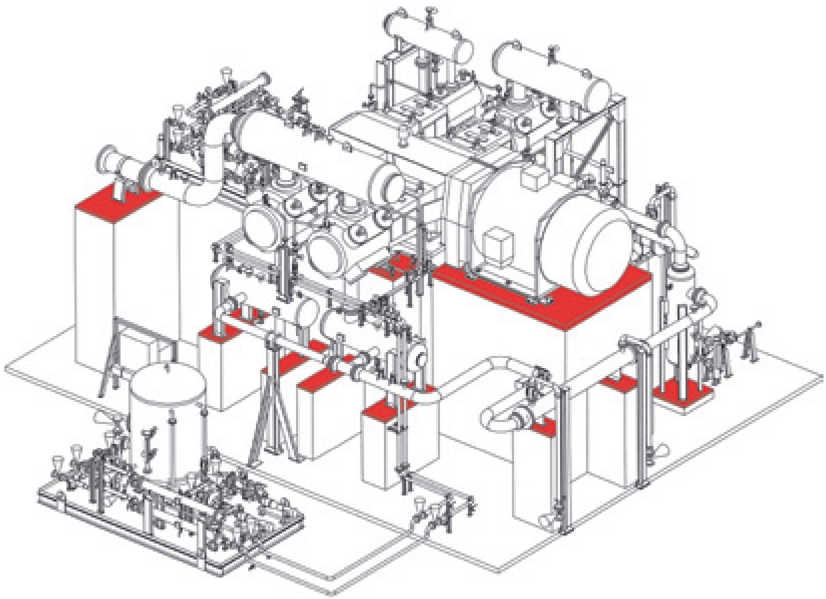


Fig. 6.51. General scheme of the seating arrangement of a K-401 NEUMAN & ESSER piston compressor

Fig. 6.52 shows some fragments of the seating arrangement of the compressor and its driving motor. The holding down bolts which fasten the devices were inserted into square holes (14 × 14 mm) and anchored by using the compound. The bolts do not fasten directly the compressor and its driving motor to the foundation, but they fasten instead 100 mm steel plate strips to which are fixed the objects to be seated. The compressor and its driving motor have been in advance properly positioned on the plate strips and screwed down to them by means of M42 bolts (Fig. 6.52b).

Next, the compressor and its electric motor (together with the plate strips fastened to them) were placed on the foundation and then aligned in their service position to ensure proper centring of the motor and compressor's crankshaft. The

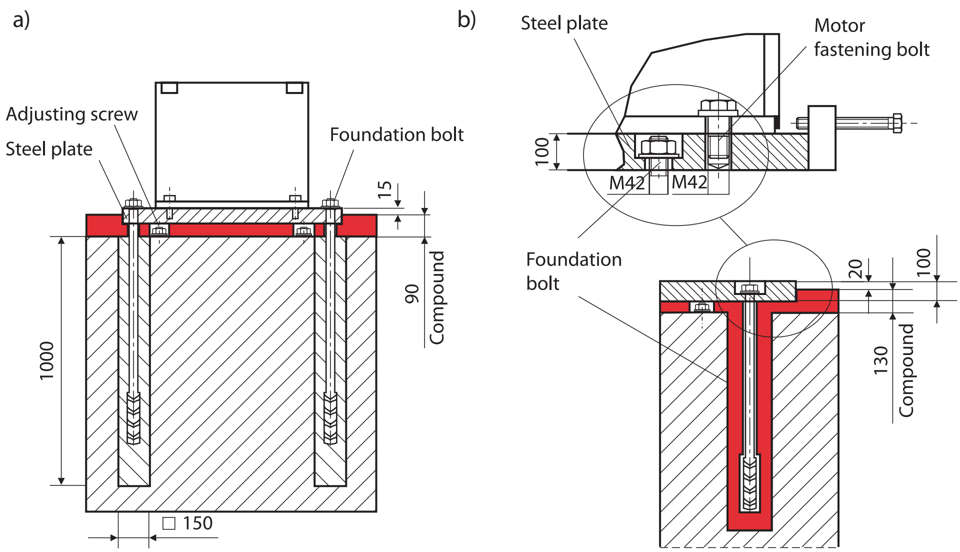


Fig. 6.52. Details of the seating arrangement of compressor crankcase (a) and driving motor (b)

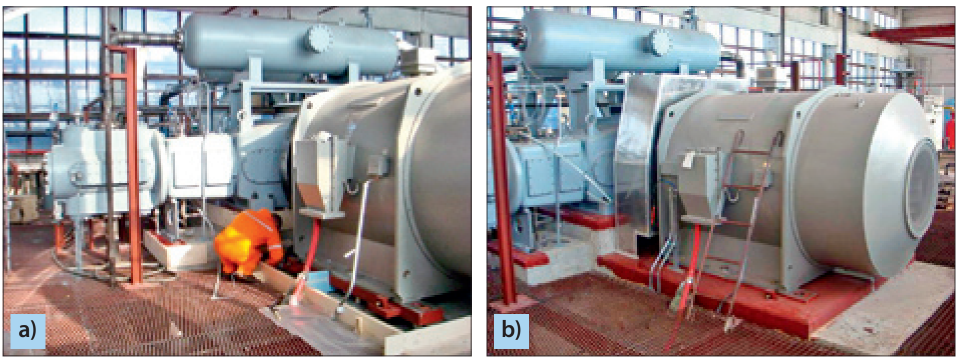


Fig. 6.53. Seating operation of the compressor unit: building the moulds for the compound (a); b) cast and cured compound layers seen just after taking away the moulds

operations were performed by using the adjusting screws placed in the plate strips. Between the plates and foundation a rather large distance (of about 30 mm) was left for pouring the compound. After checking if the compressor and its motor are properly aligned, on the concrete foundation appropriate cast moulds were made of wooden boards (Fig. 6.53a), which were then filled with the Chockfast Red S.G. compound properly mixed in advance. The foundation plate strips were poured around from the bottom up to almost their full thickness according to the design project (Fig. 6.52). After completing the operation they protruded only by about 15÷20 mm above the compound surface (Fig. 6.53b). When the compound had been cured the plate strips were fastened to the foundation by putting the nuts onto holding down bolts, and tightening them in the way shown in Fig. 6.52.

The seating work on all remaining elements of the compressor unit, shown in Fig. 6.51, was executed in a similar way. The seating arrangements made with the use of the Chockfast Red S.G. compound (of high strength and good adhesion to concrete and steel) ensure stable installation and high resistance to action of various external factors.

6.3.3. Application of EPY compound for the seating of mining machinery

Chocks of EPY compound were first used in this field for the seating of a main air exchange fan in ″Wieczorek″ hard coal mine in 1995. The layout of the fan's seating is shown in Fig. 6.54a, and the arrangement of the foundation chocks-in Fig. 6.54b. Mass of the fan amounted to about 40,000 kg. In the following years another five fans have been so seated in various coal mines.

In 1996 EPY compound was first used for the seating of a mining hoisting machine (Fig. 6.55a), which was K-6000 machine serving the ″Pułaski″ coal-pit (skip way) of ″Wieczorek″ hard coal mine in Katowice. During the long service life of the machine significant shifts of its foundation occurred as a result of mining damage. In consequence irregularities in alignment of main shaft bearings and the stators of machine driving motors took place (Fig. 6.55b).

The repair had to include a restoration of correct alignment of main shaft of the hoisting machine and stators of its driving motors. To this end, EPY compound foundation chocks were used. Vertical corrections in alignment of particular machine elements ranged from 0 to 35 mm.

The seating operation of the machine was carried out in April 1996 and it has been since then in intensive service for many years. The technology of repair with the use of EPY compound chocks has again proved to be fully useful and advantageous. Repair time was greatly shortened, accurate alignment of main shaft bearings and driving motor stators was obtained. The so repaired machine has been running stably and no objections have been raised so far.

Similar effects were obtained in the seating of a 4L4000/2400 hoisting machine, performed in "Zabrze-Bielszowice" hard coal mine, in October 1996. In February 2001 another hoisting machine was seated on EPY compound chocks in "Rudna" copper mine near Polkowice. Fig. 6.56 shows an example of EPY compound application for the seating of bearings of the cable wheel of 6000 mm diameter in the hoist tower structure (shown in Fig. 6.55a). The work was performed in ″Wieczorek″ hard coal mine in 1999.

The seating of mining machinery on EPY compound chocks have proved the significant technical and economic benefits which may be achieved by introduction of this novel method to mining industry. It makes the seating operations more effective and brings in an improvement of workmanship quality achieved both in

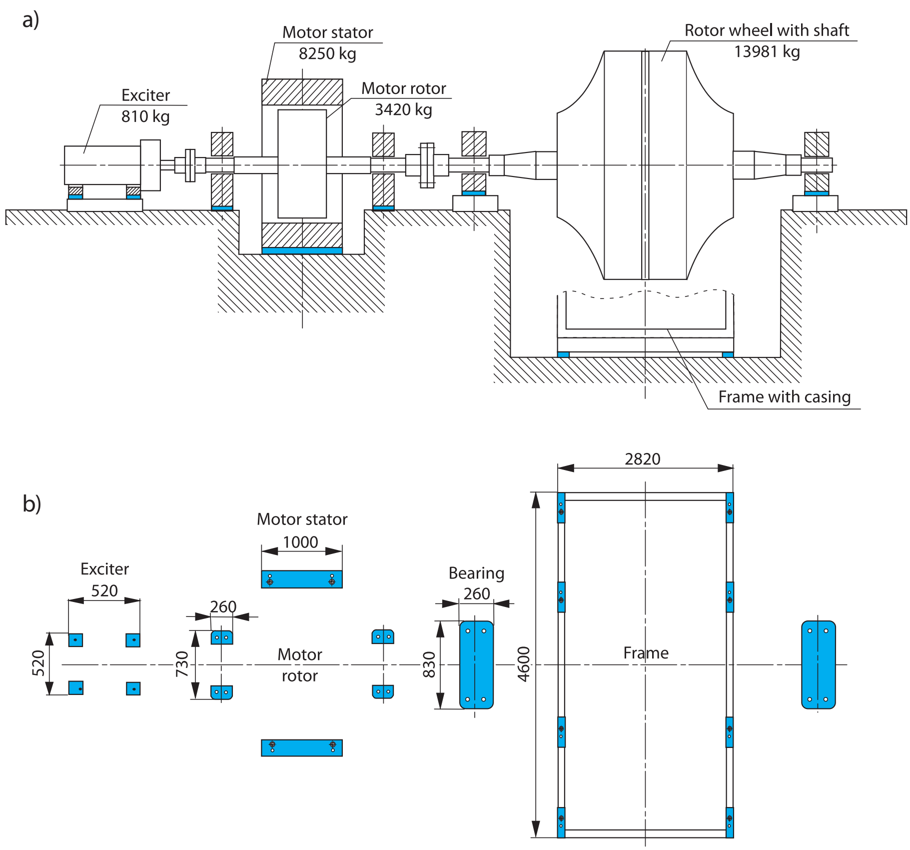


Fig. 6.54. EPY compound use for the seating of main air exchange fan in "Wieczorek" hard coal mine: a) fan seating layout; b) arrangement plan of foundation chocks

the new machinery installations and the repairs of existing machinery, also improving the safety and regularity of its operation.

6.3.4. Application of EPY compound for the seating of elements of excavators and dumping conveyors used in surface mining industry

Excavators and dumping conveyors used in surface mining industry are very large objects which operate in especially hard environmental conditions. Assembling the facilities in place of their service is a complicated and costly task. Manner and quality of its performing highly affect not only final investment cost of such object but also — at a large extent — its reliability and service life as well as its service effectiveness. One of the basic conditions for correct operation of such excavator is the proper assembling of its large-size bearings. Traditional manner of assembling the bearings requires to apply very accurate mechanical and manual machining of

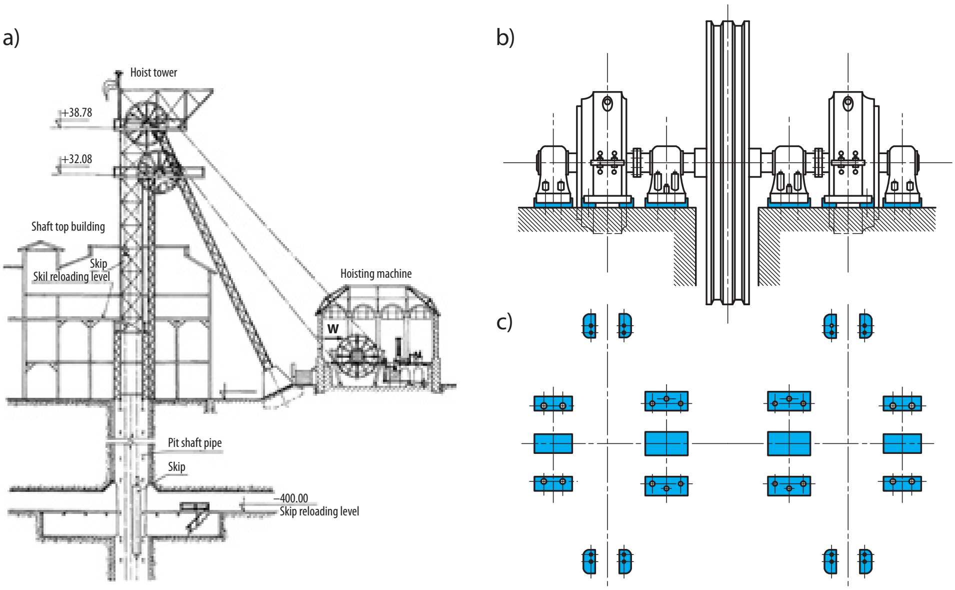


Fig. 6.55. Use of EPY compound for the seating of a K-6000 hoisting machine in "Wieczorek" hard coal mine: a) the tower and hoisting machine; b) hoisting machine seating layout; c) arrangement plan of foundation chocks

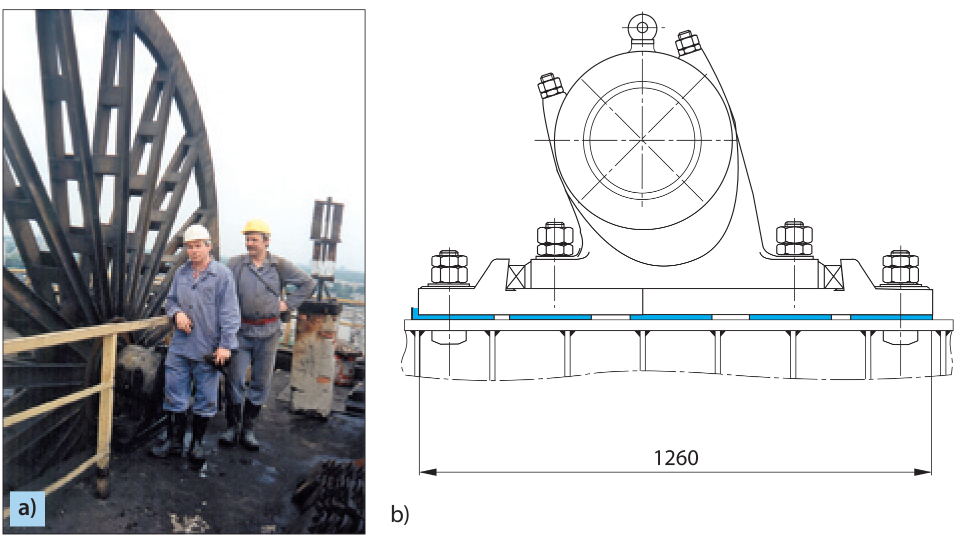


Fig. 6.56. Use of EPY compound for the seating of a ø 6000 mm cable wheel on the hoist tower of "Roździeński" pit shaft in "Wieczorek" hard coal mine: a) view of the cable wheel installed on the hoist tower; b) cable wheel seating layout

bearing surfaces of the load-carrying structure and the rotational part installed on the bearing. The technique is very troublesome, cost and labour-consuming, and its result does not guarantee that a sufficiently high reliability and durability would be reached. Repair costs and economic losses resulting from non-scheduled shutdowns are usually very high in case of the objects. Therefore efforts have been undertaken to improve the assembling work on such objects and increase its quality. The aims have been reached a. o. due to application of polymer compound, like in many previous cases of installation of machines and technical facilities. It brought good results in practice and provided countable technical, economic and operational benefits. The approach is presently used not only for assembling large-size bearings but also other structural elements of excavators and dumping conveyors. Some practical examples which illustrate a variety of possible applications of the resin compound to the assembling of such objects, are presented below.

Fig. 6.57 shows a SRs1200 excavator operating in "Konin" brown coal mine where EPY compound was first applied in 1994. During the overhaul of the excavator a thin layer of EPY compound was used to seat the segmented ball bearing bed of 8500 mm in diameter, which supports its turn-table (Fig. 6.57b). The width of the layer was 200 mm and the thickness in the range of 5÷20 mm. Static load on the excavator bed was 12,000 kN. Due to use of the compound a very labour consuming and costly procedure of machining the bearing surfaces of structural elements co-working with the excavator bed was avoided and the need to disassemble the excavator was also avoided. The compound ensured a very accurate fit of all co-working surfaces of excavator's structural elements and the bed, as well as a uniform distribution of load exerted on to bearing balls of 110 mm diameter. The overhaul time was shortened and its cost was reduced. In the subsequent years EPY compound has been applied to the assembling of the similar ball bearing beds in another four SRs1200 excavators. Multi-year service of these excavators has proved that the completed seating arrangement is of a good quality and durable.

Another large and important object whose large-size bearing bed has been seated together with its toothed ring by using EPY compound, is ZGOT15400.120 dumping conveyor, completely designed and produced in Poland (Fig. 6.58).

Diameter of the ball bearing bed was 12,500 mm, and ball diameter — 200 mm. Weight of its rotary part supported on the bed was equal to 34,000 kN. The dumping conveyor was put into service in "Bełchatów" brown coal mine at the end of 2004.

The largest ball bearing bed (of 18,000 mm diameter) was installed with the use of EPY compound on K41 excavator in the same mine in 2004.

EPY compound was used in a much wider range for assembling a KWK910 excavator. Apart from the ball bearing bed (of 9000 mm diameter) on which rotary platform of operator's cab was supported, EPY compound was also applied to the seating of toothed ring bearing (of 3808 mm diameter) of loading crane jib as well as toothed ring of slewing gear of the crane body. Fig. 6.59 shows a schematic assembling

a)

b)

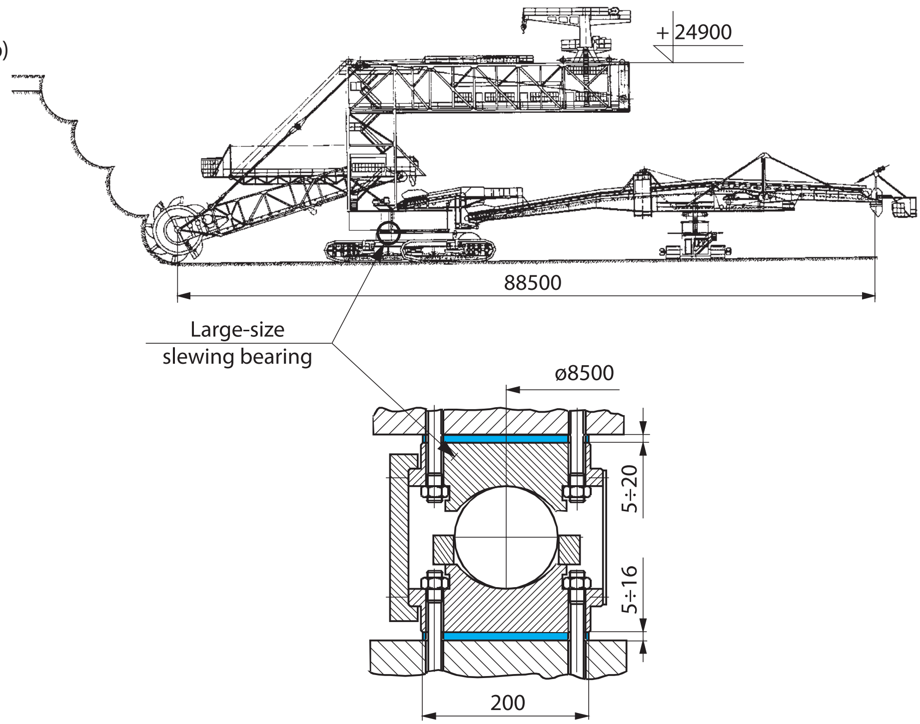


Fig. 6.57. Use of EPY compound for the seating of a turn-table bearing (ø 8.5 m) of a SRs-1200 excavator in "Konin" brown coal mine: a) view of the excavator; b) layout of the excavator and the cross-section of the turn-table bearing

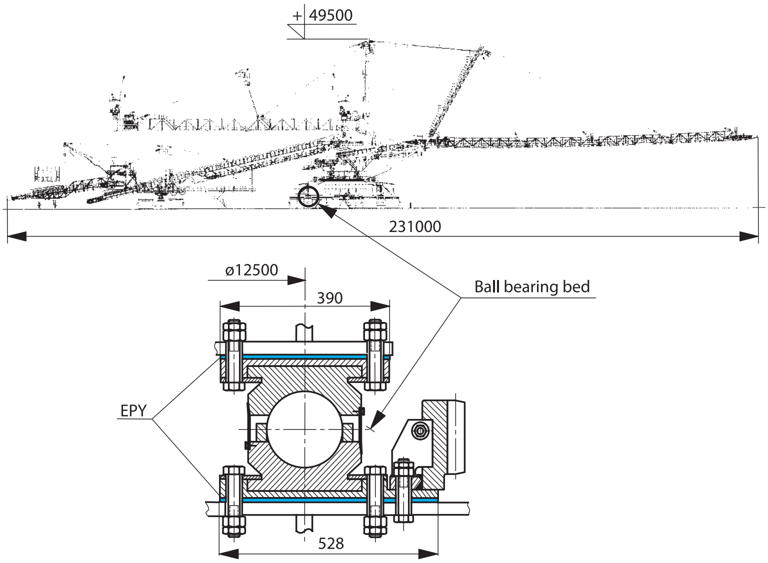


Fig. 6.58. ZGOT 15400.120 dumping conveyor with ball bearing bed (ø 12,500 mm) seated by using EPY compound

plan for the above mentioned elements and some details of it as well. Also in this case, a need of applying the troublesome and laborious machining of construction co-working surfaces was avoided and accurate and firm installation of all the elements was ensured. First, all particular elements and units were aligned in their proper service position by using adjusting screws, while leaving a gap (of at least 5 mm in height) between bearing surfaces of elements to be joined, which was then filled with liquid compound. After the compound had cured the adjusting screws were removed and the holding down bolts were tightened.

6.3.5. Application of EPY compound for the seating of power industry machinery

EPY compound is more and more used also for the seating of various power industry machines and facilities such as turbines, ball mills, fans etc. The compound finds its use for the seating of machinery on both concrete and steel foundations. Application of the compound for ready-to-use foundation chocks cast *in situ* under pre-aligned machines, greatly simplifies the assembling work also in this case, shortens the duration time of their installation and guarantees a better quality than in the case of using metal chocks. Fig. 6.60 exemplifies schematically the use of EPY compound for the seating of ball mill gear in “Siekierki” power station.

Fig. 6.61 shows how the compound can be used for the seating heavy machines and facilities on sliding plates.

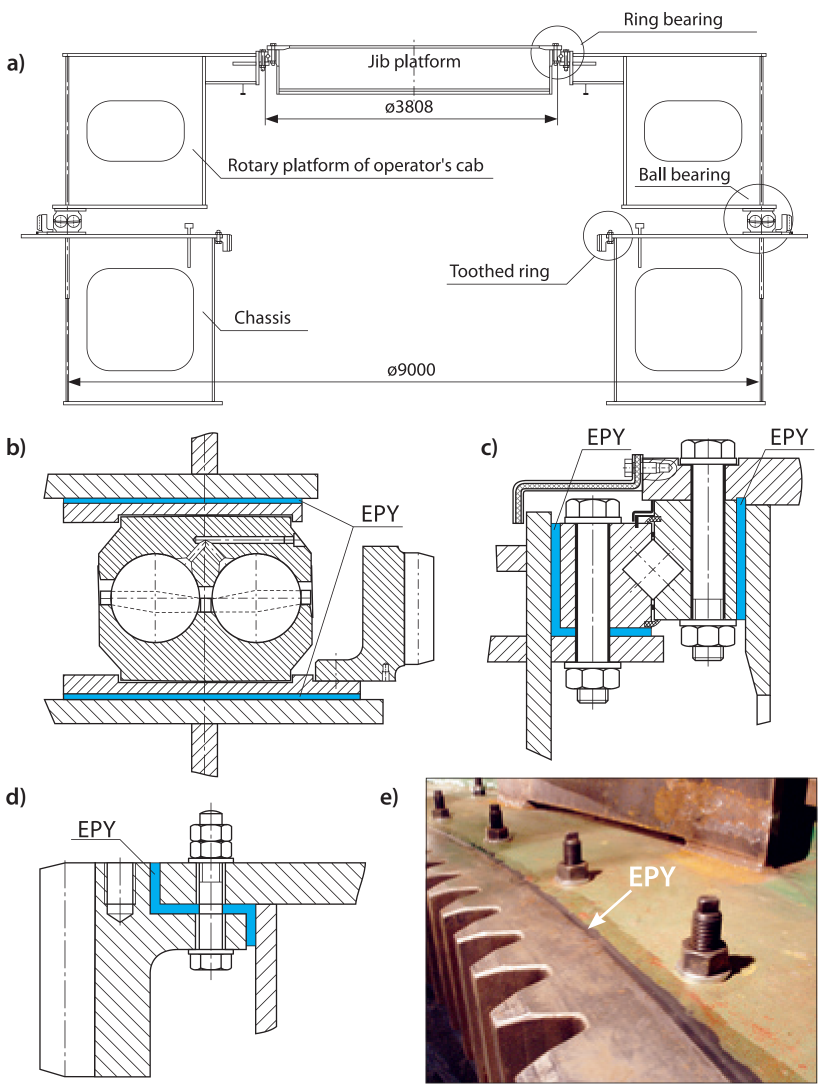


Fig. 6.59. Use of EPY compound for the seating of a ball bearing bed (ø 9000) and a toothed ring (ø 3808 mm) in KWK-910 excavator: a) schematic assembling plan; b) ball bearing bed; c) ring bearing; d) and e) toothed ring

Fig. 6.62a presents a large sorbing agent tank in “Siekierki” power station, which is seated with the use of foundation chocks cast of EPY compound, on a steel support structure of 25 m in height. A chock arrangement plan and dimensions of particular chocks are schematically shown in Fig. 6.62b. Height (thickness) of the chocks varied within the range from zero to 20 mm.

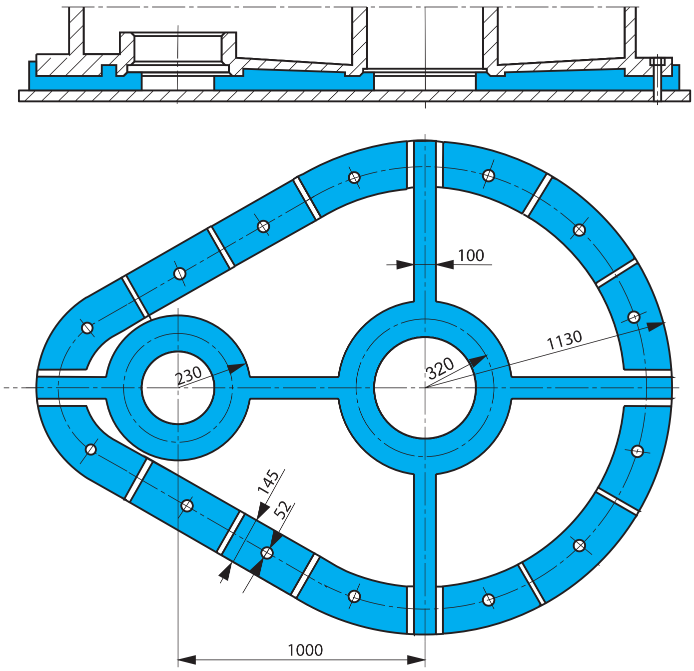


Fig. 6.60. Schematic plan of the seating of KAU ball-mill gear on EPY compound chocks

Surfaces of both foundation top and tank bottom were very uneven in macro-scale. Application of metal adjusting chocks to ensure a stable and correct position of the tank was practically not feasible in this case in view of a large and uneven area of supporting surfaces. However, application of EPY compound foundation chocks cast *in situ* together with a technological over-pour, directly under the tank which had been properly positioned in advance with the use of adjusting wedges, ensured an exact fit over whole area of contact surface between tank bottom and foundation top. The uneven and non-parallel areas of the surface have not been any obstacle in providing a correct and stable support for the tank.

Previous investigations have demonstrated that the liquid EPY compound used in this case, very accurately fills all void gaps (spaces) even those of a height close to zero. The so cast foundation chocks ensure a uniform pressure distribution over the whole area of contact surface. The total weight of the fully filled tank, estimated on the basis of available data, was equal to about 58,000 kN (5800 t). The mean value of pressure exerted onto the chocks was p = 6.8 MPa, that in view of the ultimate compression strength of the compound, R_c = 142 MPa, ensures a very large value of the safety factor n = 20.9. Its real value is even multifold greater due to a very large ratio of transverse dimensions of the chock and its height.

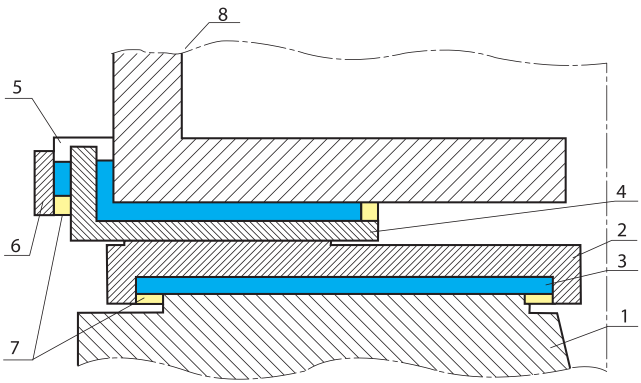


Fig. 6.61. Use of EPY compound for the seating of a turbine on sliding plates: 1 — steel or concrete foundation of the machine, 2 — lower sliding plate, 3 —EPY compound, 4 — upper sliding plate, 5, 6 — shift blocking elements for upper sliding plate, 7 — seals, 8 — machine bedplate

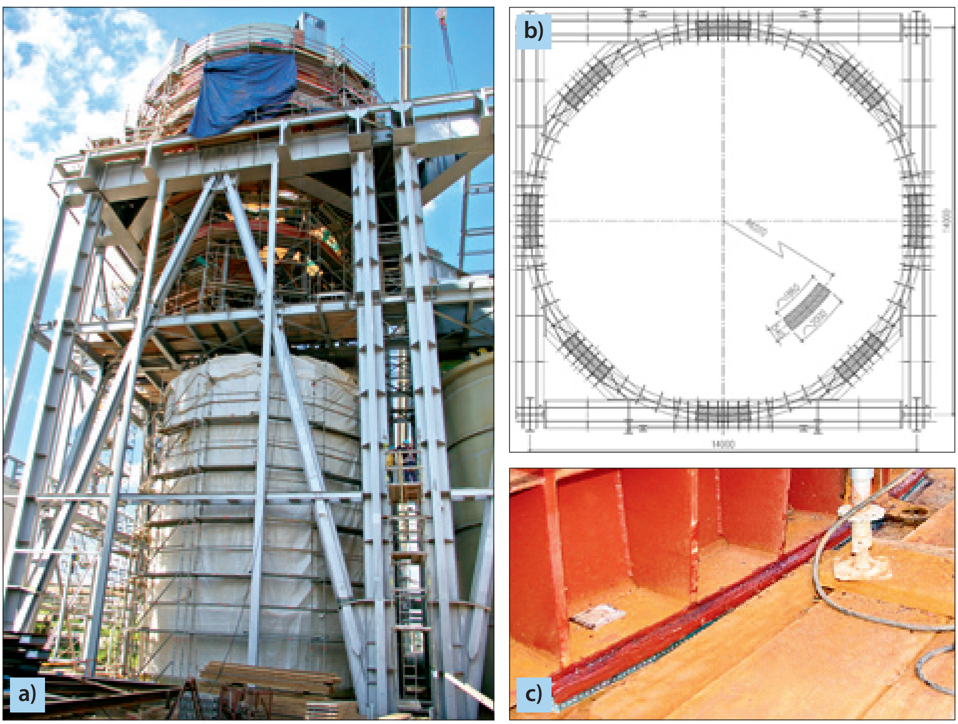


Fig. 6.62. A sorbing agent tank in "Siekierki" power station seated on EPY compound chocks: a) overall view; b) arrangement plan and dimensions of foundation chocks; c) a fragment of the seating arrangement with visible cast compound chock

6.3.6. Application of EPY compound for the seating of rails on steel structures, concrete foundations or cross-ties

EPY compound is also more and more used for the seating straight and circular rails on steel structures, concrete foundations or cross-ties. Fig. 6.63 and 6.64 show the examples of such applications.

Fig. 6.65 illustrates use of EPY compound for the seating of joint bars of excavator turntable rail track on its chassis steel structure, and also for the stiffening

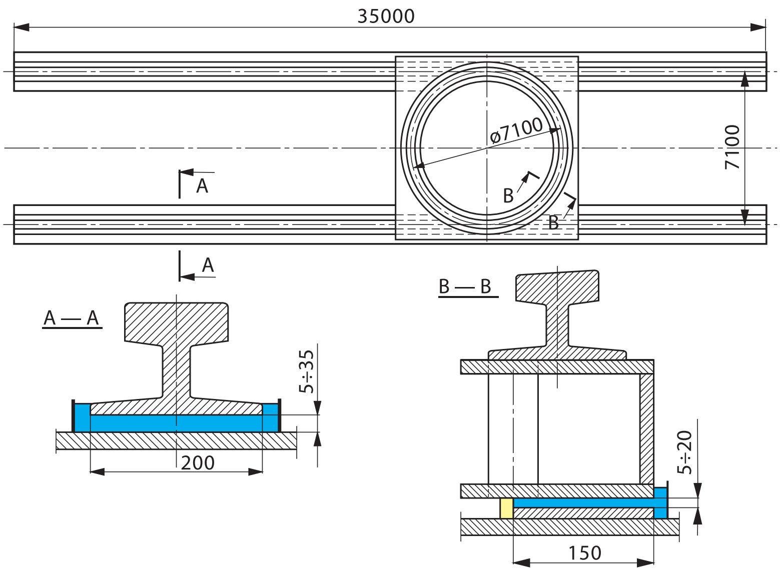


Fig. 6.63. Use of EPY compound for the seating of rail track and turntable rail of a port crane in Szczecin harbour

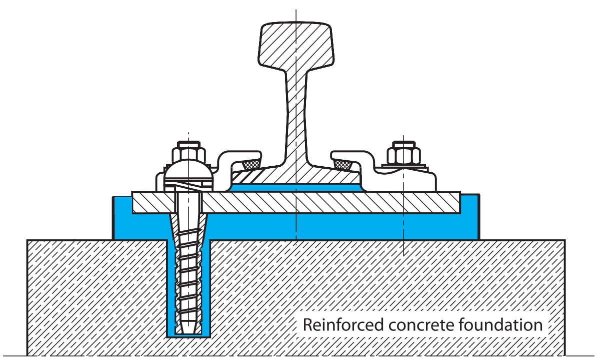


Fig. 6.64. A way of the seating of a rail on reinforced concrete foundation with the use of EPY compound

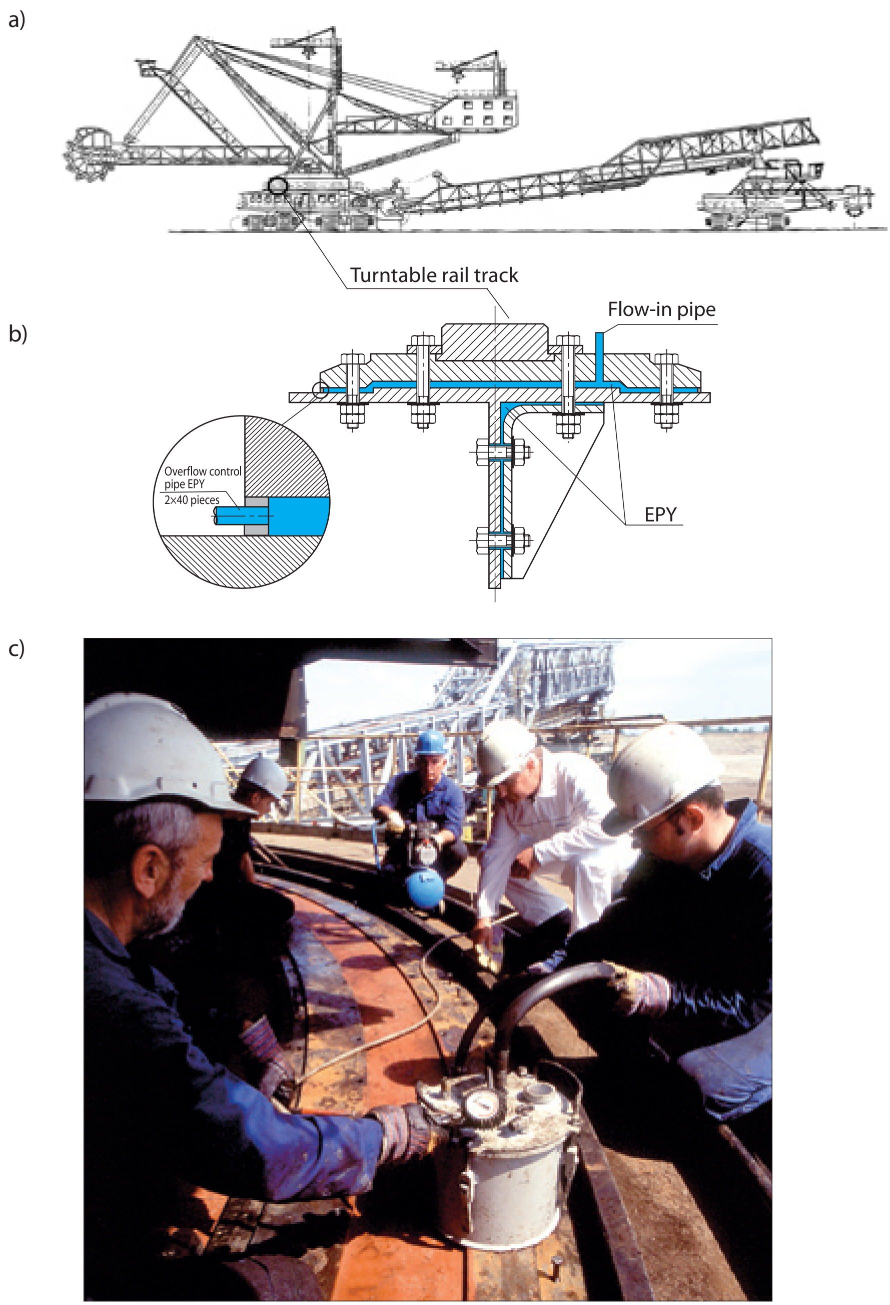


Fig. 6.65. Use of EPY compound for the seating of under-rail bar of turntable rail track of a KWK-1500s excavator (in "Konin" brown coal mine), on EPY compound: a) layout of the excavator; b) layout of the seating of under-rail bar; c) a way of pressing the compound into the space below the under-rail bar

of joints of the structure. After the rail joint bar had been aligned in its specified service position (by using distance elements and securing the minimum gap height of about 5 mm), seals had been made and the holding down bolts had been slightly tightened, the spaces formed between bearing surfaces were then filled with liquid compound by forcing it under pressure (Fig. 6.65c). When the compound had been cured, the bolts which fasten down the rail joint bar were fully tightened. Introduction of a thin layer of the compound into structural screwed joints (Fig. 6.65b) not only makes them significantly more stiff, free of micro-sliding, friction corrosion and other forms of wear, but also makes the transferring of normal and tangential loads more uniform. Experimental tests presented in Chapter 7 demonstrated that the introduction of a thin compound layer to joints of structural elements brings positive technical effects. The method has been also proved in practice.

6.3.7. Application of EPY compound for the seating of bridge span bearings

EPY compound has been also approved by Road and Bridge Research Institute, Warsaw, (Approval certificate No. AT/2006030018). Fig. 6.66 shows schematically various practical ways of application of the compound for the seating of bridge span bearings. Fig. 6.67÷6.71 show the examples of such application of EPY compound in bridge building, for the seating of railway tracks on trestle bridges and rails on steel structures.

Fig. 6.71 presents a novel application of EPY compound in bridge building. It is the case of its application to multi-bolted joints of reinforced concrete arc girders of a bridge built in Rytro, Poland. The reinforced concrete girder segments were ended with steel plates welded to their reinforcement bars (Fig. 6.71c). During their assembling the segments were properly positioned and connected to each other with the use of bolts (Fig. 6.71d, e). A very high accuracy of the assembling work was required. Any deflection of the girder from its assembling plane greater than ±5 mm was not permitted. Also, differences between real values of coordinates of arc girder axis and theoretical ones had not exceed 5 mm. Therefore already in the bridge design stage some gap between the face plates to be joined has been assumed to make it possible to properly position the segments in space, with a specified high geodesic accuracy. During the assembling process, after the elements to be joined had been properly positioned, the gap was filled with liquid EPY compound. When the curing process of the compound had ended, a compound interlayer which very well matched up with all uneven areas on joined surfaces, was obtained. This way, stable joints between the segments were produced, that guaranteed to reach their proper position in space and correct transferring the compressive and tangential loads over the whole area of their contact surfaces. As a result of such joining method no unexpected assembling stresses and deformations occurred in the joined girder segments. Stresses and deformations of the kind usually appear in fitting "by force"

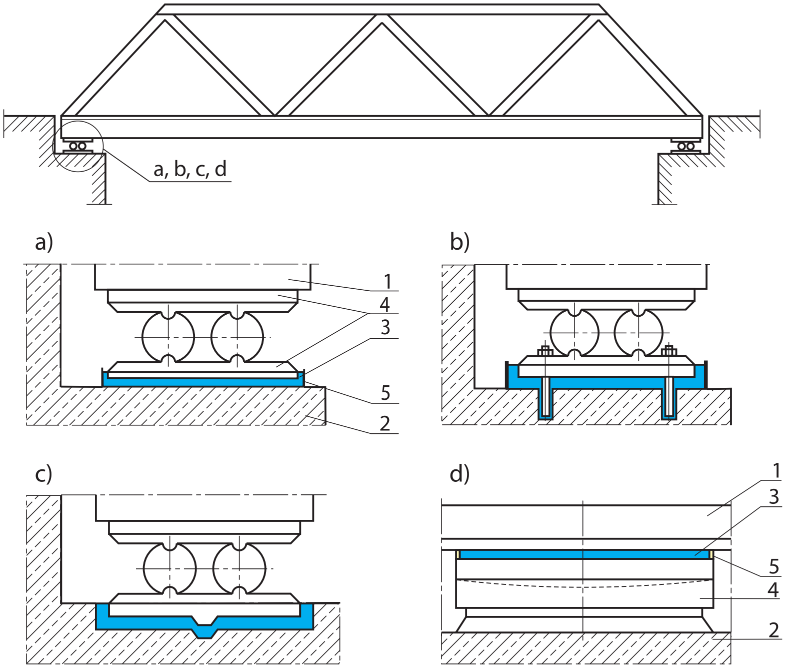


Fig. 6.66. Schemes of various solutions for the seating of bridge spans on EPY compound chocks: 1 — span, 2 — pier, 3 — EPY compound, 4 — bearing, 5 — casting mould

Fig. 6.67. Railway bridge in Wolin with bearings seated (in 1994) on EPY compound chocks (acc. the scheme shown in Fig. 6.66a)

Fig. 6.68. The "Siekierkowski" bridge under erection in Warsaw (2001): a) overall view; b) view of bridge span; c) view of a span bearing seated by using EPY compound (acc. the scheme shown in Fig. 6.66d)

the construction segments during their assembling. Sometimes they may reach even large values and cause various troubles in service. In such cases, application of the compound significantly facilitates the assembling work and ensures its high quality. The fully cured compound has much greater compression strength than that of concrete, as well as a high creep resistance. Such joint also well transfers transverse (shear) loads without occurrence of micro- and macro-sliding, fretting and other kinds of wear. It is resistant to corrosion and action of variable weather conditions. In effect, the method in question brings a better quality and greater reliability and service life of the joints.

Fig. 6.69. A bridge and a trestle bridge along the train of Wolin ring road, with bearings seated by using EPY compound

Fig. 6.70. An example of use of EPY compound for the seating of railway track on a steel over-bridge (in Szczecin)

Fig. 6.71. Use of EPY compound in erecting reinforced concrete arc girders of a bridge built in Rytro, Poland: a) overall view of the bridge; b) a segment of arc girder; c) face connection surface of an arc girder segment; d) connection of two arc girder segments with visible gap to be filled with compound; e) a fragment of a multi-bolt joint with the gap filled with EPY compound

6.4. Summary and statistical data on the seating arrangements made with the use of cast compound chocks in the years 1974÷2014

Resin compounds for foundation chocks have been developed first of all for the needs of shipbuilding industry, and there they found their first application in practice. They are now widely used for the seating of main propulsion engines and gears, stern tubes, rudder arrangement liners and also various auxiliary devices located either inside ship's hull or on ship's deck. Due to their numerous advantages they are presently used not only in shipbuilding industry but more and more for the seating of various land-based machinery which operate in engineering, chemical, and power industry, underground and surface mining, building industry, road and bridge building and many other branches of industry and economy. Application of the compounds to foundation chocks for the seating of machinery and facilities has proved in practice and provide countable technical, economic and operational benefits.

Polish EPY compound which was developed as a result of systematic, scientific research investigations, belongs to the group of the best-in-the-world compounds intended for machinery foundation chocks. It won worldwide recognition and has been deemed as good as recognized foreign compounds of the kind (Chockfast Orange and Epocast 36). It granted all the certificates which are necessary for its application to the seating of various shipboard machines and devices and land--based machinery as well.

In the period of 40 years of research and development work in this field a very rich scientific and practical experience have been gained. Polish resin compound was first used on a sea-going ship in 1974. At the beginning the seating operations were carried out by the team of Szczecin Technical University and authorized teams of some firms which gained relevant certificates from the University. Later, in 1989, Marine Service Jaroszewicz (MSJ) Co., a specialty firm was established in Szczecin. It has been managed since then by Mr Wiesław Jaroszewicz, Ph.D, Eng., (formerly the University's research worker specialized in this field), which took over all tasks dealing with the manufacturing of the compound and carrying out of all seating operations with its use. MSJ Company has been in close cooperation with the Szczecin Technical University, won in a very short time worldwide recognition and obtained significant results both in the area of research and development work and practical execution of the seating of machinery on the chocks cast of the compound. Mr. W. Jaroszewicz is the author or co-author of many scientific research and technical projects and publica-

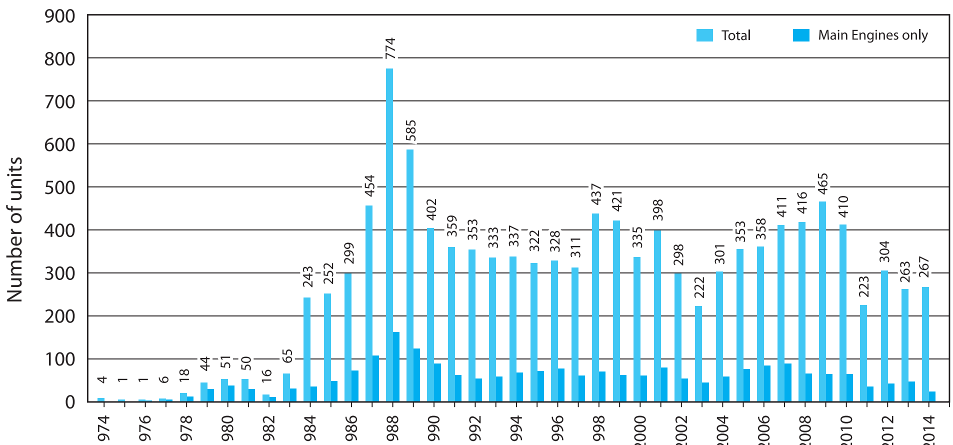


Fig. 6.72. Number of machinery seating operations by using cast compound chocks completed in years 1974÷2014

Table 6.2. Kinds and amounts of machines and devices seated on resin compound chocks in the years 1974—2014

Ship machines and devices	Number of units	Land-based machines and devices	Number of units
Main engines	2236	Engines	26
Main gears	822	Gears	57
Shaft line bearings	945	Working machines	47
Steering engines	326	Bearings	354
Stern tubes and tail shaft liners	916	Compressors and motor driven compressors	54
Rudder line sleeves	761	Railways	84
Winches (anchoring, towing, mooring, trawling)	1157	Presses	87
Electric generating sets	209	Turbines	37
Pumps	687	Fans	58
Tanks	98	Hoisting machines	6
Other machines and devices	1944	Other machines and devices	579
Total number	**10,101**	**Total number**	**1389**
Ship and land-based units in total	**11,490**		

tions. Many original and novel technical solutions put in engineering practice belong to his achievements. The working teams which operated under his supervision first within Szczecin Technical University (1974÷1981), then within KITI, a foreign enterprise in Poland (1982÷1989), and since 1990 in the frame of MSJ Company, his own firm, completed, in the years 1974÷2014, seating operations with the use of foundation chocks cast of the compound on 11,490 various objects in total, including 10,101 ship machines and devices (among them 2236 main propulsion engines) and 1389 land-based machines and facilities. Detailed quantitative data which concern the seating operations done in successive years, are given in Fig. 6.72 and those dealing with types of the objects installed in the period 1974÷2014, in Tab. 6.2.

7 Research on resin compounds used for machinery foundation chocks

7.1. General requirements concerning resin compounds for machinery foundation chocks

There are many resin compounds whose compression strength is higher than the pressure exerted on surface of foundation chocks used for the seating of ship machines and devices. The conclusion, though very important, is insufficient for selection and application of a resin compound for this purpose. Apart from sufficient compression strength it must fulfill many other general requirements concerning resin compounds used on ships [42, 43], and additional requirements concerning resin compounds applicable to machinery foundation chocks [41].

In accordance with the general requirements contained in the rules of Polish Register of Shipping [112] resin compounds used on ships should:

— undergo a flammability test according to the Subsection 2.4 of the regulations [41];

— emit no explosive gases (even in a temperature higher than its normal service temperature) and no toxic or suffocating gases when burning;

— provide reliable operation of machinery in the following temperature ranges: from –40°C to 70°C on open deck, and from –10°C to 70°C in ship internal accommodations, unless service conditions require otherwise;

— not become brittle and their mechanical properties should not worsen by more than 30% from their initial values during their service life;

— be resistant to decay and mildew action and should not negatively interact with other surrounding materials.

Apart from the general requirements, resin compounds used for foundation chocks must satisfy many additional requirements necessary for preparation of the design and engineering technology of seating arrangement to ensure reliability of mounted objects during their long-term service life. The following factors are of importance when using a chemically cured compound for the chocks cast directly under the machinery mounted on the ship:

— the method of preparing and using the compound;
— its casting properties;
— curing conditions;
— casting shrinkage and sagging of chocks during assembly work and in service;
— occupational safety and hygiene.

Due to the casting of foundation chocks directly under properly positioned machinery, their troublesome and laborious fitting was completely eliminated. Resin compound, due to its casting properties, should fully fill space intended for chocks and in particular ensure their proper adhering to bearing surfaces of machine foundation and bed plate. Casting shrinkage of the resin compound and sagging of chocks during assembling should be as low as possible. The process of mixing, casting and curing the compound composition should be feasible in the conditions occurring in shipyards or possible to be reached there (e.g. a required curing temperature).

The above discussed general and additional requirements were taken as a basis for development of a compound composition suitable for foundation chocks and technology of their casting and the seating of machinery on the chocks.

7.2. General remarks about research on resin compound applicable to foundation chocks

The above discussed requirements, hence also the research on resin compounds used for the seating of shipboard machinery may be divided into two categories: standard and special.

Standard research is usually conducted on small specimens of resin compound. The shape and dimensions of specimens as well as the testing method are precisely determined by relevant standards for resin compounds. Results of such tests generally serve to control quality of resin compounds and to compare them to other similar or different materials tested in the same way. Detailed scope of the tests and standards in force according to which they must be conducted are given in Chapter 2.

Real physical properties of resin compounds, though crucial to cast foundation chocks, are often not revealed by standard tests of such material. The elasticity and viscosity properties of resin compounds cause that small specimens behave differently under simple loads than full-size structural elements (e.g. chocks) made of the same materials. Resin compounds show especially high strength and volumetric strain resistance under three - axial compression. The basic merits of cast resin compound chocks which are most important for machinery seating, are: an exact fit to bearing surfaces of machine foundation and bed plate, almost perfect value of elasticity modulus and high value of effective friction factor in contact with steel. As a result, it ensures uniform distribution and proper transferring the loads in normal and tangential directions to the foundation surface. Resin compounds have of course other important technological and operational advantages, e.g. they can be easily poured to form *in situ* ready-to-use chocks of various dimensions and shapes, and they effectively damp vibration and isolate against propagation of structural noise. Various advantages of chemically cured compounds contributed to their wider and wider use first in shipbuilding and ship repair industry and then also for the seating of various land-based machines and facilities. For rational and effective implementation of resin compounds into engineering practice it is essential to have a sufficient knowledge on their processing and performance in various service conditions. To this end, many different research projects both standard and special have been carried out.

Further consecutive subsections of this chapter contain the descriptions and results of the tests on the resin compound itself to be used as a structural material. Most of the research tests were standard and carried out in compliance with current material standards in force. Results of the research illustrate influence of various factors on physical and mechanical properties of standard specimens of this material. They are of a basic importance, deciding on its quality and applicability to foundation chocks.

Non-standard (special) tests which illustrate performance of the compound in various practical applications are presented in the next chapter.

7.3. Research on influence of various substances and temperature on EPY compound compression strength

During their service life, foundation chocks of shipboard machinery often come into contact with water and oils. For this reason they are to be resistant to long term exposure to these media. EPY compound satisfies the condition, which was confirmed by appropriate tests.

Cylindrical specimens used for the testing had the dimensions: 20mm in diameter and 25 mm in length. They were cast in steel moulds, cured for 3 days at 20°C temperature, and then held for 2 h at 80°C temperature. All the specimens were split into four groups. The first one underwent compression test directly after the specimens were heated and then cooled down to 20°C. The specimens belonging to three remaining groups were tested in compression after 31 days. During this time the specimens of 2nd, 3rd and 4th group were kept in air, machine oil and tap water, respectively. The results of compression tests are presented in Tab. 7.1.

The obtained test results did not show any detrimental effect of exposure to air, machine oil and tap water onto the chocking compound. Little increase of compression strength after 31 days of their exposure may be explained by the influence of the additional time on curing the compound.

Tests on the influence of temperature on the compression strength R_c of EPY compound were conducted on specimens prepared and cured in the same way as those used for the tests on exposure to oil and water. The specimens were cooled in methyl alcohol for 24 h at –20°C temperature. All instruments contacting the specimens during the compression tests were also cooled to the same temperature. The tests in positive temperatures were carried out in a heating chamber. Before the compression tests the specimens were held for 2 h in a given temperature. Test results are shown in Tab. 7.2.

The tests (Tab. 7.2) showed considerable influence of temperature on the compression strength of EPY compound. The lower the temperature the distinctly higher the strength, and the higher the temperature the lower the strength, which is typical for all chocking compounds based on epoxy resins.

Apart from the above described tests of short-term influence of air, oil and water on compression strength of EPY compound (Tab. 7.1), the Technical University of

Table 7.1. Results of compression tests on specimens kept in air, oil and water

Group of specimens	Substances and storage periods of specimens	№ of specimen	Compressive strength R_c, MPa	
			Test results	Mean values
1	Air; Specimens tested directly after being cast	1 2 3	146 148 145	146
2	Air; Specimens tested after being kept for 31 days in the air	1 2 3	151 151 150	151
3	Machine oil; Specimens tested after being kept for 31 days in machine oil	1 2 3	158 156 158	157
4	Tap water; Specimens tested after being kept for 31 days in tap water	1 2 3	150 151 146	149

Table 7.2. Results of specimen compression tests conducted at different temperatures

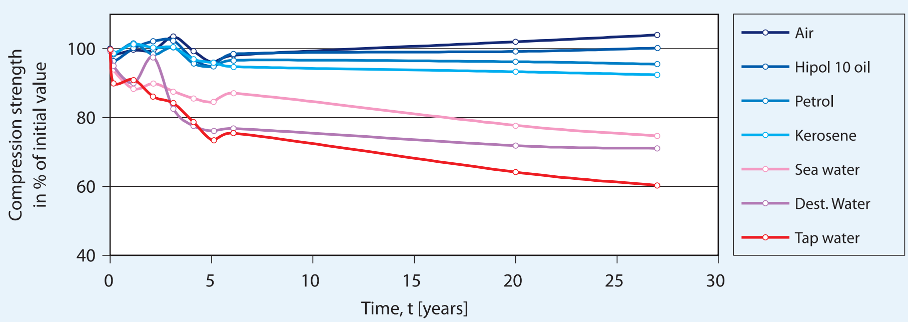
№ of series	Test temperature, °C	№ of specimen	Compressive strength R_c, MPa	
			Test results	Mean values
1	–20	1 2 3	181 181 167	176
2	+20	1 2 3	146 148 145	146
3	+60	1 2 3	102 108 100	103
4	+80	1 2 3	98 95 84	92
5	+100	1 2 3	90 99 81	90

Szczecin has also conducted the tests of long-term influence of various media on strength properties of epoxy compound. The tests started in 1975. Since that time cylindrical specimens of EP-571 compound, of the diameter d = 20 mm and the height h = 20 mm and its composition close to that of EPY compound, have been kept in glass jars with different substances. The specimens were cured only in ambient temperature for three days (without any further post curing). After some time a lot of a few specimens was taken out one by one of the jars and put to the compression tests. Their results are presented in Tab. 7.3.

As results from the tests, only water, especially tap and distilled water, distinctly lowered compression strength of the tested compound. In case of tap water the decrease of strength after 27 years amounted to 40%. In the same period of time a much lower drop in compression strength (by about 25%) was observed in case of exposure to sea water (from the Atlantic) action. In contrast, the resistance of the

Table 7.3. Compression strength of EP-571 compound specimens subjected to long-term influence of various substances

Period of specimen storage in a given substance, Years	Average compression strength R_c, MPa of specimens kept in various substances						
	Air	Hipol 10 oil	Petrol	Kerosene	Sea water	Distilled water	Tap water
0.000	102.9	102.9	102.9	102.9	102.9	102.9	102.9
0.164	101.3	99.2	101.1	106.6	96.8	97.9	92.7
1.151	102.5	103.0	104.5	104.2	91.0	93.0	93.7
2.137	102.5	105.0	101.1	103.2	92.5	90.2	88.6
3.123	106.5	105.4	103.3	103.3	90.1	85.0	86.5
4.110	102.2	99.7	98.5	99.8	88.1	79.2	81.0
5.096	98.8	97.8	97.7	98.8	87.1	78.3	75.4
6.082	100.9	101.4	99.5	97.5	89.6	79.1	77.7
20.000	105.1	102.1	99.1	96.2	80.1	74.0	66.1
27.000	107.0	103.1	98.3	95.1	76.9	73.2	62.0



compound to long-term exposure to air, kerosene and oil (Hipol 10) is very high, as no significant quantitative and qualitative changes were noticed in results of the compression tests.

It should be stressed that the conditions of the laboratory tests were much worse than hazards to which the real foundation chocks are usually exposed. It results from their relatively high ratio of surface area and volume. In real foundation chocks only their free end faces are exposed to contact with gas or liquid environment. Conclusions drawn from the laboratory tests have been fully confirmed by the correct performance of the applied chocks in service.

7.4. Research on influence of low temperatures on characteristics of the compound and values of selected compression strength parameters

The research was aimed at determination of influence of low temperature values (0, –20, –60 and –120°C) on mechanical characteristics of EPY compound additionally (post) cured at various temperatures (50, 80 and 120°C for 4 h) as well as on values of selected compression strength parameters.

Compression tests were carried out by means of an 4026-INSTRON computerized universal testing machine (equipped with a thermal chamber (Fig. 7.1)) with the use of a special software.

The tests were conducted in the temperatures: 0, –20, –60 and –120°C (in nitrogen atmosphere) on the cylindrical specimens of the dimensions (10 mm diameter × 20 mm height), post-cured in the temperatures: 50, 80 and 120°C for 4 h after their curing at the temperature 22 ±1°C for 24 h. The temperatures to which the specimens were brought in and then kept at the thermal chamber, were controlled (with ±1°C accuracy) by using thermocouples inserted into additional control specimens in a given phase of curing.

The so prepared series of specimens (each of 5 pieces in number) underwent uniaxial compression test (in the chamber at the above enumerated low temperatures) up to their damage. The tests were conducted at the machine's piston travelling speed reaching 1.3 mm/min (equivalent to the strain rate of 0.208 min^{-1}).

Fig. 7.2 shows exemplary runs of low-temperature compression characteristics of specimens of EPY compound post-cured at 80°C. Fig. 7.3 through 7.6 show a set of values of selected strength parameters obtained from the compression tests of specimens made of the compound post- cured in different temperatures. Detailed descriptions and results of the experimental tests in question are contained in the publication [162].

As shown in Fig. 7.2, low temperatures make runs of stress-strain diagrams of epoxy compound similar to those of materials fragile by nature. It may be observed that along with temperature lowering the modulus of elasticity E fast increases and the greater and greater shortening of flat plateau on the diagrams

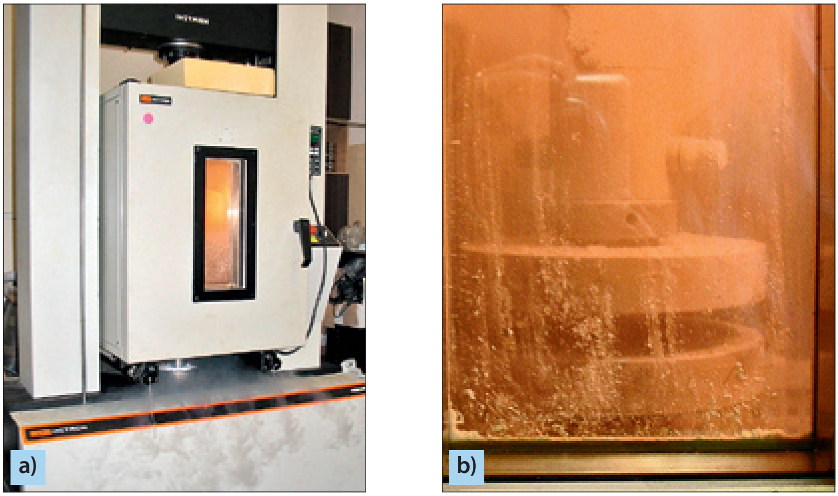


Fig. 7.1. Thermal chamber of INSTRON testing machine during measurement: a) overall view; b) view of chamber's interior

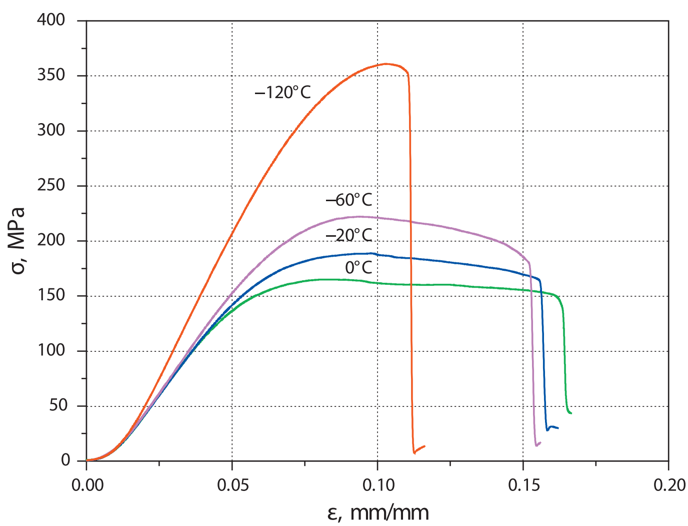


Fig. 7.2. Compression characteristics of specimens made of EPY compound post-cured in 80°C for 4 h, determined in various low temperatures

(typical for plastic materials) takes place, so strong that at the temperature –120°C EPY compound reaches brittle state in which no plastic behaviour can be found. Such increase of the elasticity modulus E and loss of plastic properties of the compound in low temperatures, due to a specific "freezing" of motion of chains of poly-

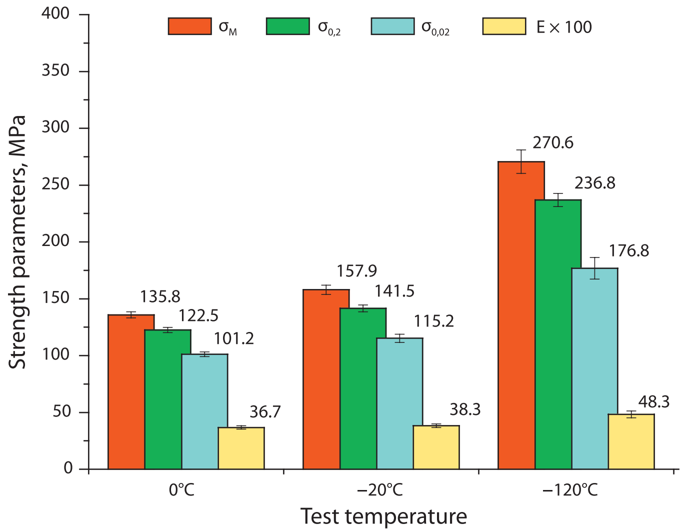


Fig. 7.3. Collected values of some strength parameters of EPY compound cured in 22 ±1°C for24 h, determined in low temperatures

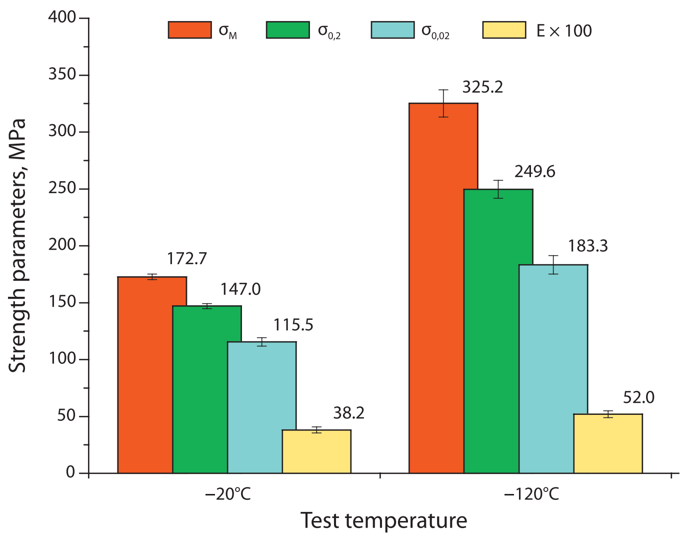


Fig. 7.4. Collected values of some strength parameters of EPY compound post-cured in 50°C for 4 h, determined in low temperatures

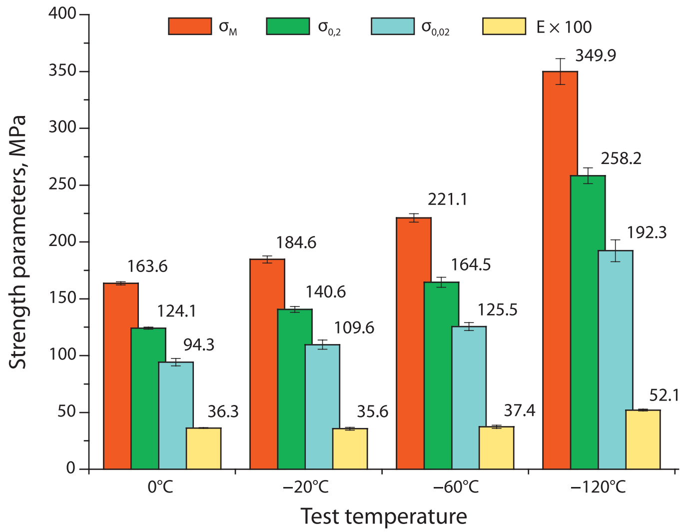


Fig. 7.5. Collected values of some strength parameters of EPY compound post-cured in 80°C for 4 h, determined in low temperatures

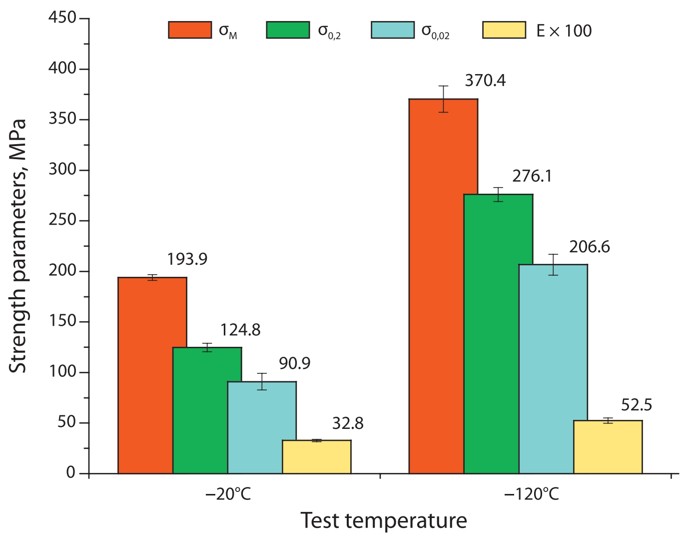


Fig. 7.6. Collected values of some strength parameters of EPY compound post-cured in 120°C for 4 h, determined in low temperatures

mer particles, result in the rise of values of compression strength parameters along with lowering the testing temperatures (Fig. 7.3÷7.6). However, the influence of low temperatures on strength properties of epoxy compound is more complex and thermodynamic analysis of load-generated strains, though similar to that used in metal engineering, is even more complicated and must be considered in the categories of nucleation and coalescence of shear micro-domains, limitation of molecular motions and nano-fluctuation of density of cross-linking and concentration of defects in cross-linking structure [163].

7.5. Determination of relation between glass transition temperature and cross-linking rate of EPY compound

The direct relation between the glass transition temperature (T_g) which increases during curing the chemically cured compounds, and their cross-linking rate (α), can be described by using the DiBenedetto experimental equation [113] which, according to Nielsen [81], is of the following form:

$$T_g = T_{g0} + \frac{(T_{g\infty} - T_{g0})\lambda\alpha}{1-(1-\lambda)\alpha} \tag{7.1}$$

where:
- T_{g0} — glass transition temperature of non-cross-linked resin (α = 0),
- $T_{g\infty}$ — glass transition temperature of fully-cross-linked resin (α = 1),
- λ — a structure dependent parameter which takes values from the interval (0;1).

The parameter λ, according to Pascault and Williams [86, 114], can be determined from the relation as follows:

$$\lambda = \frac{\Delta C_{p\infty}}{\Delta C_{p0}} \tag{7.2}$$

where: $\Delta C_{p\infty}$ i ΔC_{p0} — differences in values of specific heat capacity of epoxy system in glass transition state and elastic (or liquid) state in T_g temperature, respectively, for fully cross-linked and not-cross-linked resin.

DiBenedetto equation (7.1) in the form given by Pascault and Williams, Oleinik and Hale, which describes the relation $T_g = f(\alpha)$, is presented for EPY compound in the publication [92].

In Eq. (7.1) α value is contained within the interval (0;1), and it is usually assumed that the epoxy-amide system may reach a 100% conversion (α = 1) after additional cross-linking.

On substitution of value of the glass transition temperature (see Chapter 3, section 3.3.2) and value of the parameter λ = 0.426 calculated from Eq. (7.2) [87, 88] into DiBenedetto equation (7.1) the relation between T_g and α for EPY compound can be written as follows:

$$T_g = -45.6 + \frac{(111.2 + 45.6)\,0.426\,\alpha}{1 - (1 - 0.426)\alpha} \tag{7.3}$$

Fig. 7.7 shows this relation in the form of the curve $T_g = f(\alpha)$ (continuous line), whose run indicates that the glass transition temperature of the system linearly increases from the initial temperature T_{g0} up to its maximum temperature $T_{g\infty}$ along with growing its cross-linking rate (α). During the cross-linking process of the system, when its rate is still rather low, T_g grows as a result of greater and greater value of the numerically mean molecular weight of epoxy resin (M_n), and, beginning from the gelation point (α = 0.58) [87, 88] further increase of T_g temperature takes place in consequence of growing cross-linking density of the material.

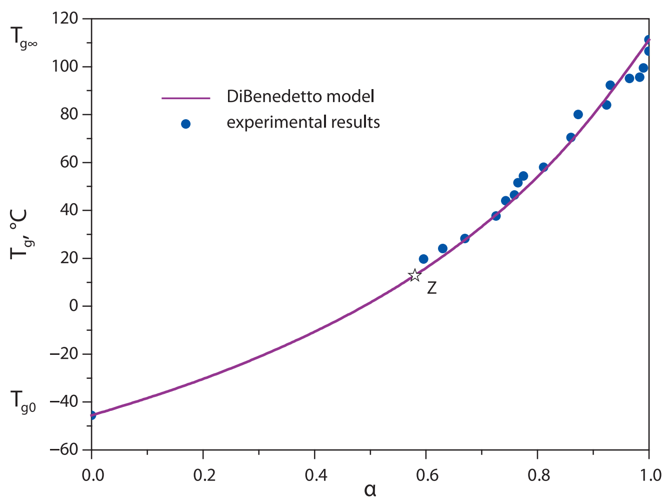


Fig. 7.7. Glass transition temperature (T_g) in function of cross-linking rate (α) of EPY compound: DiBenedetto model (continuous line) and obtained experimental results (symbols); the compound gelation point (Z) is also marked

As results from verification of the used DiBenedetto model (7.1), which has been conducted above the gelation point of EPY system (0.58 < α < 1), with the use of data on the specimens cured in 23°C temperature for different periods of time (4÷168 h) as well as on the specimens additionally cured in different temperature values (30÷100°C) for different periods of time (1÷4 h), there is a good conformity between the calculated and experimental results, that is shown in Fig. 7.7 (symbols) as well as in the publications [87, 88, 93, 94]. A rather low spread of T_g values at higher rates of cross-linking process is usually attributed to a lower sensitivity of DSC instrument in measuring conversion level in comparison with that used in measuring T_g [115].

For the verification of the selected model, the cross-linking rate (α) of the compound was calculated according to the following formula [116]:

$$\alpha = 1 - \frac{\Delta H_{res}}{\Delta H_T} \tag{7.4}$$

where:
ΔH_{res} — residual enthalpy of partly cross-linked compound specimen; ΔH_T — stagnation enthalpy of reaction, equivalent to that of a specimen of the compound in a "mixing" state without prior cross-linking (ΔH_T = 273.8 J/g) [88].

The relation between glass transition temperature and cross-linking rate, demonstrated for EPY compound, is independent of cross-linking temperature, therefore the direct relation between T_g and α (7.3) may be used for the mutual transforming of values of the cross-linking parameters. This way T_g may serve as a reliable measure of conversion, which is advantageous from practical point of view as T_g of resin system can be measured easier and even with a higher accuracy than conversion, especially at its greater values at which T_g rises even though DSC calorimeter does not show any changes in residual heat [117].

7.6. Research on influence of curing and post-curing states of EPY compound on its compression strength characteristics

The research has been aimed at determination of influence of post-curing temperature (from the range 40÷180°C) of EPY compound (preliminarily cured in the temperature of 22 ±1°C) on its mechanical characteristics obtained from compression tests.

The tests were carried out in the temperature of 23°C on cylindrical specimens (of 20 mm diameter and 25 mm length). The specimens, after their casting in steel moulds, have been first cured for 24 h in the temperature of 22 ±1°C, then they were split into eight series (of 5 pieces each) and post-cured for 2 h in the temperatures ranging from 40 to 180°C in the intervals of 20°C. The so post-cured specimens underwent compression tests up to their damage, which were conducted at the machine's piston travelling speed of 1.3 mm/min (equivalent to the strain rate $\dot{\varepsilon}$ = 0.208 min^{-1}). The tests were carried out by using INSTRON servo-hydraulic testing machine with the aid of an appropriate software. Moreover, four series of specimens (of 5 pieces each), post-cured in the temperatures: 40, 60, 80 and 100°C (for 2 h), underwent compression tests at different values of strain rate $\dot{\varepsilon}$, varying even by one order within the range of 0.0208÷20.8 min^{-1} (i.e. at the machine's piston travelling speeds ranging from 0.13 to 130 mm/min). The test results are presented in Fig. 7.8 through 7.11.

Fig. 7.8 shows, in the stress-strain coordinate system, characteristics which illustrate behaviour of the tested compound during the compression test (at the standard strain rate of 0.208 min^{-1}) in function of the post-curing temperature (T_c) of the specimens. General run of the stress-strain curves for post-curing temperatures up to 60°C maintains its typical shape. It reveals zones of fast transition from elastic to elastic-plastic state and vast zones of almost perfect "plastic" flow. Also, some rise in strength (σ_M) and the decreasing of plastic flow zone along with increasing the post-curing temperature, may be observed. At the post-curing temperature greater than 60°C, some hardening of the material takes place and its compression strength (σ_M) grows.

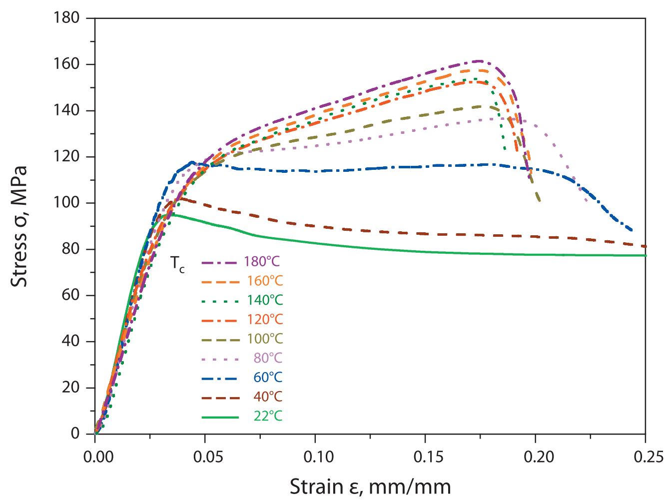


Fig. 7.8. Stress—strain curves obtained during compression tests with standard strain rate on EPY compound specimens post-cured in various temperatures

Values of the selected strength parameters (σ_M, $Rc_{0,2}$, $Rc_{0,02}$, E) and values of their standard deviations obtained from compression tests of the specimens post-cured in various temperatures, are shown in Fig. 7.9.

As results from the tests (Fig. 7.9), value of Young's modulus of elasticity (E) decreases more and more along with increasing post-curing temperature up to a value equivalent to the glass transition temperature ($T_{g\infty}$) of fully cross-linked EPY compound, whose value measured by using DSC instrument, amounts to 111.2°C (see Chapter 3, Subsection 3.3.2). The drop of elasticity modulus values may be explained by the fact that disintegration of second-order links begins along with temperature increasing and in consequence chain segments may be easily displaced to each other. When growing temperature exceeds the glass transition temperature T_g, polymer compound starts expanding and occurrence of an additional void space makes sliding greater clusters of macro-particles possible [118], which results in decreasing values of Young

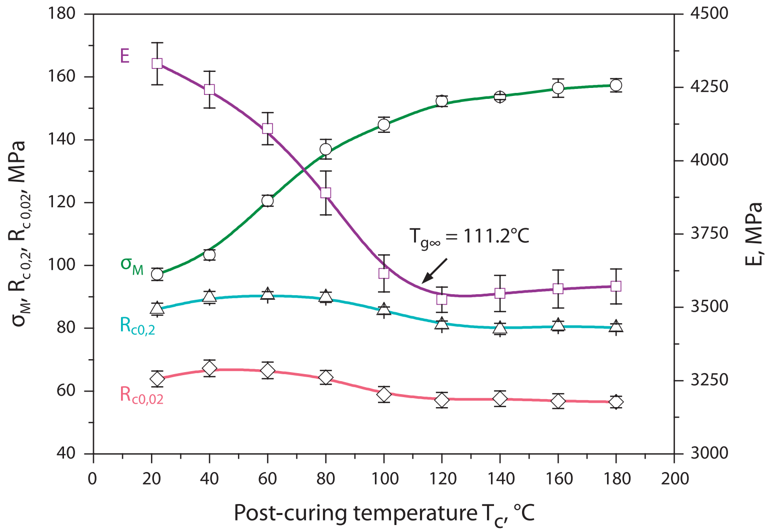


Fig. 7.9. Values of some strength parameters of EPY compound post-cured in various temperatures, determined in the tests with standard strain rate in 23°C temperature; the given value of T_g was determined from DSC instrument at 10°C/min (see Ch. 3, Subsec. 3.3.2)

modulus of elasticity. Values of compression stresses which determine the conventional yield point ($R_{c0,2}$) and conventional elastic limit ($R_{c0,02}$) in the vicinity of glass transition temperature of tested material, undergo change in a similar way. (Fig. 7.9).

The compression strength (σ_M) in function of the post-curing temperature (T_c) lower than the glass transition temperature of fully cross-linked thermo-curing compound ($T_{g\infty}$) can be approximated by using the following Lesser's equation [119]:

$$\sigma_M = \alpha\left(T - T_{g\infty}\right) + \sigma_M^{T_g} \qquad \text{dla } T = T_c < T_g \tag{7.5}$$

where: σ_M^{Tg} — compression strength at $T_{g\infty}$, α — coefficient which describes linear increase of σ_M, when $T = T_c < T_{g\infty}$.

In the case of the tested compound, a good conformity (coefficient of correlation $R^2 = 0.9899$) was reached between results of experimental measurements (Fig. 7.10) and calculation results according to the relation (7.5), that allows to reduce the expression to the following form:

$$\sigma_M = 0.6584\,(T_c - 111.2) + 154.0 \tag{7.6}$$

The equation in this form may be used in practice for the foretelling of compression strength of EPY compound in function of its post-curing temperature.

The compression strength (σ_M) of EPY compound post-cured in various temperatures (40÷100°C for 2 h) increases along with the increasing of strain rate (Fig. 7.11)

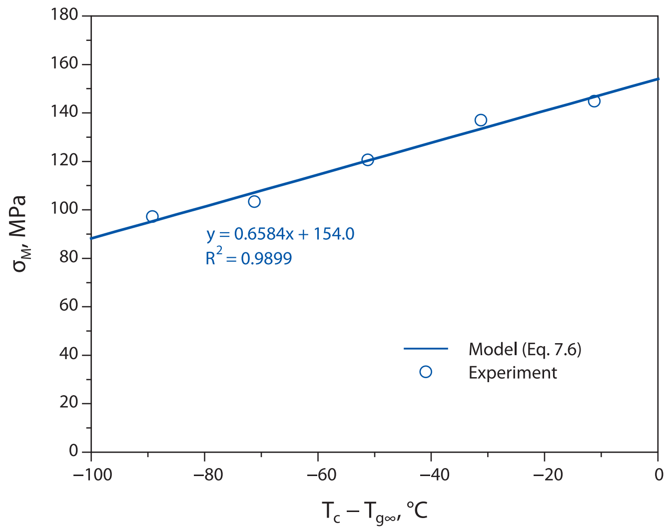


Fig. 7.10. Compression strength (σ_M) of EPY compound in function of (T_c—$T_{g\infty}$), both experimentally obtained and calculated acc. Eq. (7.6)

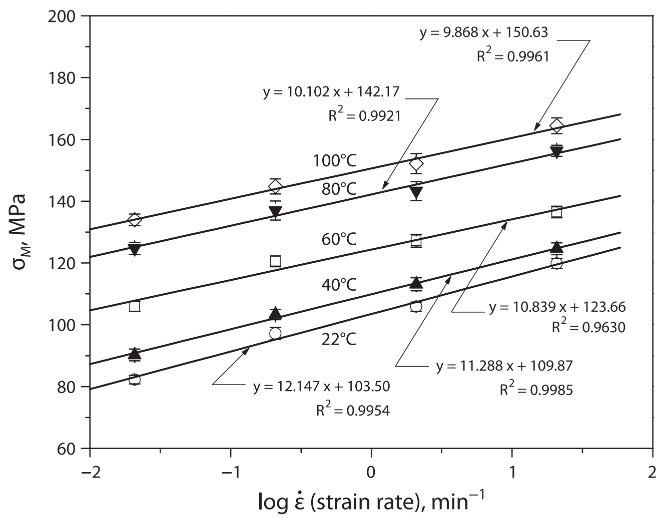


Fig. 7.11. Compression strength (σ_M) in function of strain rate logarithm for EPY compound post--cured in various temperatures

and, like in the compound cured only in 22 ±1°C temperature for 24 h, the increase is linear over the whole range of strain rate. And, slope angles of the line $\sigma_M = f(\dot{\varepsilon})$ indicate that along with the increasing of post-curing temperature of compound its sensitivity to change in strain rate decreases a little.

The results obtained from compression tests of EPY compound indicate that its behaviour as well as values of its basic strength parameters (σ_M, $R_{c0,2}$, $R_{c0,02}$, E) greatly depend on its curing state and strain rate. Detailed results of the tests are presented in the publications [93, 120÷122]. The above mentioned factors should be seriously taken into consideration in various practical applications of the compound.

7.7. Research on influence of strain rate of EPY compound on its compression strength characteristics

Standard compression test on resin compound specimens, according to ASTM D695 standard, is carried out with the testing machine's piston travelling speed v = 1.3 ±0.3 mm/min. In dynamic load conditions of foundation chocks loading force velocities may be different. Therefore, the strain rate, called also compound's rate of deformation, is a significant parameter:

$$\dot{\varepsilon} = \frac{\Delta\varepsilon}{\Delta t} = \frac{v}{L_o}, \ \mathrm{min}^{-1} \tag{7.7}$$

where:
v — loading force velocity, L_o — initial dimension (length) of specimen.

The tests were aimed at determination of influence of strain rate of EPY compound specimens on its compression strength characteristics and then, on this basis, determination of values of selected parameters which characterize crucial mechanical properties of the compound to be used as a structural material, namely:

— compressive stress σ_M under maximum load, which determines compression strength of the compound (marked R_c — acc. PN-57/H-04320 standard);

— compression stress $\sigma_{0,2}$ at conventional value of permanent deformation ε = 0.2%, called also conventional yield point (marked $R_{c0,2}$);

— compression stress $\sigma_{0,02}$ at conventional value of permanent deformation ε = 0.02%, called also conventional elastic limit (marked $R_{c0,02}$);

— Young modulus of elasticity (E).

The tests were performed on cylindrical specimens of the dimensions: 20 mm diameter and 25 mm length. The specimens, after casting in steel moulds, were cured at 22 ±1°C temperature for 24 h. Their upper face surfaces were planned (precisely turned) to get a required dimension. The so prepared series of specimens (of 5 pieces each) underwent uniaxial compression up to damage, under the strain rate $\dot{\varepsilon}$ of values varying in the range from 0.0208 to 20.8 min^{-1} (i.e. at the machine's piston travelling speeds ranging from 0.13 to 130 mm/min). Compression tests were carried out by using an 8501 Plus INSTRON computerized testing machine with the aid of a special software (Series IX Automated Materials Testing System 8.09.00). Fig. 7.12 shows a view on the test stand. Results of measurements are presented in Fig. 7.13 through 7.15.

Fig. 7.12. Test stand for determination of mechanical characteristics during compression test at various strain rates

Fig. 7.13 illustrates behaviour of the tested compound specimens, presented in the stress-strain coordinate system for various values of the strain rate $\dot{\varepsilon}$: 0.0208; 0.208; 2.08 and 20.8 min^{-1} which correspond to values of testing machine's piston travelling speed ranging from 0.13 to 130 mm/min. Run of the curves indicates that the compression strength (σ_M) increases along with the strain rate increasing. Manner of

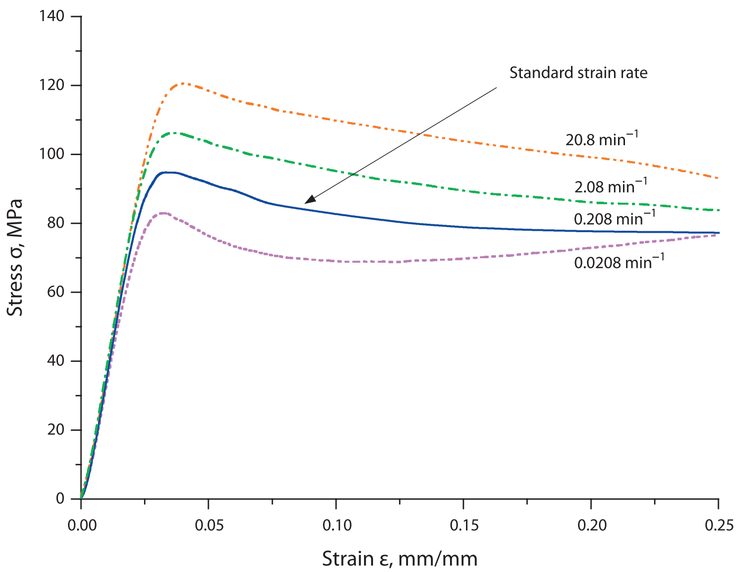


Fig. 7.13. Stress—strain curves for EPY compound cured in 22 ±1°C for 24 h determined at various strain rates

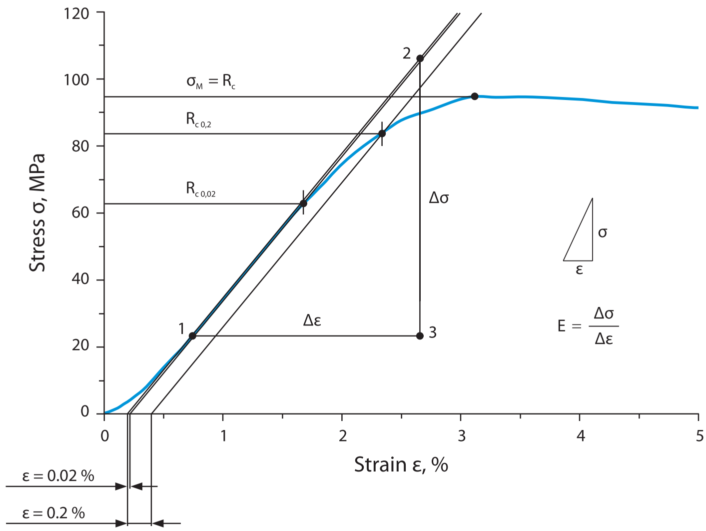


Fig. 7.14. Manner of determination of values of the selected strength parameters in static compression test: compression strength σ_M,conventional yield point ($R_{c0,2}$), conventional elastic limit ($R_{c0,02}$), and Young modulus (E)

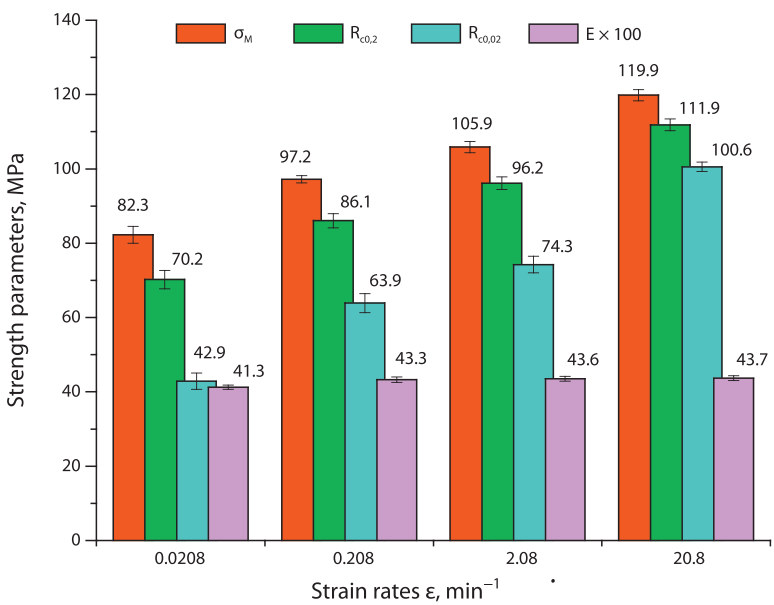


Fig. 7.15. Values of selected strength parameters (determined acc. Fig. 7.14) obtained from compression test on EPY compound specimens (cured at 22 ±1°C for 24 h) compressed at various strain rates

determination of values of the selected strength parameters: σ_M (R_c), $\sigma_{0,02}$ ($Rc_{0,2}$),$\sigma_{0,02}$ ($Rc_{0,02}$) and E, is shown in Fig. 7.14, and the obtained results of measurements are shown in Fig. 7.15.

As results from these tests (Fig. 7.15), the greater strain rate the much greater values of σ_M (R_c), $\sigma_{0,02}$ ($R_{c0,2}$) and $\sigma_{0,02}$ ($R_{c0,02}$), whereas values of Young modulus (E) are only slightly dependent on strain rate. Detailed descriptions and results of the experimental tests in question are contained in the publications [121, 124, 125].

7.8. Research on influence of elevated temperature on characteristics of EPY compound and values of selected compression strength parameters

The research was aimed at determination of influence of elevated temperature (ranging from 30 to 160°C) on mechanical characteristics of EPY compound post-cured in various temperatures (from 40 to120°C for 2 h) as well as values of its crucial strength parameters which can be determined in compression test.

The mechanical characteristics of EPY compound under compression at various testing temperatures and with various strain rates were determined with the use of 8501 Plus INSTRON testing machine equipped with a thermal chamber. The tests were conducted on cylindrical specimens (of 20 mm diameter and 25 mm height) post-cured for 2 h at different temperatures in the range from 40 to 120°C (changing in 20°C intervals) and previously cured at 22 ±1°C temperature for 24 h.

Before starting the compression test at an assigned temperature (changing in 10°C intervals with ±1°C accuracy, in the range from 30 to 160°C) the specimens were kept in the thermal chamber of testing machine to heat them thoroughly, and their heating period (5÷30 min) was determined on an auxiliary specimen fitted with a thermocouple.

The so prepared series of specimens (each of 5 pieces) underwent uniaxial compression test (in the chamber) up to their damage. The tests were conducted with the strain rate $\dot{\varepsilon}$ of values varying in the range from 0.0208 to 20.8 min^{-1} (equivalent to machine's piston travelling speed in the range from 0.13 to 130 min^{-1}). The compression test diagrams and values of selected strength parameters related to initial cross-section areas of specimens, were determined. Results of the experimental tests on EPY compound are in detail presented in the publications [87, 93, 120, 123÷125]. Some results of the compression tests are shown in Fig. 7.16 through 7.24.

Fig. 7.16 shows the averaged compression characteristics of EPY compound specimens post-cured at 80°C temperature for 2 h, which were determined in different measurement temperatures (23÷160°C), with the standard strain rate of 0.208 min^{-1}. General runs of the curves in stress—strain coordinate system, which were obtained in the measurement temperatures up to 100°C, maintain their typical shape. After its initially fast rise (linear elastic stage) the compression curve ”bends” to form a characteristic knee whose middle point corresponds to the yield point σ_y of the material at a given temperature. The curve then goes through a slightly elevating plateau ("plastic" flow stage with some strengthening) ended with a gentle peak which determines value of maximum compression stress, called the compression strength σ_M, and then the curve drops sharply (damage stage). The compression curves (Fig. 7.16) determined in the temperatures ranging from 110 to 160°C, are of a completely different course. From the very beginning of the test the strains reach high values and are of elastic – plastic character. They increase almost linearly until the peak which determines the compression strength σ_M is reached, afterwards the damage stage follows. The obtained results indicate that the compression strength σ_M of the compound and its yield point σ_y distinctly decreases along with the measurement temperature decreasing.

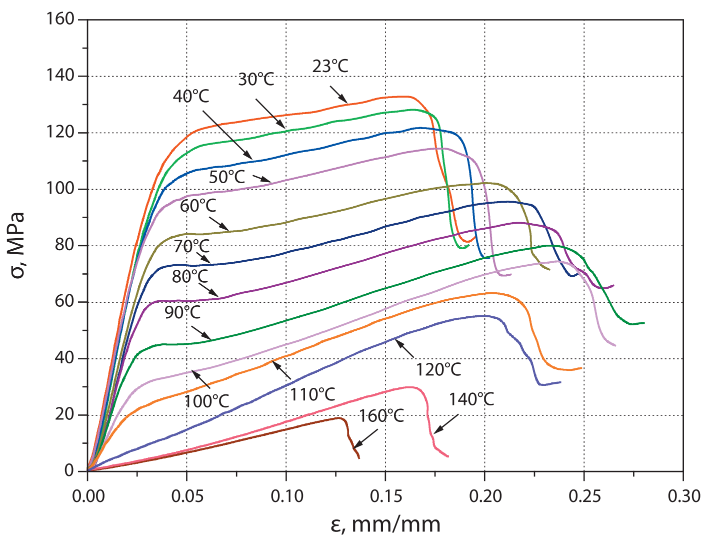


Fig. 7.16. Compression characteristics of specimens made of EPY compound post-cured at 80°C temperature for 2 h, determined at standard strain rate (0.208 min^{-1})

Fig. 7.17 shows (in function of temperature) values of the selected strength parameters (σ_M, $\sigma_{0,2}$, $\sigma_{0,02}$, E) and their standard deviations, determined during the compression tests on EPY compound specimens (see Fig. 7.16). As expected, Young modulus of elasticity E distinctly decreases along with the measurement temperature increasing. On the level of the glass transition temperature (T_g = 95.6°C) of EPY compound (post-cured in 80°C for 2 h) and the fully cross-linked compound temperature ($T_{g\infty}$ = 111.2°C) (see Ch. 3, Subsection 3.3.2 and Ch. 7, Subsection 7.5), values of the elasticity modulus E, distinguished by arrows in Fig. 7.17, are over one and a half and threefold smaller, respectively, than those in 23°C temperature. The significant drop of values of E — modulus in temperatures exceeding T_g results from that cross-linking density decreases, because of heating, as a result of disintegration of second-order links [118] which constitute a peculiar stiffening for the network. This way, the setting of the chain segments in motion and the sliding of greater clusters of macro-particles become possible, that results in worsening strength parameters of the compound. Therefore, the greater the measurement temperature the much smaller values of the strength parameters in compression (σ_M, $\sigma_{0,2}$ and $\sigma_{0,02}$).

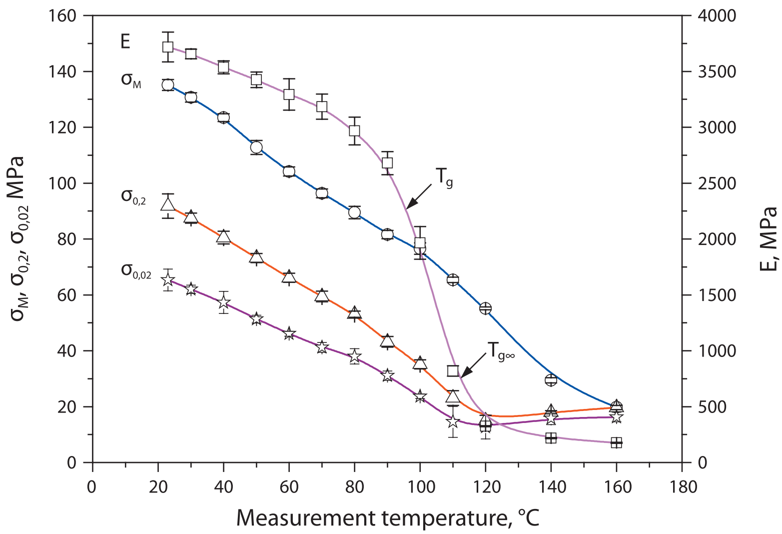


Fig. 7.17. Values of selected strength parameters of EPY compound post-cured at 80°C temperature for 2 h, determined in the compression tests presented in Fig. 7.16, at various temperatures; the given values of T_g and $T_{g\infty}$ were determined from DSC instrument at 10°C/min (see Ch. 3, Subsec. 3.3.2 and Ch. 7, Subsec. 7.5)

Fig. 7. 18 presents, in function of ($T–T_g$), the compression strength σ_M experimentally obtained at successive measurement temperatures T, for EPY compound post-cured in 80°C temperature for 2 h (Fig. 7.17). Results of the measurements can be generally expressed by a simple mathematical relation (at correlation coefficient $R^2 = 0.997$) [120]:

$$\sigma_M = -0.8193\,(T - T_g) + 76.24 \tag{7.8}$$

where: T_g — glass transition temperature; for EPY compound post-cured at 80°C temperature for 2 h, $T_g = 95.6$°C (see Subsection 7.5).

Runs of the curves shown in Fig. 7.19 in stress-strain coordinate frame, which illustrate performance of specimens of EPY compound post-cured (at 80°C for 2 h), during

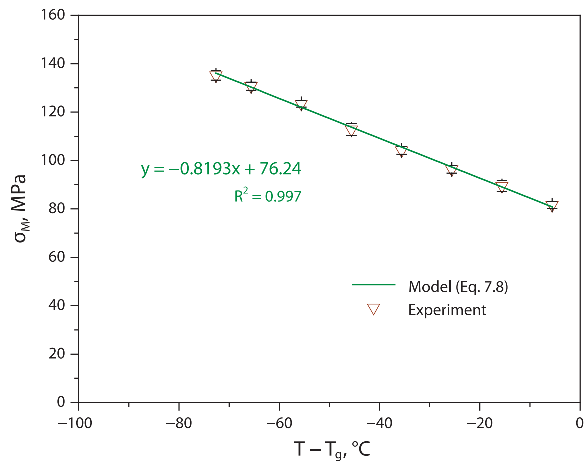


Fig. 7.18. Compression strength (σ_M) of EPY compound post-cured at 80°C temperature for 2 h, in function of ($T-T_g$), experimentally determined at standard strain rate and that calculated acc. Eq.(7.8)

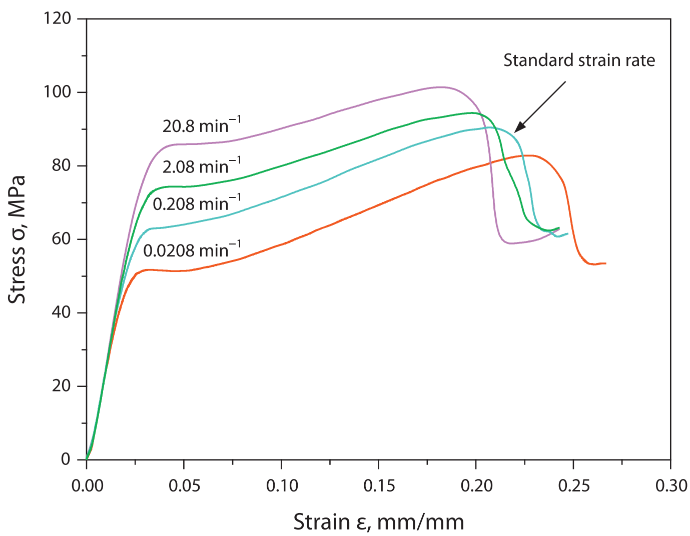


Fig. 7.19. Sress-strain curves ($\sigma - \varepsilon$) of EPY compound post-cured at 80°C temperature for 2 h, determined in compression tests at 80°C temperature and various strain rates

compression test at the measurement temperature of 80°C, and various values of the strain rate $\dot{\varepsilon}$ in the range from 0.0208 to 20.8 min^{-1}, indicate that the compound is very sensitive to changes in strain rate.

Measurement results for the selected strength parameters (σ_M, $R_{c0,2}$, $R_{c0,02}$ and E) of the tested compound in relation to four different values of the strain rate $\dot{\varepsilon}$, are shown in Fig. 7.20. It may be clearly observed that the greater values of $\dot{\varepsilon}$ the much greater values of σ_M, σ_y, $R_{c0,2}$ and $R_{c0,02}$, whereas value of Young modulus of elasticity (E) shows only a slight dependence on strain rate.

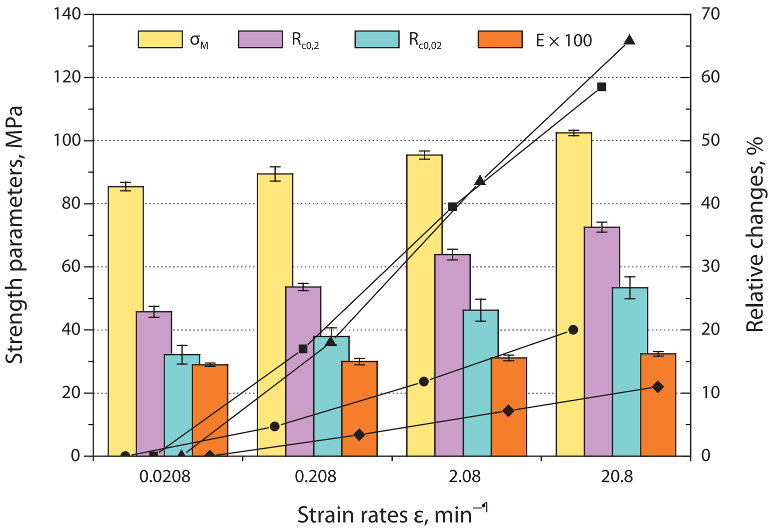


Fig. 7.20. Collected values and relative changes of selected strength parameters of EPY compound post-cured at 80°C temperature for 2 h, determined in compression tests at 80°C temperature and various strain rates

Fig. 7.21 shows the compression strength σ_M of EPY compound post-cured in 80°C for2 h, for different measurement temperatures (23÷100°C) and different strain rates (0.0208÷20.8 min^{-1}). As results from the tests (Fig. 7.21), σ_M linearly increases along with its strain rate logarithm increasing over the whole test range. It's worth mentioning, that slopes of the lines $\sigma_M = f(\dot{\varepsilon})$ decrease along with the compound's measurement temperature increasing. It indicates that its sensitivity to changes in strain rate decreases.

And, Fig. 7.22 presents the relation between Young modulus of elasticity E and measurement temperature (from 23°C to T_g + 20°C) for specimens of EPY compound post-cured in various temperatures (40÷120°C), determined on the basis of compression curves. As results from the tests (Fig. 7.22), Young modulus of elasticity E decreases along with both post-curing temperature and measurement temperature increasing. It's worth mentioning, that in ambient temperature (23°C) EPY compound cross--linked (post-cured) in too low temperatures (lower than 60°C) has approximately

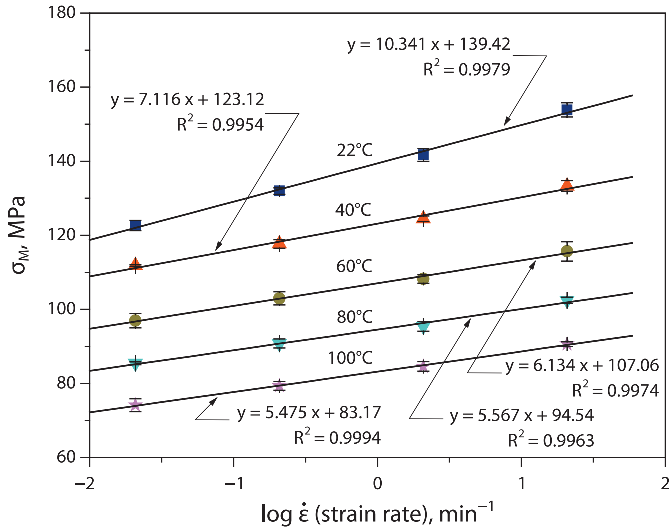


Fig. 7.21. Compression strength (σ_M) of EPY compound post-cured in 80°C for 2 h, in function of strain rate logarithm, determined at various measurement temperatures

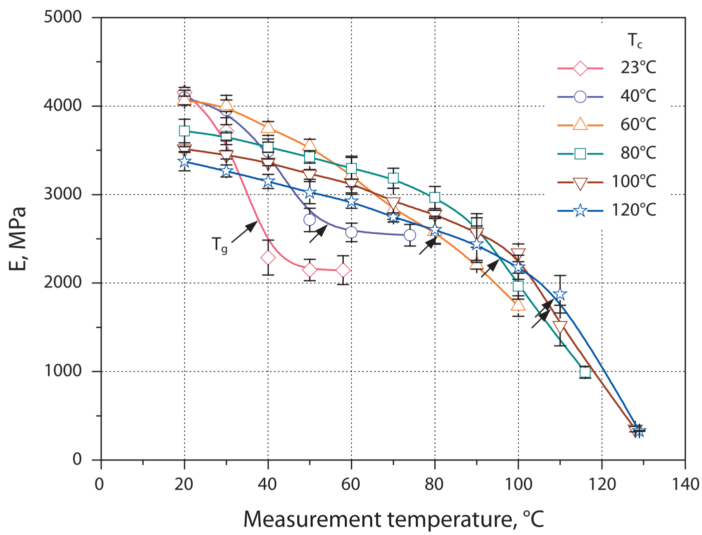


Fig. 7.22. Young modulus of elasticity (E) in compression for EPY compound post-cured at various temperatures, determined at measurement temperatures ranging from 23°C to T_g + 20°C); arrows indicate glass transition temperatures (T_g) [93]

the same value of E ≈ 4100 MPa. However, the compound cross-linked at rather low temperatures shows high sensitivity to changes in measurement temperature. A distinct drop in values of E-modulus takes place only at a greater cross-linking density. On the level of the glass transition temperature T_g (distinguished with arrows in Fig. 7.22), value of E-modulus of the compound is about 1½-fold lower than that in the temperature of 23°C. The significant drop takes place in value of E-modulus at temperatures exceeding T_g, as it was already mentioned, as a result of disintegration of second-order links within the compound [118], that makes setting the chain segments in motion and sliding greater clusters of macro-particles, possible, and causes strength properties of the compound to worsen. Comprehensive descriptions and results of the tests are contained in the publication [93].

Fig. 7.23 presents values of the yield point σ_y in compression of EPY compound post-cured in various temperatures (from the range of 40÷120°C), determined in a wide range of measurement temperatures (from 23 to T_g + 20°C). In view of legibility of the figure, standard deviations of the yield point σ_y have not been inserted to it because of their rather low values (less than 3 MPa). Value of the yield point σ_y of the compound increases along with post-curing temperature increasing and decreases as the measurement temperature increases. It should be noticed (Fig. 7.23) that the relations $\sigma_y = f(T)$ have generally a linear form up to the glass transition temperature (T_g) for the compound post-cured in temperatures $T_c \geq 60$°C.

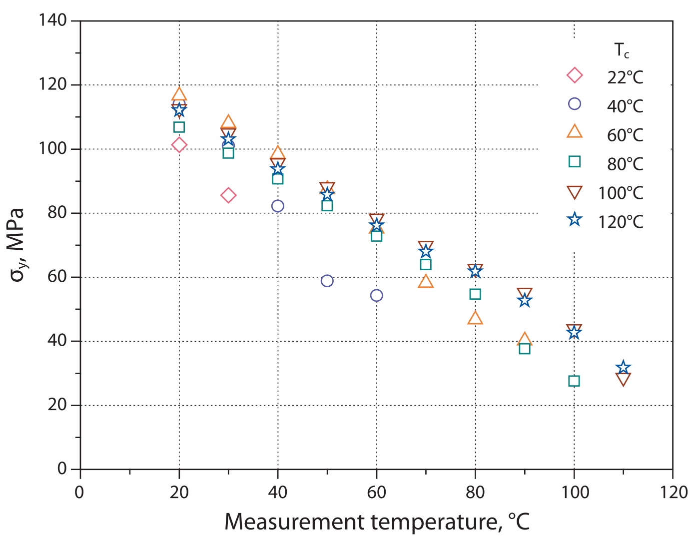


Fig. 7.23. Yield point (σ_y) in compression for EPY compound post-cured at various temperatures (40÷120°C), determined at measurement temperatures ranging from 23°C to T_g + 20°C)

Values of the function $\sigma_y = f(T)$ shown in Fig. 7.24 in the form of $\sigma_y = f(T–T_g)$, and also $\sigma_y = f(T/T_g)$, for the compound post-cured in various temperatures (read from Fig. 7.23), allow to clearly demonstrate influence of the glass transition temperature (T_g) on plastic performance of the tested compound.

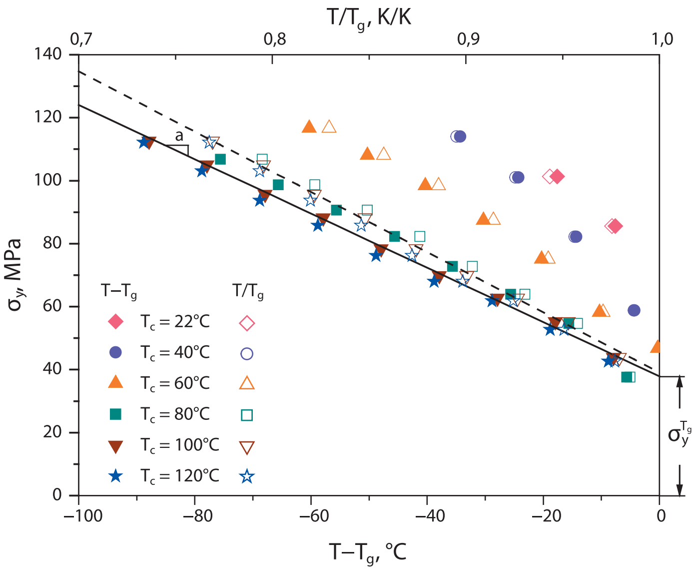


Fig. 7.24. Yield point (σ_y) in compression in function of measurement temperature, obtained by shifting or normalizing the function argument by value T_g ($T–T_g$ or T/T_g), for EPY compound post-cured at various temperatures (40÷120°C); parameter "a" determines slope of tangent lines for $T < T_g$, and $\sigma_y^{T_g}$ is the yield point extrapolated up to T_g (Eq. 7.10)

The relations $\sigma_y = f\,(T–T_g)$ for different T_c (Fig. 7.24) run in such a way, depending on cross-linking density of the compound, that for a given ($T–T_g$) the yield point takes a greater value only when compound cross-linking density is lower. Moreover, in Fig. 7.24 it can be observed that the relations $\sigma_y = f\,(T–T_g)$ tend to run linearly at higher values (≥ 80°C) of post-curing temperature of the compound, i.e. at higher values of its cross-linking density ($0.98 < \alpha < 1$) [93]. The linear form which may be obtained with the help of shifting the argument of the function $\sigma_y = f\,(T)$ by value of T_g, allows to describe plastic performance of the compound, especially that post-cured at higher temperatures, by means of a simple algebraic equation.

In case of rather low cross-linking (post-curing) temperatures of the compound ($T_c \leq 60$°C), when values of the yield point σ_y do not run along a straight line (Fig. 7.24), it may be concluded that the yield point value will be affected in a different way by a change in testing temperature T, and even more differently by a change in T_g temperature. It means that chemical shift (change in cross-linking density) leads to an effect which is distinctly different from the simple shifting of measurement temperature with respect to T_g.

Dependence of the yield point σ_y of thermo-curing compound on the temperature difference $(T–T_g)$, shown in Fig. 7.24, may be approximated by means of an empirical equation proposed by Lesser [119]:

$$\sigma_y = a\left(T - T_g\right) + \sigma_y^{T_g} \quad \text{dla } T < T_g \tag{7.9}$$

where: $\sigma_y^{T_g}$ — yield point at T_g ; a — coefficient which describes linear decrease of σ_y, when T drops below T_g.

Owing to the empirically determined values of the yield point σ_y for EPY compound of high cross-linking density ($\alpha > 0.98$) [93] and the glass transition temperatures determined by means of DSC method, it was possible to transform the relation (7.9) into the form as follows:

$$\sigma_y = -0.8617\,(T - T_g) + 37.88 \tag{7.10}$$

Due to a good conformity obtained between results of experimental tests and calculations (with the correlation coefficient $R^2 = 0.987$) (Fig. 7.24) the equation (7.10) may be used in practice for foretelling yield point values of EPY compound post-cured at the temperature from the range ($80 < T_c < 120$°C), in function of measurement temperature. Comprehensive descriptions and results of the tests are contained in the publication [93].

Fig. 7.24 presents also, by means of an additional axis of abscissae, the considered values of the yield point σ_y in the reference frame normalized with respect to T_g value. Location of respective data in the normalized reference frame $\sigma_y = f(T/T_g)$ (open symbols) is very similar to that in the reference frame $\sigma_y = f(T - T_g)$ (full symbols). It results from simple transformation: $(T - T_g)/T_g = (T/Tg) - 1$, which shifts a little the data and makes them forming a broken line (Fig. 7.24) with a greater slope. Such normalization of the data allows to relate epoxy system's plasticity to one of its inherent features, i.e. T_g, that facilitates the analyzing of plastic performance of compound.

The mechanical characteristics of EPY compound, obtained from the tests, indicate that its performance and values of the crucial strength parameters: (σ_M, $R_{c0,2}$, $R_{c0,02}$, σ_M, E) greatly depend on measurement temperature, as values of all the determined strength parameters decrease along with its rising up to the glass transition temperature ($T_{g\infty} = 111.2$°C).

The equations in the form (7.8) and (7.10) correctly describe the dependence of the compression strength σ_M and yield point σ_y of EPY compound on measurement temperature, respectively, and may be used advantageously in engineering practice.

7.9. Research on susceptibility of EPY compound to deformation under constant compression load at various heating rates

The tests were aimed at identification of symptoms and determination of influence of EPY compound heating rate on deformations under constant load, as a result of the so called softening. Possible occurrence of the softening of chocking compound is a serious drawback which may be very hazardous to objects to be seated on chocks; therefore some measures should be taken to prevent against its occurrence in machinery seating arrangements with the use of the compound.

The tests were carried out on cylindrical specimens of the dimensions: 20 mm in diameter and 25 mm in length. The specimens, after their casting in steel moulds, were cured at the temperature of 22 ±1°C for 24 h, and a part of them was then post-cured at the temperature of 80°C for 2 h.

The 8501 Plus INSTRON testing machine fitted with the thermal chamber (Fig. 7.25) and WAVEMAKER, special software was used for the test on the softening of EPY compound. Compression load was generated on tested specimens according to a uniform procedure which consisted in its linear rising with the rate of 0.314 kN/s (i.e. within 5 s up to the assigned load value of 1.57 kN) and next maintaining it (with 0.5% accuracy) for the period of temperature rising from 25 to 120°C. The

Fig. 7.25. Test stand for determining compound deformation characteristics under constant compression at increasing temperature

assumed load generated the compression stresses σ = 5 MPa in specimens. It corresponds to the maximum permissible stress value applied to calculations of seating arrangements of shipboard machinery. The tests were conducted at various heating temperature rates: 5, 10, 20, 40 and 60°C/h.

Process of the conducting of particular tests in the assumed conditions and recording of their results was controlled by a WAVEMAKER, special computer software. Measured values of the force F and deformations Δh were recorded with an appropriate frequency in ASCII files which were then transferred to EXCEL spreadsheet to be properly processed there and prepared for graphical presentation in the form of run of particular tests and their results. The test results are graphically presented in Fig. 7.26 and 7.27.

Fig. 7.26 shows test results of specimens cured at the temperature of 22 ±1°C for 24 h, without any post-curing. Particular curves of this figure illustrate runs of deformations in function of temperature for different heating rates of specimens (5÷60°C/h). The so cured specimens reach a relatively high compression strength (σ_M = 97.2 MPa), good elastic properties ($R_{c0,02}$ = 63.9 MPa) and high value of modulus of elasticity (E = 4331.2 MPa). A longer curing time in this temperature only a little improves the properties. From the practical point of view, these properties are very suitable for the material intended for foundation chocks of machines which operate in temperatures up to about 45°C. Unfortunately, in temperature over 45°C the properties deteriorate to a large extent. The compound ″softens″, and in consequence of the achieved features characteristic for an elastic-plastic-viscous material it yields to large permanent deformations even under low pressure (σ = 5 MPa).

As results from the conducted tests (Fig. 7.26), run and range of deformation values substantially depend on heating rate of the compound. During the heating of specimen to which a small, constant compression load is applied (σ = 5 MPa), two opposite macro-processes take place in it: its lengthening due to thermal expansion and its shortening due to creeping. Intensity of the two processes is different at different heating rates. At low heating rates (5, 10 i 20°C/h) an increase of specimen's height initially occurs. It means that the effect of creeping is lower than the effect of heating which results in increasing height of specimen. At higher heating rates (in the range of 40÷60°C/h) a state of balance between deformations resulting from temperature rise and creeping deformations takes place initially. It lasts up to some critical temperature at which more or less violent process of creeping starts. During the process specimen yields to large deformations. Critical temperature and creeping rate distinctly depend on heating rate of specimens. Deformation which then occurs, is of elastic-plastic-viscous character, an undesired effect, commonly called "softening" of the compound. At low heating rate (5°C/h) the critical temperature (of softening) reaches about 45°C. Intensity of creeping process and its range are then relatively low. Therefore, foundation

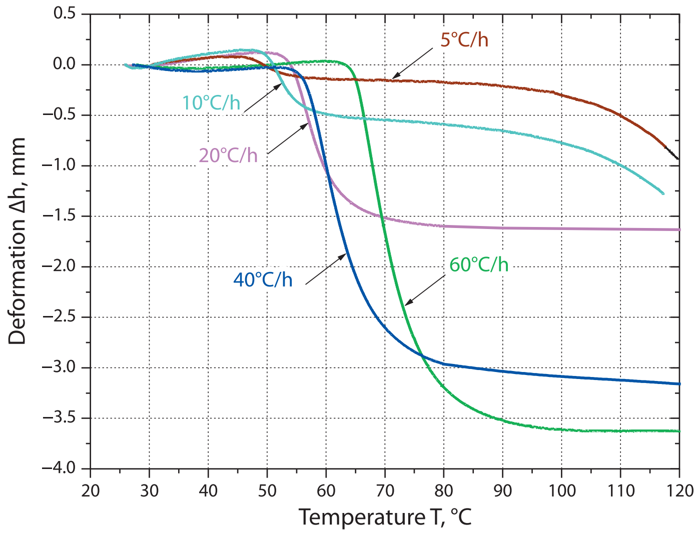


Fig. 7.26. Deformations (Δh) in function of temperature at various heating rates for EPY compound cured in 22 ±1°C for 24 h, under constant compression load (σ = 5 MPa)

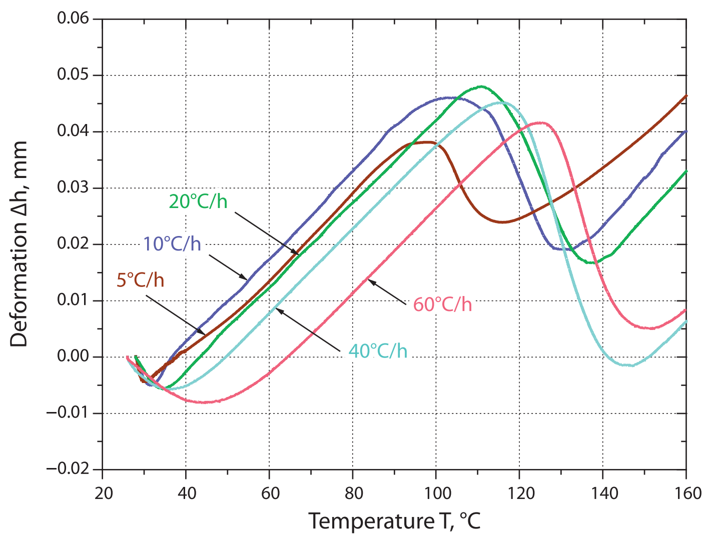


Fig. 7.27. Deformations (Δh) in function of temperature at various heating rates for EPY compound post-cured (in 80°C for 2 h), under constant compression load (σ = 5 MPa)

chocks should operate in a temperature lower than 80°C, reached with as low as possible heating rate, in order to protect them against excessive deformations in service. Such requirement for foundation chocks of resin compound has been formulated by classification societies which supervise building process of sea-going ships [41, 42]. As heating rate increases, critical temperature at which softening starts, a little increases too, and also intensity of creeping process and its range substantially rises. At the heating rate of 60°C/h, the critical temperature reaches about 63°C (Fig. 7.26).

Casting and curing processes are subject to a suitable control, in order to eliminate danger of occurrence of the softening of foundation chocks during operation of an object seated on them. According to the requirements of classification societies [41, 42, 126] during curing process of foundation chocks cast in ambient temperature, their exotherme should reach — in a natural way (owing to exothermal features of cross-linking process of epoxy system) — its peak value of about 80°C. In practice of the conducting of machinery seating operations, if to fulfill the condition in a natural way is not possible, the after-baking of chocks by heating them from external energy sources, e.g. warm air blowing, is applied.

To check influence of heating the compound on occurrence of softening phenomenon, the tests were also carried out on specimens post-cured at the temperature of 80°C for 2 h. The tests were conducted in the same loading and heating conditions as previously. Fig. 7.27 shows results of the tests. They illustrate performance of the post-cured specimens subject to a rather small, constant compression load ($\sigma = 5$ MPa), at different heating rates. In this case the deformation characteristics in function of temperature have entirely different run than in the case of not-post-cured specimens (Fig. 7.26). Initially, just after starting the heating process (to temperature of 23°C), a rather small shortening of specimens, distinctly dependent on heating rate, is observed. Next, a distinct, more or less linear rise of height of specimens occurs up to some temperature (in the range from 95 to 125°C), depending on heating rate.

The initial decrease in height of specimen (Fig. 7.27) may be explained by occurrence of creeping process and a lag in heating the specimen within its entire volume. The lag grows along with heating rate increasing in thermal chamber where a tested specimen is placed. Thermal expansion effect which occurs with certain delay, subsequently dominates in the period of the tests. It may be approximately assumed that thermal expansion coefficient in the temperature range of 20÷90°C for post--cured specimen is of a constant value (see Subsection 7.10). For this reason runs of deformations (Fig. 7.27) are approximately linear and parallel to each other in the above mentioned range of temperature.

On the basis of the conducted tests it may be concluded that in the compound post-cured in 80°C temperature for 2 h, a weakening of softening effect and its shifting towards a higher temperature within the range of 90÷150°C, depending on heating rate, takes place. (Fig. 7.27). This way, such after-baking eliminates possible occurrence of this dangerous effect in service conditions of shipboard machinery foundation chocks where their temperature is in the range from 20 to 80°C. As results from the tests (Fig. 7.27), the ultimate operational temperature value of foundation chocks cast of EPY compound may be assumed to be 90°C. It means that in this value some safety margin is practically contained.

The above described phenomenon of softening and limitations resulting from it concern also epoxy compounds of other kinds applicable to machinery foundation chocks.

7.10. Research on thermal linear expansion of EPY compound

In order to foretell and analyze performance of EPY compound i various conditions of its use, apart from many other thermo-mechanical properties, knowledge of its thermal expansion is also needed. To this end, appropriate investigations concerning the relative elongation $\Delta L/L_0$ were performed on specimens made of EPY compound cured at 23°C for 24 h, and subsequently post-cured at 80°C for 2 h. Fig. 7.28 shows a test stand prepared according to the authors' own design project, and described in the publications [127, 128]. The project was based on the recommendations of ASTM D 696 standard according to which a measurement system was built and

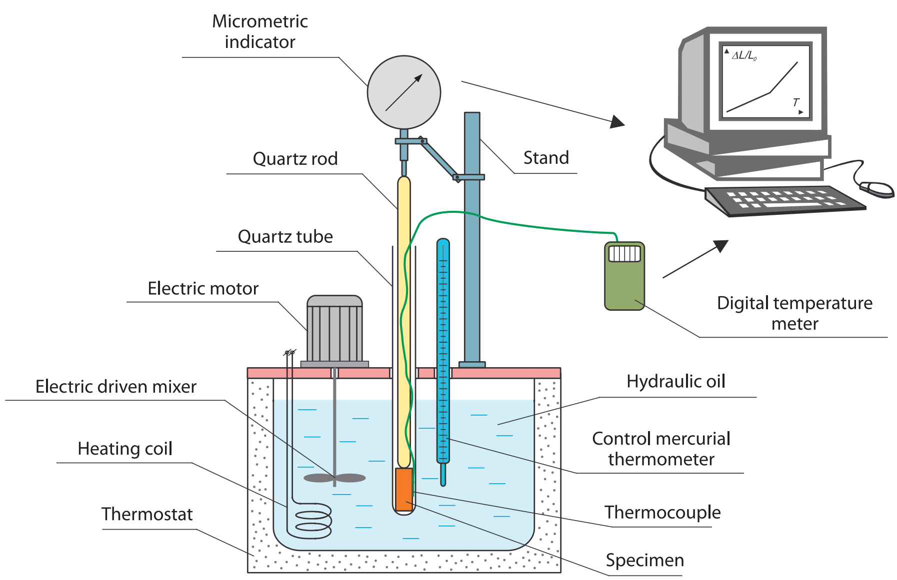


Fig. 7.28. Schematic diagram of test stand for measuring linear thermal expansion of resin compound

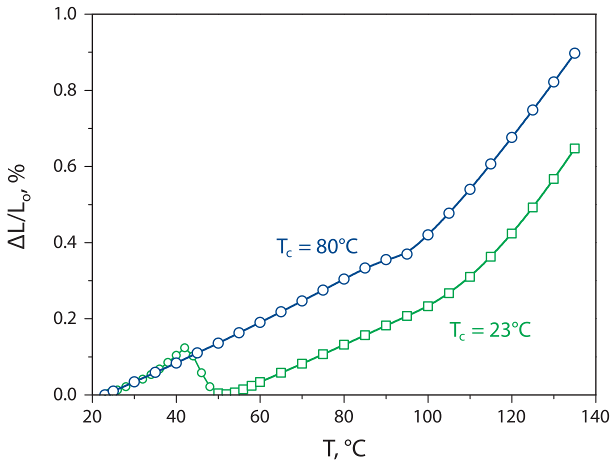


Fig. 7.29. Relative elongation ($\Delta L/L_o$) in function of temperature for EPY compound specimens cured at 23°C for 24 h and post-cured at 80°C for 2 h

a measurement procedure was adopted. During the tests specimens were heated from 23 up to 135°C, with the rate of 1.5°C/min. Fig. 7.29 and 7.30 present results of the investigations.

Fig. 7.29 shows values of the relative elongation $\Delta L/L_0$ for EPY compound specimens during their heating. In the case of not-post-cured compound, when heating temperature reaches about 42°C, slope angle of the curve $\Delta L/L_0$ undergoes a radical change, which is a symptom of glass transition, and the slope reverse point of the curve $\Delta L/L_0$ may be used for determination of value of the glass transition temperature (T_g) of the material in its curing state. Within the range of temperature from 42 to 52°C, where the reverse of slope angle of the curve $\Delta L/L_0$ takes place, the compound yields to chemical shrinkage. When the heating is continued, the compound undergoes further cross-linking as temperature rises, and run of the curve $\Delta L/L_0$ becomes similar to that of the curve determined for an post-cured compound. And, in the run of the curve $\Delta L/L_0$ for the compound post-cured (at 80°C for 2 h) the point of a violent change in its slope angle may be indicated (at the temperature close to 95°C), which may also serve for determining T_g value of the material in a given state of post-curing. The so determined T_g values of the compound in the tested curing state are equal to 42 and 96.5°C, respectively, and are in a good conformity with those obtained by using DMTA method [127]. The precise tracking down of $\Delta L/L_0$ values in the range of interest of $T < T_g$ reveals their non-linear relation to temperature (Fig. 7.29) hence a certain variability of the coefficient of thermal linear expansion (α).

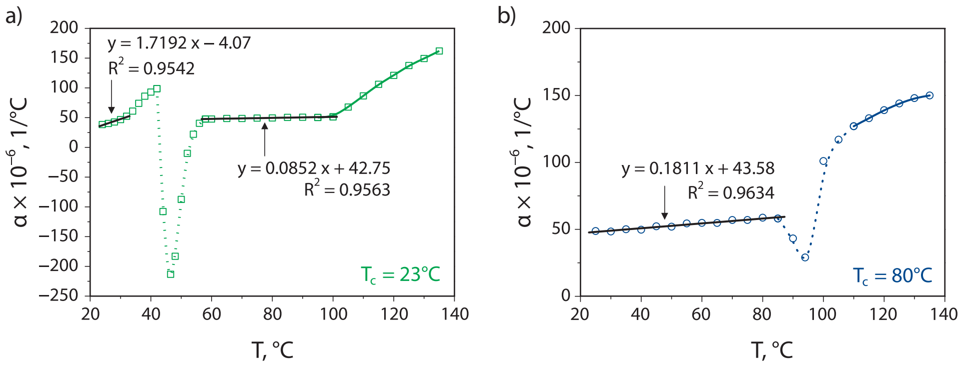


Fig. 7.30. Thermal linear expansion coefficient (α) in function of temperature for EPY compound: a) cured at 23°C for 24 h, b) post-cured at 80°C for 2 h

Fig. 7.30 shows values of the coefficient of thermal linear expansion α for EPY compound in function of temperature, calculated by means of the formula (7.11):

$$\alpha_{T_1}^{T_2} = \frac{\Delta L}{L_0 \cdot \Delta T} \tag{7.11}$$

where:

ΔL — a change in length of specimen caused by change in its temperature by ΔT, mm,
L_0 — initial length of specimen at room temperature (23°C), mm,
ΔT — a rise of temperature from T_1 to T_2, after which change in specimen's length was measured, °C.

At temperatures below the beginning of glass transition, both in case of the not-post-cured and post-cured compound, a rather small increase in value of the coefficient α takes place.

For the not-post-cured compound the coefficient α increases from 38.3×10^{-6} to 52.3×10^{-6} 1/°C in the temperature range of 23÷32°C (Fig. 7.30a), and its mean value reaches 44.1×10^{-6} 1/°C. In this range, α-value may be approximated with the use of the following equation:

$$\alpha = 1.7192 \times 10^{-6} - 4.07 \times 10^{-6}\,T \qquad (1/°C) \tag{7.12}$$

in which T is given in Celsius degrees. Coefficient of correlation (R^2) equals 0.954.

And, for the post-cured compound α- value increases from 48.8×10^{-6} to 58.1×10^{-6} 1/°C (Fig. 7.30b) in the range of 23÷85°C and may be approximated by the equation as follows:

$$\alpha = 0.11811 \times 10^{-6} + 43.58 \times 10^{-6}\,T \qquad (1/°C) \tag{7.13}$$

with the coefficient of correlation (R^2) equal to 0.963. In the temperature range of 20÷80°C, which corresponds to the range of temperature in which ship machinery foundation chocks made of EPY compound usually operate, the mean value of the coefficient α is equal to 53.2 × 10^{-6} 1/°C. This value corresponds to that of the thermal linear expansion coefficient (50 × 10^{-6} 1/°C) required, according to Lloyd's Register of Shipping [42], for epoxy compound working in the temperature range typical for ship machinery foundation chocks.

The beginning of glass transition is manifested by a departure from the linearly approximated rise of the coefficient α, observed both in the case of the not-post-cured and post-cured compound in 32 and 85°C temperature, respectively, (Fig. 7.30a and b). When the temperature T_g is reached, molecular mobility of polymer chains grows and a glassy "rigid body" becomes viscous-liquid, which is manifested by a sudden change of the coefficient α, as shown in Fig. 7.30a and b. The not-post-cured compound undergoes after-baking during measurement process. The temperature T_{gM} is reached close to the value of 100°C (Fig. 7.29 and 7.30a). In the temperature range of 58÷100°C α-values continue to grow rather slightly from 47.6 × 10^{-6} to 51.3 × 10^{-6} 1/°C (its mean value equal to 49.4 × 10^{-6} 1/°C). Beginning from the temperature of about 95÷100°C, the coefficient α both for the not-post-cured compound and post-cured one, rises violently, reaching, at the measurement ending temperature (135°C), the values of about 162 × 10^{-6} and 150 × 10^{-6} 1/°C, respectively, (Fig. 7.30a and b).

According to ASTM D 696 standard, the thermal linear expansion coefficient is not required to be determined in the glass transition range in which the softening of compound occurs, i.e. 26÷58°C and 82÷105 °C for the not-post-cured compound and post-cured one, respectively, (Fig. 7.30a and b). Nevertheless, in Fig. 7.30 it is shown (by dotted line) how big contraction takes place in the glass transition temperature range.

Difference between values of the coefficient α for EPY compound and metal (five times in case of steel: α = 11 × 10^{-6} 1/°C [42]) is of a great practical importance as it contributes in generating thermal stresses in compound-metal joints. In application of the compound to foundation chocks, the stresses have a favourable effect on fastening the seated objects as they increase a little tension in holding down bolts.

7.11. Research on creep process and heat bending deflection temperature of EPY compound

EPY compound is characterized not only by good properties of compression strength but also high creep resistance in elevated temperatures.

Creep resistance of any compound is a crucial factor which limits the permissible pressure and operational temperature of foundation chocks. Their permissible values were determined on the basis of results of long-term creep tests of compound, carried out at different values pressure and temperature.

Creep tests were conducted in accordance with ASTM-D621 standard by using creep testing machines designed and manufactured specially for this purpose at the Technical University of Szczecin (Fig. 7.31).

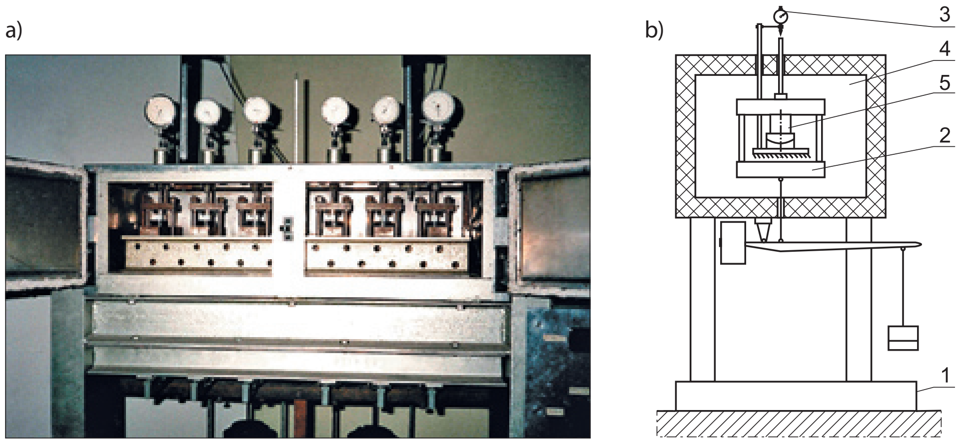


Fig. 7.31. Creep testing machine intended for chocking compound tests: a) overall view; b) simplified drawing: 1 — base, 2 — specimen counterweight, 3 — specimen deformation (changes in height ΔH) measuring system with dial indicator (of 0.001 mm accuracy), 4 — thermal chamber, 5 — tested specimen

Specimens used in the tests had the dimensions: 12.7 × 12.7 × 12.7 mm. They were cast in special moulds and cured in various ways: at room temperature (23°C) for 24 h without any additional heating or with additional heating for 4 h at temperatures ranging from 50 to 90°C. Additional creep tests were carried out on specimens of the same dimensions cut out from a foundation chock of 300 × 300 × 40 mm, cast between two steel plates 14 mm thick.

All creep tests at temperatures from 50 to 90°C were done under compressive stress of 5 MPa. Specimens were put into the chamber of a creep testing machine at ambient temperature (about 23°C) and loaded to a compressive stress equal to 5 MPa. Sensors were set to zero and the temperature started to increase at a rate of about 8°C/h until the assumed test temperature was reached. Readings of the sensors were recorded during the heating and the testing when the assumed temperature was reached. Creep curves were drawn on the basis of mean values calculated from records of three specimens. The tests took 500 h to complete. The example creep curves are shown in Fig. 7.32 through 7.34. The detail results of all tests are contained in the report on creep tests [130].

As results from the curves (Fig. 7.32÷7.34), at the beginning, during the heating of specimens in the creep- testing machine, their height rises as a result of thermal expansion of the compound. The rise is higher than the concurrent creep. Creep process is characteristic for all resin compounds and evidently present during the first period (a few dozen of hours) of load action. In the case of the tested compound, the process slows down considerably after 200 h and almost stops after 500 h. The rate of creep for EPY compound depends mainly on the temperature at which specimens

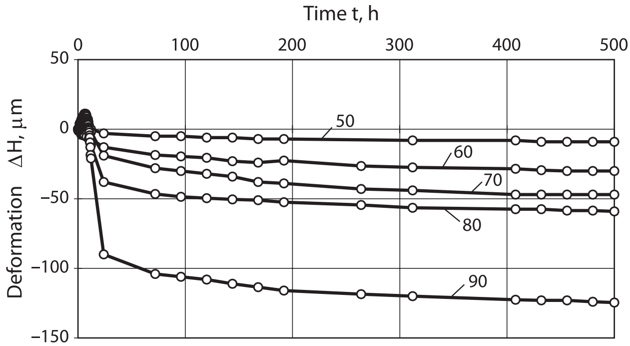


Fig. 7.32. Creep curves of EPY compound at various temperatures for specimens cast in moulds and cured for 24 h at 23°C + 4 additional hours at 80°C

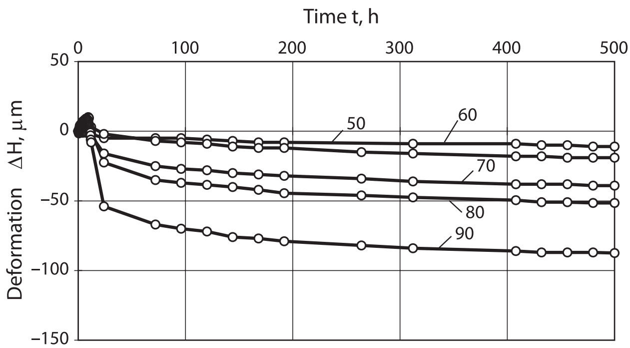


Fig. 7.33. Creep curves of EPY compound at various temperatures for specimens cast in moulds and cured for 24 h at 23°C + 4 additional hours at 90°C

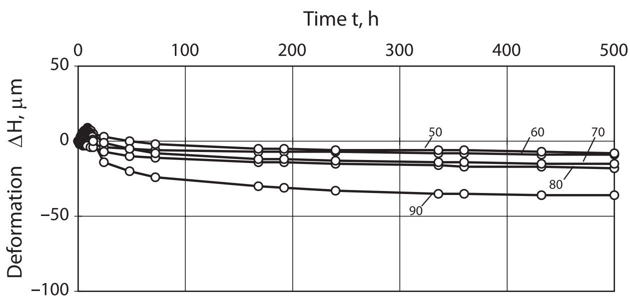


Fig. 7.34. Creep curves of EPY compound at various temperatures for specimens cut out from a foundation chock of 300 × 300 × 40 mm cast between steel plates at ambient temperature of 23°C, and cured for 30 h

are cured, and also on the temperature of the test. Low creep of specimens cut out from the chock (Fig. 7.34) results from the high temperature of compound exothermal point (about 90°C), which was reached when the compound was cured.

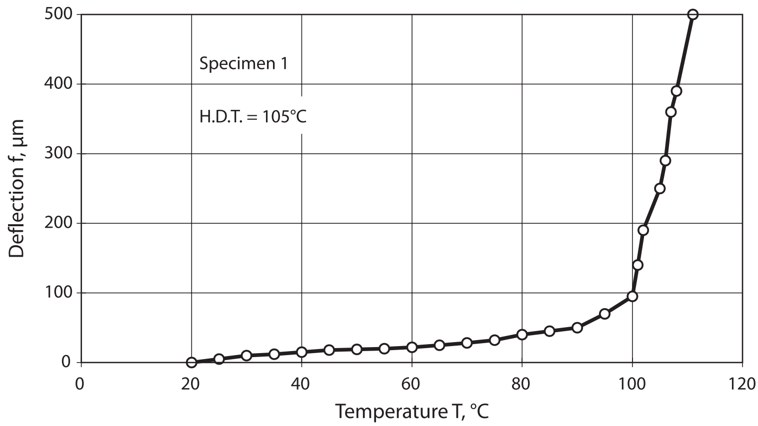


Fig. 7.35. Thermal deflection curve for EPY compound specimen

The heat bending deflection temperature of EPY compound under load was determined in accordance with the guidelines given in ASTM-D-648-82 standard. The specimens were cast ready-to-use in steel moulds. Their dimensions were: the length l = 127 mm, height h = 12.7 mm, breadth b = 5.5 mm. They were cured for 24 h at 20°C and then for 4 h at 80°C. The specimens were symmetrically supported in two points and bent with transverse force applied in the mid-length, generating bending stress of σ_g = 1.8 MPa. Bending test was performed in the chamber filled with heated air. The temperature was measured by means of thermometers placed close to the specimen. The bending deflection temperature (acc. ASTM-D-648-82 standard) for three tested specimens was equal to: 105°C, 102°C and 105°C [130]. Exemplary diagram which illustrates run of specimen bending in function of temperature is shown in Fig. 7.35.

7.12. Research on the influence of cooling down EPY compound in liquid nitrogen on its compression strength and impact resistance

The technological process of assembling the forced - in sleeves requires sometimes to cool them in order to properly reduce their diameters and make their assembling without use of any axial force possible. As a result, a so-called forced-in expansion joint is obtained [131]. In the case of rudder bearing liner, usually made of a special resin compound (called "Thordon"), its cooling down in liquid nitrogen of temperature as low as –195°C, is used. The so-cooled bearing liner is then inserted into a steel sleeve seated in frame with the use of EPY compound, and causes the steel sleeve and surrounding EPY compound to cool down significantly. Therefore, the question arose: whether the temporary, significant lowering of EPY compound temperature might cause its compression strength properties and impact resistance to drop. In order to answer this question, appropriate compression and impact tests were performed [132].

The compression test was conducted at room temperature in compliance with ASTM-D695-69 and PN-83/C-89031 standards by using 8501 Plus Instron testing machine and a computer software of the series IX "Automated Materials Testing System 7.03.00". Specimens for the test, of diameter d = 20 mm and height h = 25 mm, were cast in steel moulds, cured for 24 h at room temperature (23°C), post-cured for 2 h at 80°C, and then kept for 6 days at the room temperature again. After this time 6 specimens were selected out of the lot and cooled down for 10 min in liquid nitrogen (of temperature equal to about –195°C). The specimens, after they were taken out of liquid nitrogen, (Fig. 7.36) were left at room temperature for 4 h. Compression tests were then carried out on 5 non-cooled specimens and 5 cooled ones. Tab. 7.4 and 7.5 present results of the tests, in a form as achieved directly from the testing machine.

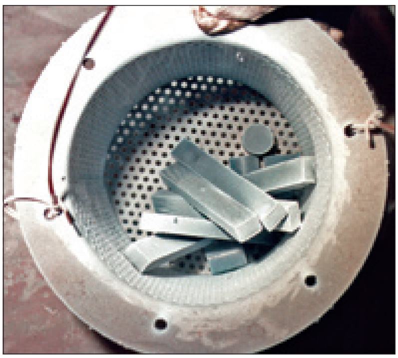


Fig. 7.36. EPY compound specimens after taking out from liquid nitrogen

The impact test was performed in accordance with PN-81/C-89023 standard at room temperature by using a Kogel-Leipzig impact testing machine (made in DDR) having an energy capacity of 0.4 kGm ≈ 3.924 Nm. Plain specimens of 10 × 15 mm rectangular cross-section and the length l = 120 mm, were used for the tests. The curing and then cooling down of the specimens in liquid nitrogen was performed in the same way as in the case of specimens for the compression test. Tab. 7.6 shows results of the tests.

On comparison of the test results contained in Tab. 7.4 and 7.5 as well as in Tab. 7.6, for specimens cooled in liquid nitrogen and not cooled down, it may be concluded that there are no significant quantitative differences between the respective results. By examining the compression test diagrams and the specimen fractures resulting from the impact test, no qualitative differences between the results, were observed

Table 7.4. Results of compression tests on EPY compound specimens not cooled down, as obtained directly from testing machine

No.	Load at Max. Load kN	Stress at Max. Load MPa	Strain at Max. Load mm/mm	Displacement at Max. Load mm	Modulus Aut Young MPa	Stress at offset Yield 1 MPa	Energy to Yield Point J
1	48.452	154.230	0.211	5.269	4491.805	92.522	8.949
2	49.010	156.007	0.209	5.221	4352.488	95.109	9.543
3	49.135	156.405	0.206	5.146	4549.125	94.041	8.937
4	48.768	155.238	0.211	5.271	4561.89	91.706	8.566
5	49.210	156.644	0.212	5.294	4480.378	92.058	8.763
Mean	48.915	155.705	0.210	5.240	4487.137	93.087	8.952
S.D.	0.309	0.982	0.002	0.059	83.109	1.439	0.366
C.V.	0.631	0.631	1.125	1.125	1.852	1.546	4.085

Table 7.5. Results of compression tests on EPY compound specimens cooled down in liquid nitrogen, as obtained directly from testing machine

No.	Load at Max. Load kN	Stress at Max. Load MPa	Strain at Max. Load mm/min	Displcement at Max. Load mm	Modulus Aut Young MPa	Stress at offset Yield 1 MPa	Energy to Yield Point J
1	49.806	158.541	0.218	5.442	4237.602	98.114	10.537
2	49.468	157.466	0.203	5.065	4447.826	94.976	9.325
3	49.623	157.957	0.213	5.315	4468.742	93.942	9.288
4	50.210	159.828	0.211	5.282	4617.564	93.836	8.827
5	48.393	154.044	0.181	4.517	4560.415	93.517	8.896
Mean	49.500	157.567	0.205	5.124	4466.430	94.877	9.375
S.D.	0.678	2.158	0.015	0.366	145.249	1.890	0.687
C.V.	1.370	1.370	7.133	7.133	3.252	1.993	7.331

Table 7.6. Results of EPY compound impact resistance tested on specimens both not cooled down and cooled down in liquid nitrogen

State of specimens	№ of specimen	Work to fracture, Nm	Impact resistance, kJ/m²	
			For particular specimens	Mean value
Not cooled down specimens	1	1.128	7.69	8.49
	2	1.422	9.85	
	3	1.079	7.32	
	4	1.471	9.89	
	5	1.226	8.05	
	6	1.226	8.14	
Specimens cooled down in liquid nitrogen	1	1.117	7.79	8.26
	2	1.079	7.14	
	3	1.570	10.52	
	4	1.422	9.27	
	5	1.079	7.15	
	6	1.128	7.68	

either. Therefore it may concluded that the short-term (lasting for 10 min) cooling down of EPY compound in liquid nitrogen (to about −195°C) has practically no influence on compression parameters and characteristics of the compound as well as its impact strength measured during the tests conducted at room temperature.

7.13. Research on the influence of constant humid heat on dielectric properties of EPY compound

The tests were performed in the Electrical Engineering Institute, Technical University of Szczecin [133]. They were aimed at determination of the long term effect of constant humid heat (Φ = 96%, T = 40°C) onto:

— dielectric loss,
— permittivity,
— through resistivity,
— dielectric strength,
— surface resistivity.

Experimental tests were conducted in compliance with the applicable Polish standards (Tab. 7.7). Flat, 3 mm thick disk specimens of 100 mm diameter were used for the tests. And, five specimens were tested in each test series. Tab. 7.7 shows the averaged results.

Table 7.7. Results of tests on the influence of constant humid heat (WGS) on dielectric properties of EPY compound

WGS h	Dielectric loss tg δ PN-86/E-04403	Permittivity ε PN-86/E-04403	Through resistivity ρ_v, Ωcm PN-86/E-04405	Dielectric strength kV/mm PN-86/E-04404	Surface resistivity Ω PN-86/E-04405
0	0.041	2.8	$5.2 \cdot 10^{14}$	15.7	$8.0 \cdot 19^{12}$
45			$1.9 \cdot 10^{14}$		
51		3.84			
70	0.083				
75		3.70	$1.3 \cdot 10^{14}$		
100		4.20			
150		4.20			
164	0.082	4.40	$2.7 \cdot 10^{13}$		
191			$6.0 \cdot 10^{12}$		
240	0.079	4.10			
309	0.074		$9.1 \cdot 10^{12}$		
341	0.069	3.70	$7.5 \cdot 10^{12}$		
376			$6.2 \cdot 10^{12}$		
427	0.064	3.72	$3.9 \cdot 10^{12}$		
470			$4.5 \cdot 10^{12}$	14.3	

7.14. Research on fatigue strength of EPY compound under compression loads

Apart from constant loads due to the weight of the machinery and tension in holding down bolts, also variable service loads affect foundation chocks of shipboard machines and devices. For this reason it was decided to conduct appropriate fatigue strength tests of the compound under compression. The tests were carried out in compliance with guidelines contained in DIN 50 100 standard. For the tests special cuboidal specimens of dimensions 12.7 × 12.7 × 25.4 mm were cast of EPY compound, then cured for 24 h at 23°C temperature and post-cured for 2 h at 80°C.

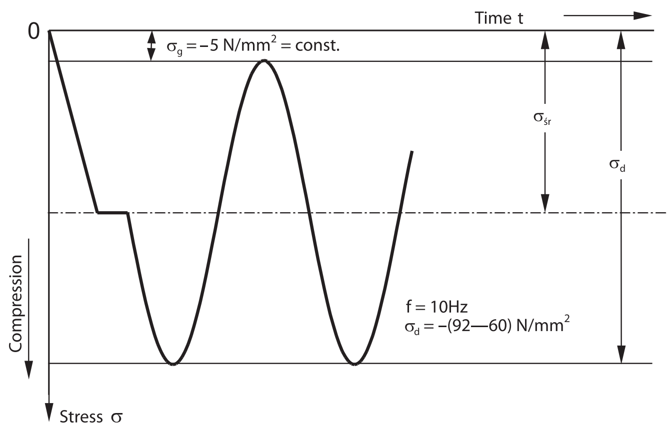


Fig. 7.37. Loading scheme for fatigue testing of EPY compound specimens

Table 7.8. Results of tests on EPY compound fatigue strength under compression loads (at upper compressive stress $\sigma_g = -5$ N/mm^2 = const)

Specimen №	Lower compressive stress σ_d N/mm^2	Number of load cycles	
		n	$n_{śr}$
1	−92	725	
2	−92	611	824
3	−92	1135	
4	−80	1676	
5	−80	1989	1805
6	−80	1749	
7	−78	3360	
8	−65	$> 100 \cdot 10^3$	
9	−65	$> 350 \cdot 10^3$	
10	−60	$> 10 \cdot 10^6$	

The tests were carried out with the use of a 8501 Plus INSTRON servo-hydraulic testing machine. The upper value of compressive stresses was assumed constant and equal to $\sigma_g = -5$ N/mm^2, while its lower value varied in the range from −92 to −60 N/mm^2. The EPY compound specimens were loaded in compliance with the schematic diagram shown in Fig. 7.37, and the test results are presented in Tab. 7.8.

The tests showed that EPY compound has a very high fatigue strength under compression loads. The specimens of a very unfavourable shape in comparison with foundation chocks (of high slenderness) endured safely 100×10^3 i 350×10^3 load cycles under variable compressive stresses with its lower value $\sigma_d = -65$ N/mm^2, and 10^7 load cycles, with its lower value $\sigma_d = -60$ N/mm^2 without being damaged. Next, the specimens were subjected to a static compression test. The test diagrams and values of basic parameters concerning the specimens which underwent earlier the cyclic load tests differed neither qualitatively nor quantitatively from results of analogue compression tests conducted on specimens of the same dimensions but not subjected earlier to fatigue loads.

Taking into account the fact that the permissible compressive stresses for chocking compounds amounts to 5 N/mm^2, one can conclude that the fatigue strength of EPY compound satisfies the safety condition with a very large margin. Therefore, in case of application of the results obtained from the tests on small compound specimens of unfavourable shape to machinery foundation chocks, their safety margin both for static and fatigue strength will be increased many times.

7.15. Research on the dynamic properties of EPY compound

7.15.1. Preliminary remarks

The striving to reduce mechanical vibration and noise on mechanically driven ships as much as possible was always present. Following the development of technology, higher and higher requirements in this regard were laid down to producers of ship machines and devices and to shipbuilders. Nowadays the mitigation of vibration is one of the fundamental problems in shipbuilding and ship service.

There are many sources generating vibrations of various frequencies. Unbalanced forces and moments acting in main engine produce a fundamental vibration of a low frequency (up to 60 Hz). Apart from that they also excite vibrations of higher frequencies. There are many other machines and devices generating vibrations on ships. Vibrations of higher frequencies (in 1000 Hz band) are especially nagging for crew and passengers. A part of the vibration is emitted to surrounding air and results in troublesome and detrimental noise. The rest of vibration energy, in case of rigid connections, goes to the foundation supporting a given machine or to other objects joined with it, and is transferred in a form of structural sound to all, even very distant elements of ship structure. As a result, highly undesirable side effects, e.g. noxious noise due to vibration of walls and various shields, as well as secondary vibration (often resonance ones) excited in other devices, may occur both in engine room and other ship compartments. The counteraction to the propagation process of vibration consists usually in application of rubber pads or special vibration isolators. Their application, however, is not always possible, as to exactly align a seated objects is required, and also in view of a large additional cost and serious technical difficulties in case of use of vibration isolators.

The use of foundation chocks cast of resin compounds brings, apart from many technological advantages, also favourable effects connected with damping and isolation of vibration usually noticeable by ship crews. Chocking compounds dampen mechanical vibration better than steel, traditionally used for this purpose. On the other hand, the contact surface between the compound and steel forms an effective barrier against structural sound propagation.

The aim of the research on dynamic properties of EPY compound was to determine:

- the logarithmic vibration damping decrement and the dynamic shear modulus;
- the dynamic longitudinal modulus of elasticity and the energy loss factor;
- the acoustic impedance.

7.15.2. Determination of logarithmic vibration damping decrement and dynamic shear modulus

The tests [39] were conducted with the use of a torsional pendulum in compliance with the guidelines contained in PN-83/C-89042 and EN ISO 672 1-2 standards. Identical specimens (flat bars of dimensions: L = 60 mm, b = 10 mm and h = 1 mm) made of EPY compound and steel were tested for comparison. The logarithmic vibration damping decrement and the dynamic shear modulus were determined experimentally. Fig. 7.38 shows exemplary time-amplitude characteristics of both the tested materials determined at 20°C temperature, and Fig. 7.39 — the diagrams of the logarithmic vibration damping decrement and the dynamic shear modulus in function of temperature for EPY compound and Epocast 36 compound (made in Germany).

As results from the tests (Fig. 7.38),under the same conditions, fading rate of free vibration in EPY compound is much greater than in steel. The ratio of logarithmic vibration damping decrement of EPY compound and that of steel is: $\Lambda_t : \Lambda_s = 0.1326 : 0.0413 = 3.21$. It means that EPY compound used for foundation has over three times greater vibration damping coefficient than steel, the material traditionally used for foundation chocks of ship main propulsion engines. The dynamic shear rigidity of EPY compound is much lower than that of steel. The ratio of the two rigidity values (at 20°C) is $G_t' : G_s' = 2511 : 80{,}000 = 0.0314$.

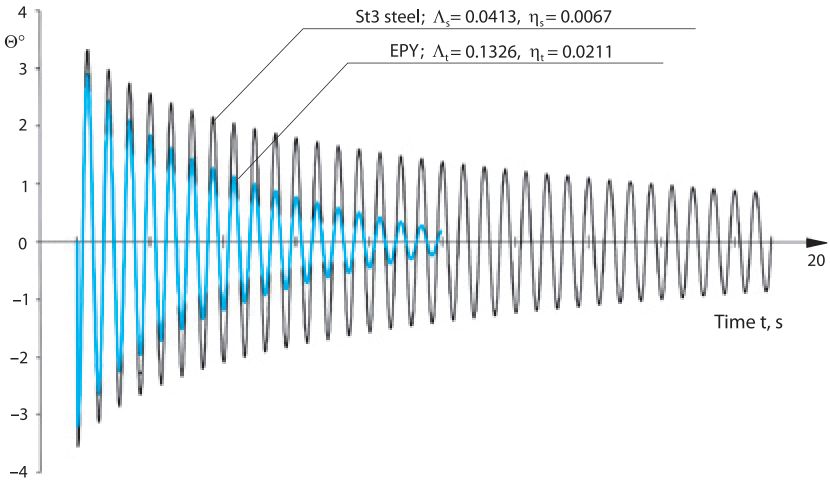
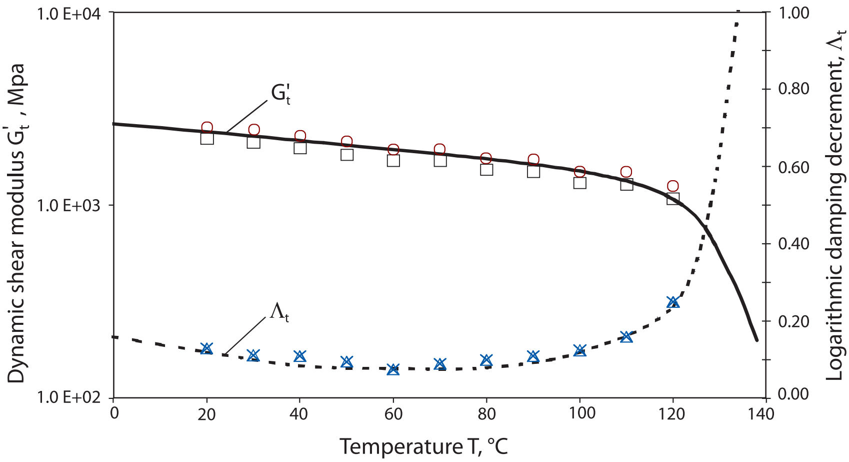


Fig. 7.38. Time-amplitude characteristics for EPY compund and St3 steel obtained at 20°C and the frequency f = 1.77 Hz



Results of the tests for the dynamic shear modulus G'_t:

○ — Polish EPY compound tested by these authors acc. PN-83/C-89042

□ — Polish EPY compound tested by these authors acc. EN ISO 6721-2

—— — German Epocast 36 compound (data acc. H.A. Springer's report)

Resuts of the tests for the logarithmic damping decrement Λ_t:

△ — Polish EPY compound tested by these authors acc. PN-83/C-89042

× — Polish EPY compound tested by these authors acc. EN ISO 6721-2

- - - — German Epocast 36 compound (data acc. H.A. Springer's report)

Fig. 7.39. The dependence of the logarithmic vibration damping decrement Λ_t and the dynamic shear modulus G'_t on temperature for EPY compounds and Epocast 36 compound

The feature of EPY compound is very advantageous in comparison to steel. High flexibility of resin compound chocks together with a high friction coefficient on contact surface between machine bed plate and its foundation allow for considerable thermal and mechanical deformations of a machine without slipping. The surfaces of resin compound foundation chocks do not wear off, so the trend for the loosening of holding down bolts is much lower than in case of steel ones.

7.15.3. Determination of the energy loss factor and the dynamic longitudinal modulus of elasticity under compression

In order to collect more comprehensive data on the dynamic properties of EPY compound, useful for the application of the material for machinery foundation chocks, it was subjected to a relevant compression test (Fig. 7.40). The test was aimed at determining the energy loss factor η and the dynamic elasticity modulus E_d under compression.

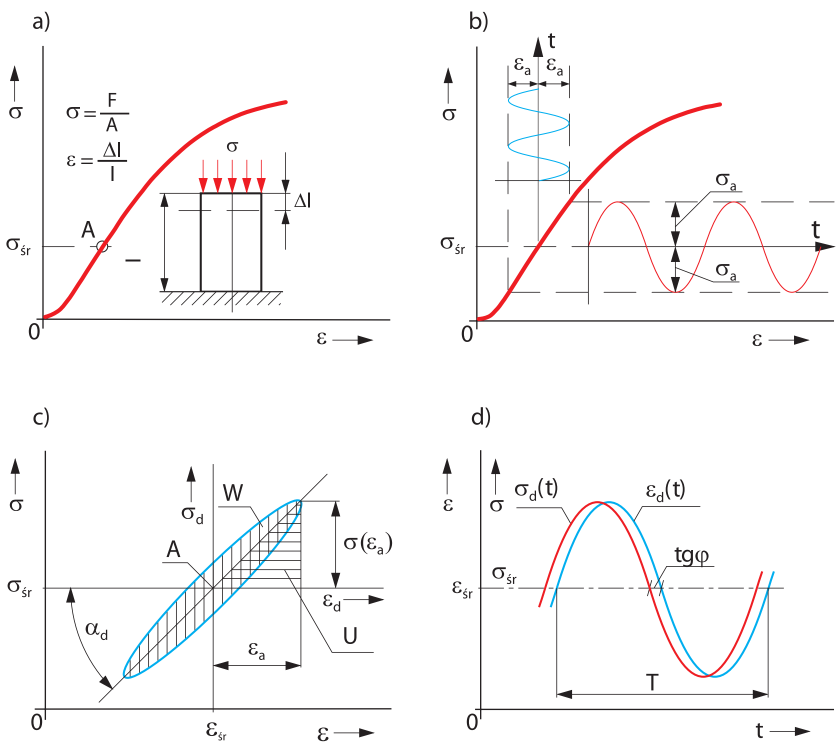


Fig. 7.40. Schematic diagrams of dynamic compression test for EPY compound specimens

The energy loss factor η is a basic measure which quantitatively determines damping properties of a material. The factor is derived from the following relation:

$$\eta = \frac{W}{2\pi U} = \frac{\psi}{2\pi} \tag{7.14}$$

where:

W — the energy dissipated during one vibration period, related to volume unit,
U — the potential energy of elastic deformation corresponding to maximum dynamic deformation, related to volume unit,
ψ — the vibration energy dissipation factor (the relative dissipation of vibration energy); ψ = W/U.

Cylindrical specimens of dimensions: 20 mm in diameter × 55 mm in height, cast of EPY compound in steel moulds, cured for 24 h at 23°C and then post-cured for 2 h at 80°C were subjected to the test in 8501 Plus Instron servo-hydraulic testing machine.

The energy W was determined by using the method of hysteresis dynamic loop. In view of the working conditions of foundation chocks the tests were conducted under compression loads in accordance with the schematic diagrams shown in Fig. 7.40.

The energy W, dissipated during one vibration period (related to volume unit) is proportional to the area of contained within hysteresis dynamic loop, determined in σ – ε coordinate frame (Fig. 7.40c). The amount of energy was obtained by means of numerical integration of the relation:

$$W = \oint \sigma(\varepsilon)\, d\varepsilon \tag{7.15}$$

The elastic deformation energy U was determined according to the formula (Fig. 7.40c):

$$U = 0{,}5\, \varepsilon_a \sigma(\varepsilon_a) \tag{7.16}$$

where:

ε_a — deformation amplitude due to dynamic load (Fig. 7.40c).

For a simple compression test, the dynamic compressive rigidity in a considered point of static characteristics (Fig. 7.40a) is determined by the dynamic modulus of longitudinal elasticity E_d derived from the following formula (Fig. 7.40c):

$$E_d = tg\alpha_\alpha = \frac{\sigma(\varepsilon_a)}{\varepsilon_a} \tag{7.17}$$

The tests were performed for a wide range of variability of values of the parameters $\varepsilon_{śr}$, ε_a and frequencies f = 1÷20 Hz. The exemplary, experimentally determined hysteresis loop is shown in Fig. 7.41, and some of the test results are given in Fig. 7.42 through 7.45. Detail reports and results of the tests are presented in the publications [37÷40].

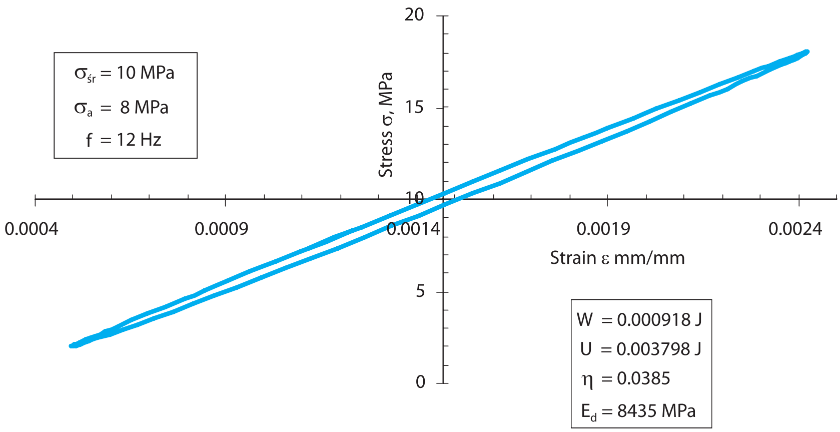


Fig. 7.41. The dynamic hysteresis loop determined experimentally for the values: $\sigma_{śr} = 10$ MPa, $\sigma_a = 8$ MPa, f = 12 Hz

As generally results from the obtained test results (Fig. 7.42—7.45), values of the energy loss factor η and the dynamic modulus of longitudinal elasticity E_d depend on the parameters $\sigma_{śr}$, σ_a, f and T. The dynamic load frequency f has the greatest impact on the energy loss factor η, and the temperature T — on the dynamic modulus of longitudinal elasticity E_d. Within the assumed range of variability the following values of these parameters were obtained for EPY compound: $\eta = 0.012 \div 0.047$, $E_d = 5000 \div 8500$ MPa. The respective values obtained for steel are [134]: $\eta = 0.0016 \div 0.0028$, $E_d = 2.1 \times 10^5$ MPa.

The values of the energy loss factor η obtained for EPY compound are comparable to those for vibration isolation materials based on natural rubber ($\eta = 0.02 \div 0.16$) [134]. As results from that, this compound may be effectively used for the damping of mechanical vibration in machines. Research focused on effective implementation of these properties of EPY compound is under way.

Tab. 7.9 contains the values of the dynamic modulus of longitudinal elasticity E_d and the energy loss factor η for some selected materials.

Table 7.9. Values of dynamic elasticity modulus E_d and energy loss factor η

Material	E_d, N/mm^2	η
EPY	$(0.05—0.085) \cdot 10^5$	0.012—0.047
Steel	$2.1 \cdot 10^5$	0.0016—0.0026*
Grey cast iron	$(0.09—1.1) \cdot 10^5$	0.036*
Rubber (20÷80 Shore's deg.)	2—24	0.02—0.16*
* acc. [134]		

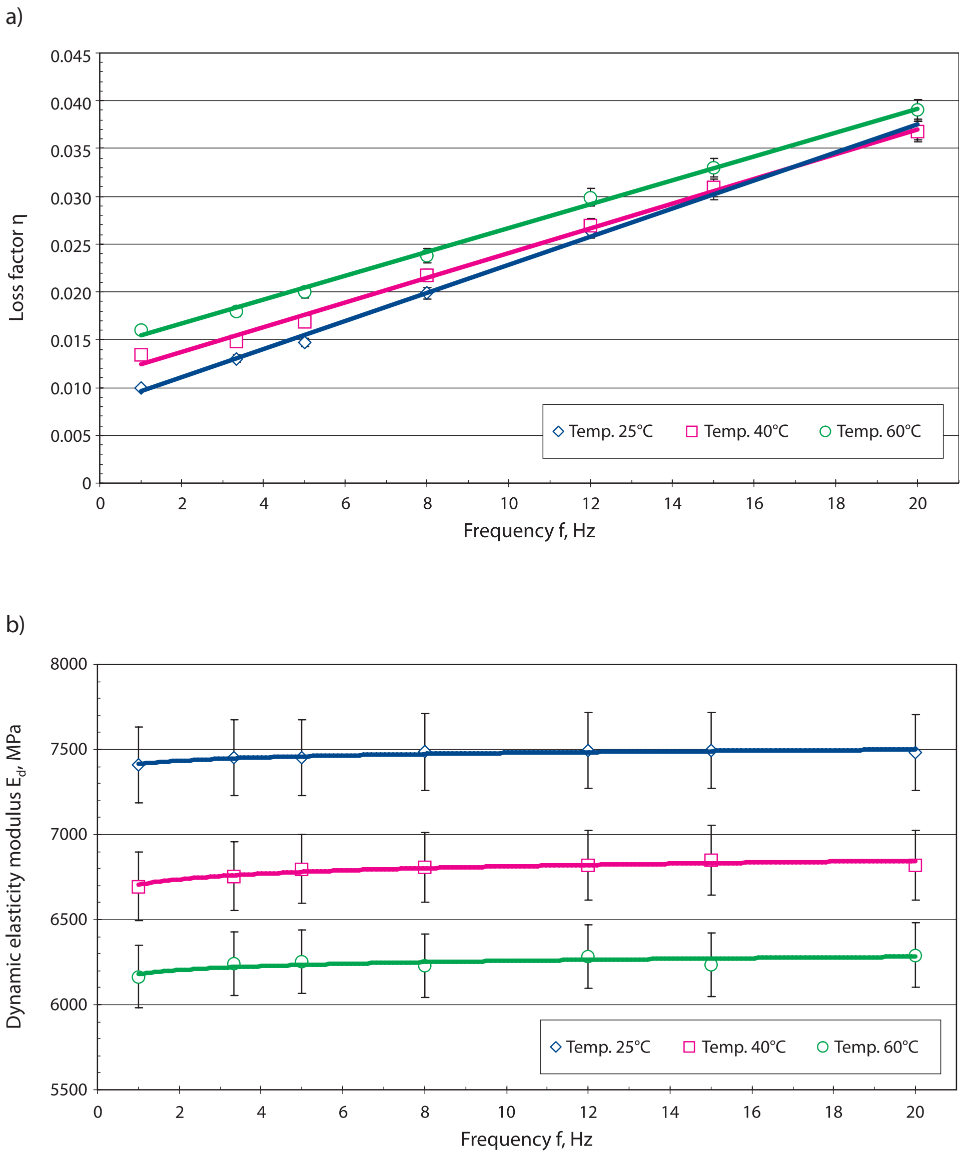


Fig. 7.42. Exemplary results of the tests on relation of the energy loss factor η and the dynamic elasticity modulus E_d to frequency and temperature at the stresses: $\sigma_{śr} = 18$ MPa, $\sigma_a = 4$ MPa

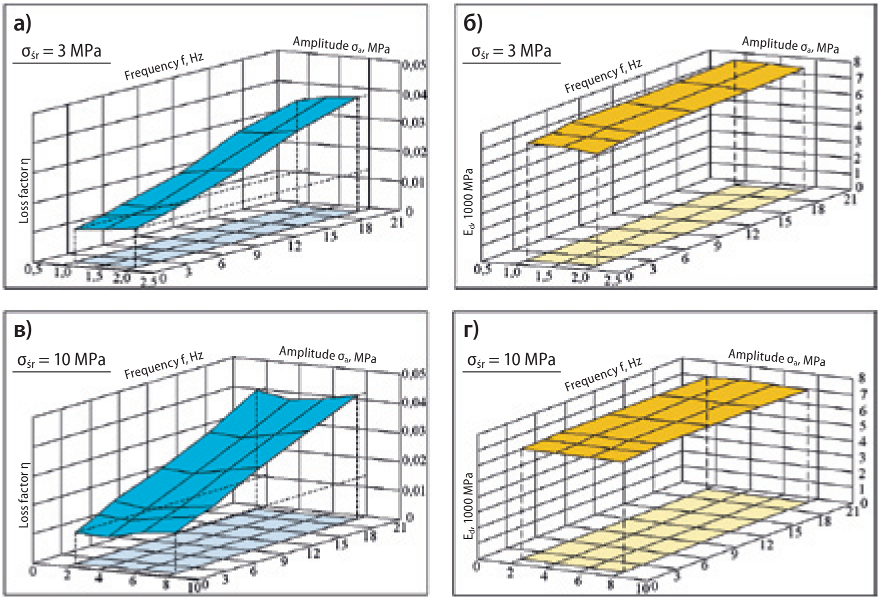


Fig. 7.43. Exemplary results of the tests on the energy loss factor η and the dynamic elasticity modulus E_d at 23°C temperature and the mean stresses: 3 and 10 MPa

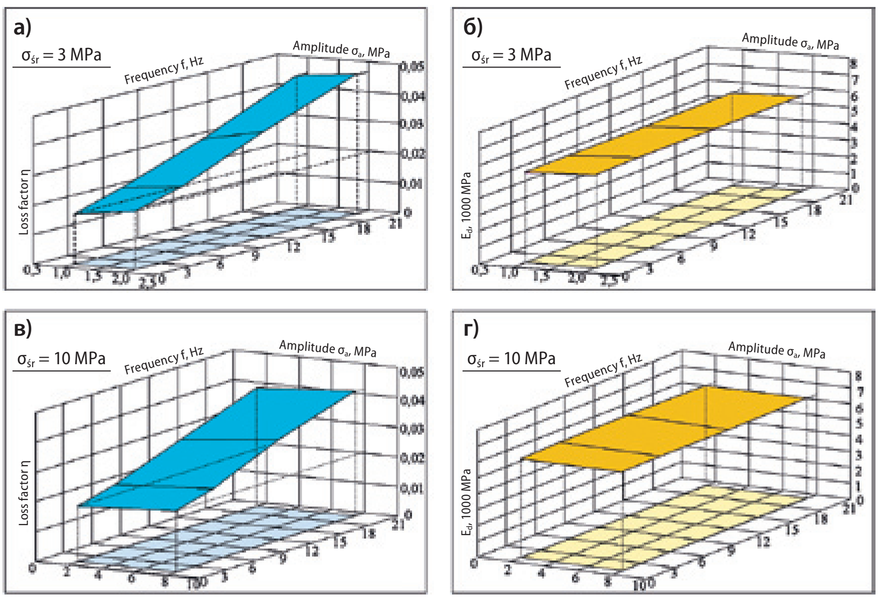


Fig. 7.44. Exemplary results of the tests on the energy loss factor η and the dynamic elasticity modulus E_d at 60°C temperature and the mean stresses: 3 and 10 MPa

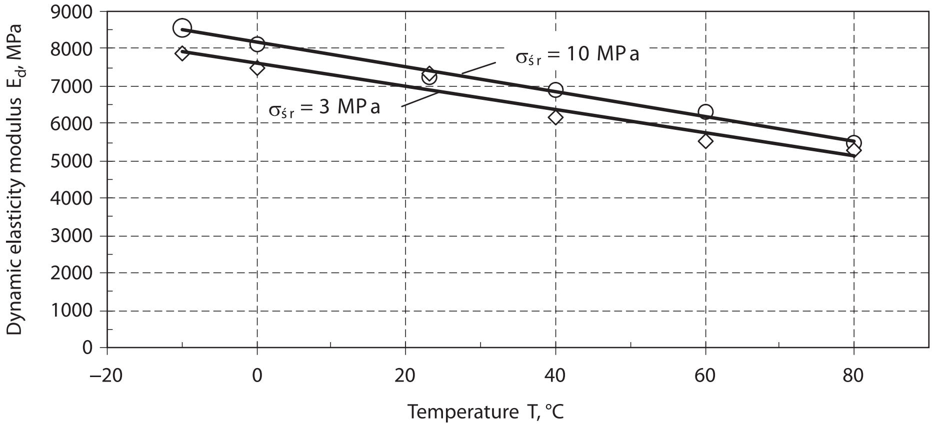


Fig. 7.45. The relations between the dynamic elasticity modulus and temperature for EPY compound

7.15.4. Determination of acoustic impedance

The concept of the acoustic impedance is a useful tool for the analysing of structural sound isolation. It is a measure of resistance of a medium to propagation of structural sound. It is known from physics [135, 136] that sound waves propagate in different media with different speeds. If a sound wave, propagating in a material, hits another material of a different acoustic impedance, then the flow of energy becomes very ineffective.

In case of a plane and spherical sound wave travelling far from its source, the unitary acoustic impedance R can be derived from the following formula for solid, liquid or gaseous bodies [135]:

$$R = \rho v \tag{7.18}$$

where:

ρ — density of a medium, kg/m^3,
v — speed of acoustic wave in a medium, m/s.

The speed of sound in the analysed medium depends on the elasticity and density of the medium. The unitary acoustic impedance for a longitudinal wave propagating in a solid body can be derived from the following formula [136]:

$$R = \sqrt{E\rho} \tag{7.19}$$

where:

E — longitudinal modulus of elasticity.

Sound propagating in a material becomes to a large extent reflected when coming into contact with the surface of another medium (the compound here) and only a small part penetrates into the second medium. Then, a part of acoustic energy transmitted through the barrier changes into heat and disperses. The remaining part goes to the other side of a chock where it encounters another barrier and becomes reflected in a major portion again.

If the following values are assumed for steel and EPY compound, respectively: $E_1 = 2 \times 10^{11}$ kg/ms², $\rho_1 = 7800$ kg/m³, $E_2 = 4915 \times 10^6$ kg/ms², $\rho_2 = 1590$ kg/m³, then the following values of unitary acoustic impedance for the analysed materials will be obtained from the formula (7.19):

— for steel $R_1 = 39.50 \times 10^6$ kg/m²s,
— for EPY compound $R_2 = 2.85 \times 10^6$ kg/m²s.

Acoustic energy transmitted from body 1 to body 2 through the contact surface may be calculated from the following formula [135]:

$$P_{1,2} = \frac{4R_1R_2}{(R_1 + R_2)^2} \tag{7.20}$$

If it is taken into account that the acoustic energy emitted by a machine and propagating through EPY compound chock to the steel foundation must go through two contact surfaces, then such an energy transmitted from the machine to foundation 3 may be calculated according to the formula [135]:

$$P_{1,3} = \left[\frac{4R_1R_2}{(R_1 + R_2)^2}\right]^2 \tag{7.21}$$

By substituting the above given values to the formula the following is obtained:

$$P_{1,3} = \left[\frac{4 \cdot 39.5 \cdot 10^6 \cdot 2.80 \cdot 10^6}{(39.5 \cdot 10^6 + 2.80 \cdot 10^6)^2}\right]^2 = 0.061 \tag{7.22}$$

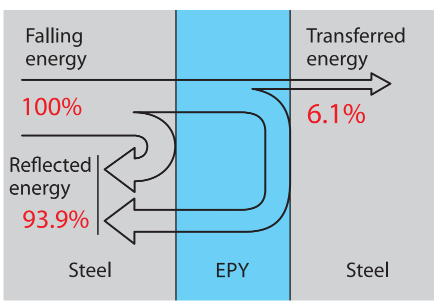


Fig. 7.46. Schematic diagram which illustrates sound energy fall, reflection and penetration through EPY compound interlayer (with no loss taken into account)

This estimate shows that only about 6% of the sound energy is transmitted from the machine through the EPY compound chock to the foundation. Fig. 7.46 illustrates the discussed problem.

This is in fact the most favourable situation out of all possible to occur. However in reality the problem of sound wave isolation by means of a chock is more complex. It depends not only on acoustic impedance taken into account in the formula (7.21) but also on parameters of a given system and acoustic wave frequency [136]. Real value of the impedance may be lower than that resulting from the above presented calculations.

The propagation of noise on a ship depends also on many other factors. Main and auxiliary machines seated on compound chocks are fixed to the foundation by steel bolts which transmit some part of sound energy without much resistance (loss). The amount of this energy depend on the diameter and length of the bolt, as well as on the design solution and the rigidity of the connection between the machine and its foundation.

Application of EPY compound to foundation chocks and separators in various constructional joints may certainly bring significant effects in mitigating vibration and noise. However this is neither a simple nor obvious problem. Therefore, further, more complex research on this matter and development of appropriate design solutions is required in order to utilize the vibration insulation properties of the compound in an optimum way.

7.16. Comparative research on static and dynamic properties of three various machinery chocking compounds

There are only three special chocking compounds which have found wide application for the foundation chocks of main and auxiliary shipboard machines. Apart from an American compound called Chockfast Orange (produced by ITW Philadelphia Resins) and a German compound Epocast 36 (produced by H.A. Springer marine + Industrie service GmbH), Polish EPY compound produced by Marine Service Jaroszewicz company in Szczecin obtained the approvals of the classification societies supervising the construction and repair of ships, as well as the certificates of the manufacturers of main and auxiliary shipboard machinery.

The principal aim of the research presented in this point was to experimentally determine the basic static and dynamic properties of all three compounds (Chockfast Orange, Epocast 36 and EPY) in identical conditions so that the Polish compound can be evaluated in comparison with the best known world products of this kind.

The static strength tests were aimed at determining the compression characteristics and the following parameters based on them:

— compressive strength R_c,
— proof stress (yield point) $R_{0,2}$,
— limit of elasticity $R_{0,02}$,
— longitudinal modulus of elasticity (Young's modulus) E.

The testing was conducted at ambient temperature on cylindrical specimens of a diameter d = 20 mm and height h = 25 mm. The specimens of all three tested compounds were cast, cured and kept in the same conditions. Preparations for casting the specimens were done in accordance with the guidelines of the manufacturers. Specimens cast in metal moulds were cured for 24 hours at 23°C and then (after their removal from the moulds) post-cured for 2 hours at 80°C.

Compression test was carried out by means of a 8501 Plus Instron servo-hydraulic testing machine and a special computer software for static compression tests. This way it was ensured that the tests on all the specimens and the determination of values of the selected parameters were carried out in the same way. The results of compression tests are presented in Fig. 7.47.

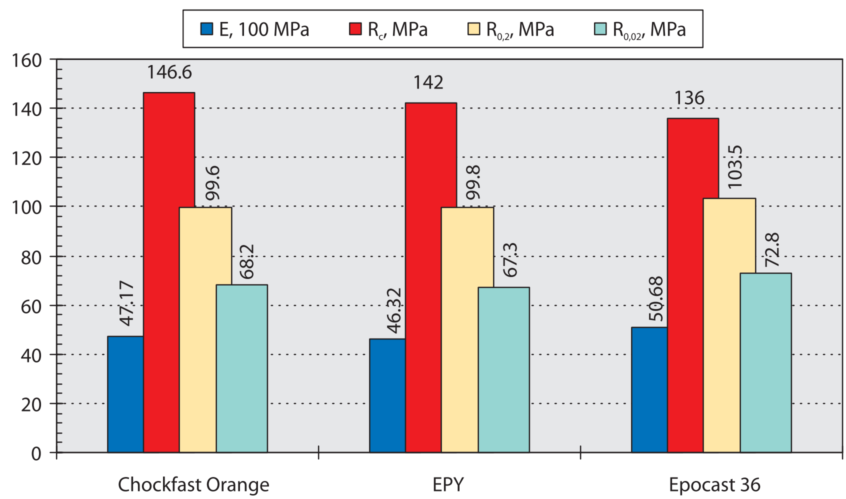


Fig. 7.47. Collected results of static compression tests on three resin compounds

The tests proved (Fig. 7.47) that all three compounds undergoing static compression tests behave identically in a qualitative sense and the observed quantitative differences are minor and unimportant for the application of the compounds for shipboard machinery foundation chocks.

The aim of research into dynamic properties was to determine the dynamic elasticity modulus E_d and the loss factor η for all three compounds.

a)

b)

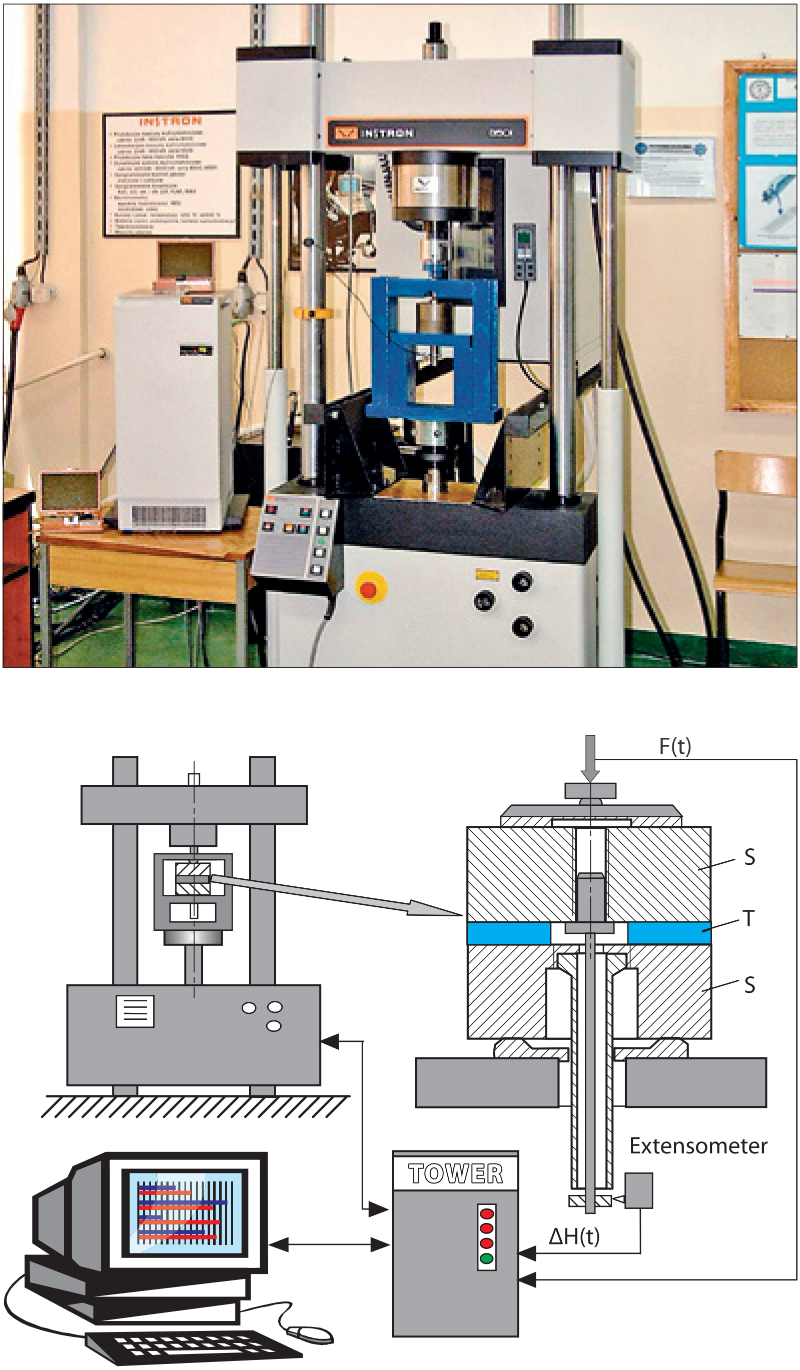


Fig. 7.48. The test stand comprising Instron testing machine: a) overall view; b) schematic diagram

a)
b)
c)
d)

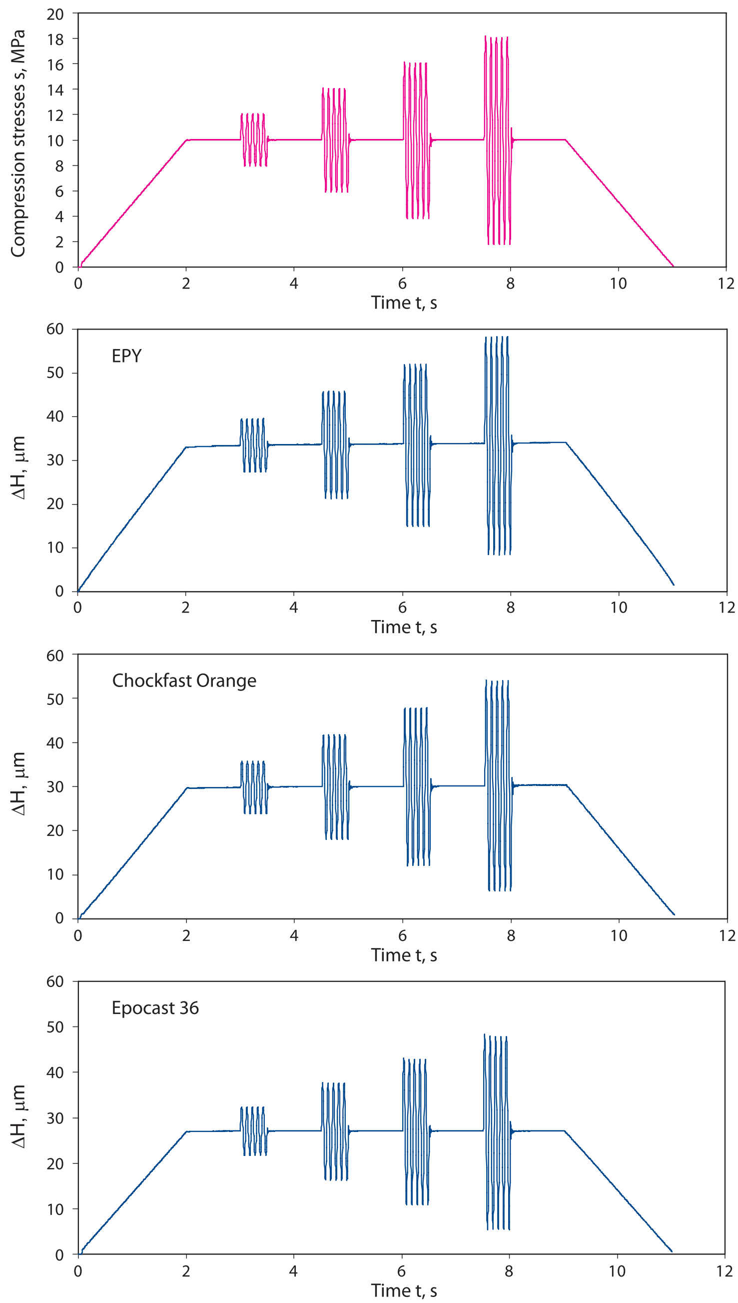


Fig. 7.49. Time runs of compression stresses (σ) and resulting deformations (changes in height ΔH) in foundation chock models made of three different resin compounds ($\sigma_{śr}$ = 10 MPa, σ_a = 2, 4, 6, 8 MPa, f = 10 Hz, T = 80°C)

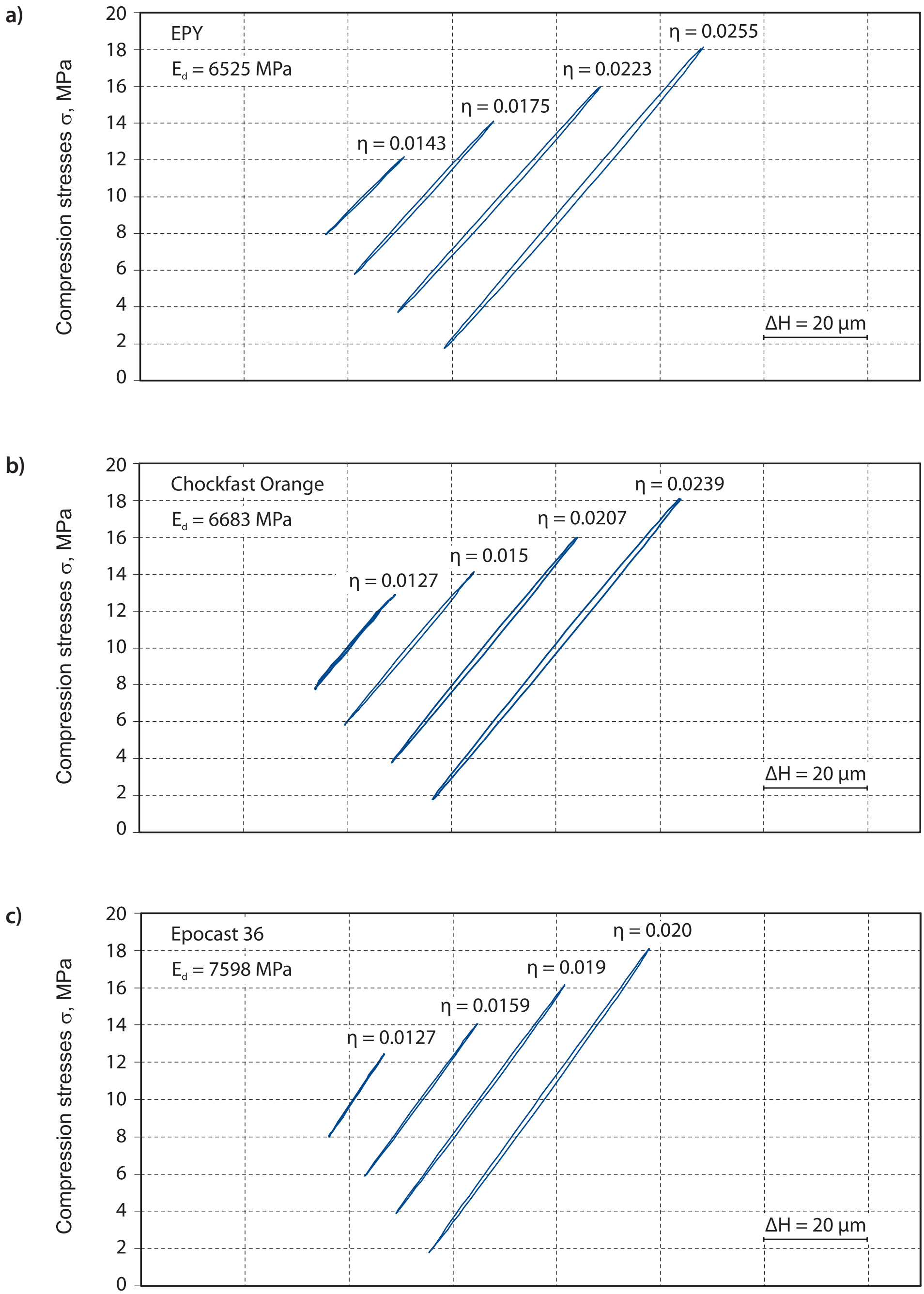


Fig. 7.50. Dynamic hysteresis loops for foundation chock models made of three different resin compounds (run of deformations as shown in Fig. 7.49)

The fundamental characteristic of dynamic tests is the fact that both input quantities (force for instance) and output ones (deformation for instance) must be treated as functions of time. The dynamic tests were conducted on simplified axially symmetrical models of the chocks (of outside diameter D = 60 mm, inside diameter d = 25 mm and height H = 20 mm). In order to provide test conditions as close as possible to the real operating conditions of foundation chocks the chock models were cast and cured between two steel disks simulating the foundation and the bedplate of a seated machine. The models were cast ready to use in special moulds. To prevent adhesion of compound to adjoining surfaces, a thin layer of release agent was put on steel disk surfaces. Cast models of chocks were cured for 24 h at 23°C and post-cured for 4 h at 80°C.

The models of chocks prepared this way along with the steel disks were compressed by using the servo-hydraulic testing machine (Instron, model 8501 Plus) and special instrumentation (Fig. 7.48). To measure deformation (change in height ΔH) of tested chocks an Instron extensometer was applied. The tests were conducted at the ambient temperature of 23°C and at 80°C. Application of a special computer software (Wavemaker) ensured that the dynamic tests were conducted in exactly the same way for all three tested compounds.

Variable parameters during the tests were: the mean stress ($\sigma_{śr}$ = 5 and 10 MPa), amplitude of dynamic stresses (σ_a = 2, 4, 6 and 8 MPa), frequency (f = 1, 5, 10, 15 and 20 Hz) and temperature (T = 23 and 80°C). Detailed descriptions and results of the dynamic tests are presented in the publication [137]. Exemplary test results are presented graphically in Fig. 7.49 i 7.50. Figure 7.49a presents time runs of compressive stress, executed as programmed by the testing machine, and Fig. 7.49b, c, d, respectively — the time runs of contact deformations (change in height ΔH) in chock models made of the three tested compounds. Figure 7.50 presents the dynamic hysteresis loops of the tested chock models made of the three different compounds.

Time runs of deformations in the tested chock models demonstrate (Fig. 7.49 and 7.50) that the dynamic properties of the three compounds are identical with regard to quality. Slight quantitative differences are insignificant in practical applications. Therefore it may be concluded that the tested compounds are in the same class as far as their static and dynamic properties are concerned.

8 Research and modeling of structural joints in which EPY compound is applied

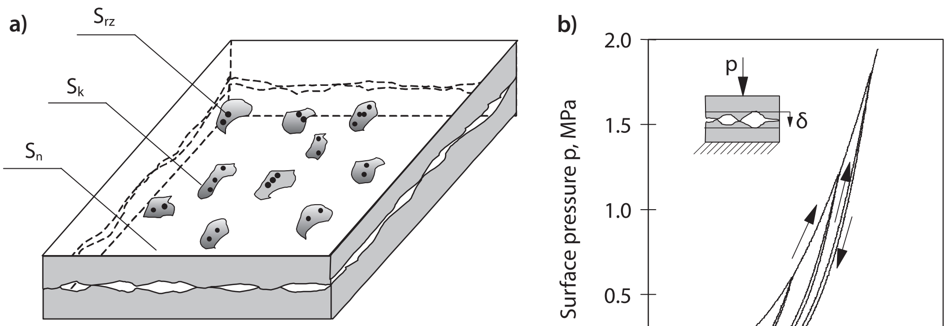
8.1. Research on flat direct contact joints and joints with a thin layer of EPY compound

8.1.1. Contact joints loaded with normal force

Machined surfaces of machinery elements are not perfectly smooth. Existing irregularities (roughness, waviness and shape imperfections) cause that two such surfaces cannot contact each other over the whole nominal contact surface but only in its little part (Fig. 8.1a). The actual contact surface is a small percentage of the nominal contact surface and depends on the value of normal pressure exerted on the surfaces [138, 139]. As a result, the actual contact stress distribution and values are rather much different from the ones obtained on the basis of assumptions or calculations made for contact joint of perfectly smooth surfaces. Contact stress distribution and values greatly depend on the type and accuracy of surface finishing operations and the physical properties of surface layers. Discontinuous contact of machined surfaces has a significant influence on the mechanical characteristics (Fig. 8.1b) of contact joints between machinery components, and as a consequence, also on static and dynamic properties (stiffness and vibration damping) of entire complex mechanical systems.

Application of a thin layer of compound in the joints between machinery components required conducting the research on flat contact joints with the compound and without it. Figure 8.2 presents the experimentally determined characteristics illustrating the relation of normal contact deformations to mean pressure in a direct contact between two steel cylinders compressed together axially in a compression testing machine. The face of cylinder 1 was milled ($R_a = 5$ μm), and the face of cylinder 2 — turned ($R_a = 5.5$ μm). The tested specimens were pressed against one another with a mean pressure increasing from 0 to 100 MPa. Next, they were unloaded and loaded again.

The curves *a* in Fig. 8.2 illustrate the relation of contact deformations to mean normal pressure for the contact joint of specimens 1 and 2 without any compound layer, and the curves *b* — for the contact joint of the same specimens with a thin layer (about 0.5 mm) of cured EPY compound. The compound was introduced in a liquid state and under some pressure of connected components, it exactly filled the uneven gap between metal surfaces. In order to facilitate the disassembly of



S_n — Nominal contact surface area
S_k — Contour contact surface area
S_{rz} — Actual contact surface area

Fig. 8.1. Contact connection between two machined surfaces and its characteristics: a) schematic drawing of the connection; b) relation between contact normal deformations and surface pressure (experimentally determined for contact connection of two steel surfaces of the roughness parameter $R_a = 5$ μm)

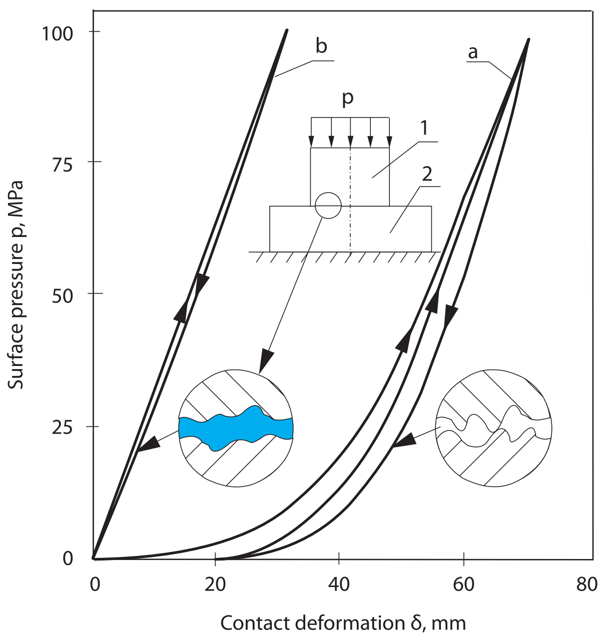


Fig. 8.2. Relation between normal contact deformations and mean surface pressure for contact connection of two cylinders without any compound layer (curves a) and with thin compound layer (curves b)

the connected components, their metal surfaces were covered with a thin layer of a release agent.

The tests (Fig. 8.2) show that the thin layer of the compound significantly changes the characteristics of contact joints between machined surfaces. Deformations in the joint of components without any compound layer have non-linear runs (curves *a*). Considerable plastic deformations (on the peaks of uneven contact surface) are present during the first loading. During the subsequent loadings (not exceeding original values), deformations are elastic and have non-linear runs.

Deformations of contact joint of components divided by a layer of compound (Fig. 8.2, curves *b*) are elastic, approximately linearly depending on the applied load, and much smaller. Compression characteristics of tested joints differ in capability of vibration damping as well (the surface areas inside the hysteresis loops are different).

The actual contact deformations occurring in the joint without the compound layer are highly non-uniform. Locally, where the surfaces actually make contact, deformations exceed the yield point, which results in a so-called surface sagging, which in turn causes a loosening of the bolts. Under cyclic loads this may lead to "hammering" on the surfaces and result in failure situations.

The compound layer provides a full contact of connected components as well as a continuous and more uniform distribution of contact stresses not exceeding the yield point. It ensures a very good interaction of connected components not only under static loads, but also under long-term dynamic loads.

In case of thin layers of compound cast between two metal surfaces, the ratio of the cross-section area A and the height (thickness) H of the compound layer, is very high. The tests were conducted on steel specimens of 20 mm in diameter and 25 mm in height composed of two parts with a thin layer (about 0.5 mm) of EPY compound in between (Fig. 8.3a). The specimens were subjected to axial compression in a com-

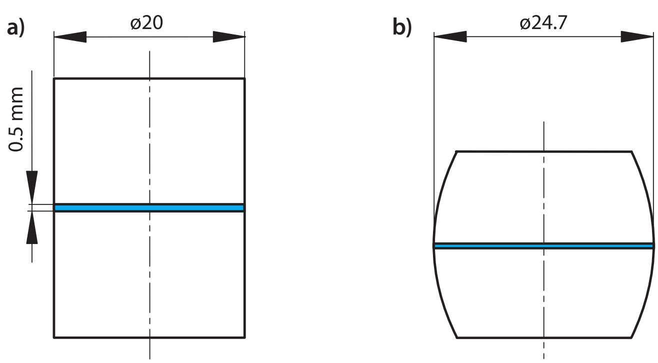


Fig. 8.3. Schematic drawing of a steel specimen with compound layer before and after compression test

pression testing machine until considerable plastic strains occurred (Fig. 8.3b). During the test, the thin layer of EPY compound underwent plastic deformations together with the metal parts, increasing its diameter and decreasing its thickness. Nevertheless, it maintained its full tenacity and could be easily separated from steel surfaces due to usage of a release agent.

The maximum value of compression stress during the test was $\sigma_{max} = 1000$ MPa. In spite of very high values of compression stress, exceeding the compressive strength R_c of standard compound specimens (20 mm × 25 mm) many times, thin layers of the compound compressed between two metal surfaces were not destroyed. Very high compression strength of the compound may be explained by the limited freedom to transverse deforming and by a complex state of stress in the compound. The effective friction coefficient between contact surfaces of metal and compound (cast and cured between metal surfaces) is usually higher than 1, which eliminates any sliding of the contact surfaces.

Fig. 8.4 presents stress distribution and stress values in the middle cross section of 2 mm thick layer of the compound, calculated by using the finite element method (FEM) for a specimen of 20 mm diameter and 25 mm height, compressed with uniformly distributed stress $\sigma_o = 170$ MPa. The following data were assumed for the compound: $E_t = 5000$ MPa, $\nu = 0.37$. As results from Fig. 8.4, the compound layer undergoes three-axial compression which is very favourable. Reduced stress in the

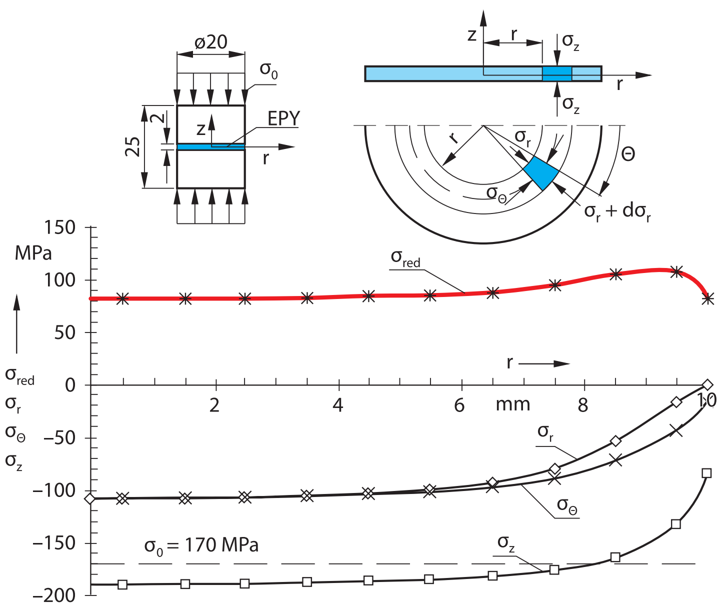


Fig. 8.4. Stress distribution in the middle cross-section of the compound layer

compound, calculated on the basis of Huber hypothesis [140], is much lower than the component stresses. It explains why the compressive strength of thin layers of compound can be so high.

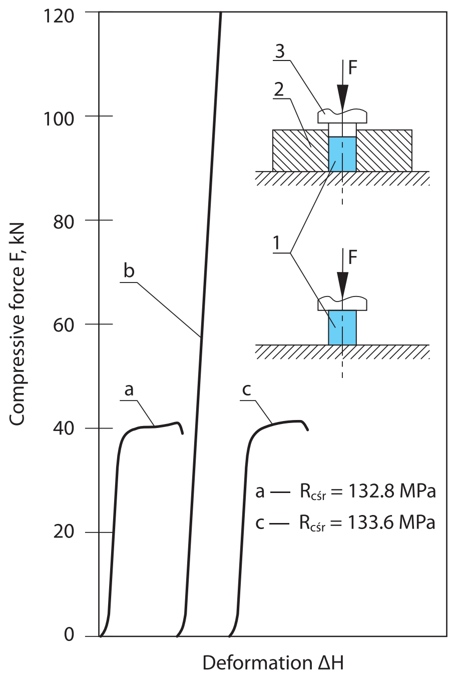


Fig. 8.5. Results of compression tests on EPY compound specimens (ø20×25): a — for freely compressed specimen; b — for specimen compressed in a steel plate hole (2); c — for overloaded specimen taken out from steel plate hole and then freely compressed [141]

After the compression tests of thin layers of the compound the question arose whether after such high compressive stresses (considerably exceeding the compound strength R_c which was determined from the tests on standard specimens), the compound still maintains its original strength properties. To answer this question a compression test was performed on specimens [141]. Fig. 8.5 shows its results. The curve *a* illustrates the compression process of EPY compound specimen, determined in the standard compression test, and the curve *b* — shows the compression process of the same specimen tightly inserted into the hole in steel plate constraining freedom of the specimen to transverse deformation. The specimen could not be destroyed in such conditions. After the specimen was taken out of the hole, it underwent standard one-axial compression test, where it showed its original strength properties, which is illustrated by the curve *c* in Fig. 8.5.

On the basis of the tests and additional theoretical analysis it may be concluded that a thin layer of the compound, compressed between two metal surfaces, is able to safely transfer high compression loads. Practical experience gained during 40 years of activity prove that the conclusion is valid not only in the case of static loads but also dynamic ones which usually occur during operation of various technical objects. Results of these tests were applied to the seating of large bearings installed in ship cranes, dredgers, brown coal excavators, dumping conveyors etc.

8.1.2. Contact joints under constant normal force and variable tangential force

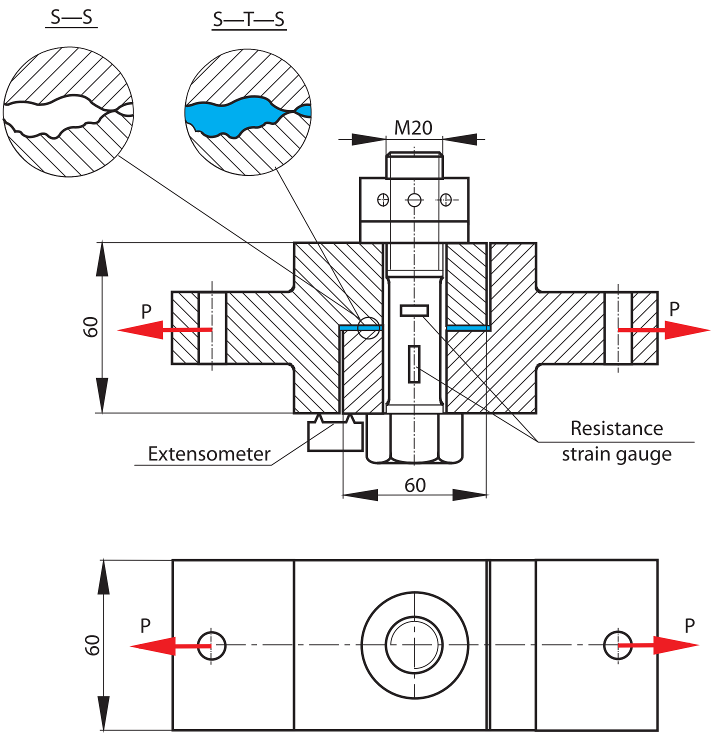
Contact joints of machinery components are subjected not only to normal forces but the tangential forces as well (Fig. 8.6a). Also in such cases, a thin layer of EPY compound considerably influences their static and dynamic characteristics, and in consequence the operational quality, reliability and durability of contact joints so commonly present in any machinery.

Figure 8.6 presents a model of a bolt joint and the test results [142] concerning its reaction to a constant axial force and a slowly growing load in direction tangential to connected surfaces. In the joint, the external (tangential) load is transferred by a friction force which depends on the friction coefficient and exerted normal force. The experimental tests were conducted for a direct contact of joint elements (S—S) and contact with a thin layer of EPY compound cured between two joint surfaces (S—T—S; Fig. 8.6a). In order to prevent the contact surfaces against permanent adhesion, they were covered with a thin layer of release agent. Detailed test records are presented in the publications [142, 143].

Static characteristics of tested joints, demonstrating the relation of tangential displacement and the mean value of tangential stresses, are presented in Fig. 8.6b. Just like under normal loads, considerable qualitative and quantitative differences occur also in this case. Static characteristics of a bolt joint without the compound (Fig. 8.6b, curve 1) is non-linear in the range of the applied loads and shows elastic--plastic character of the tangential displacements δ_τ. Irreversible sliding is noticeable. Besides, there are also elastic displacements which have very low values. On the other hand, the static characteristics of a contact joint with a thin layer of compound (about 0.7 mm thick) is of a linear and elastic character even under a tangential load three times higher (Fig. 8.6b, curve 2). Under the load, no relative sliding between contact surfaces was observed which guarantees a better performance of such joint in service.

Figure 8.7 presents the characteristics of tangential contact displacements in a bolt joint under tangential static and dynamic stresses. In direct contact joint (S—S) considerable sliding of joined surfaces was observed already under low mean stress (τ = 1 MPa, Fig. 8.7a) and the dynamic sinusoidal stress with relatively small amplitude. On the other hand, if a thin layer of the compound is present (S—T—S joint), even three times higher values of mean stress and dynamic stress amplitude caused

a)



b)

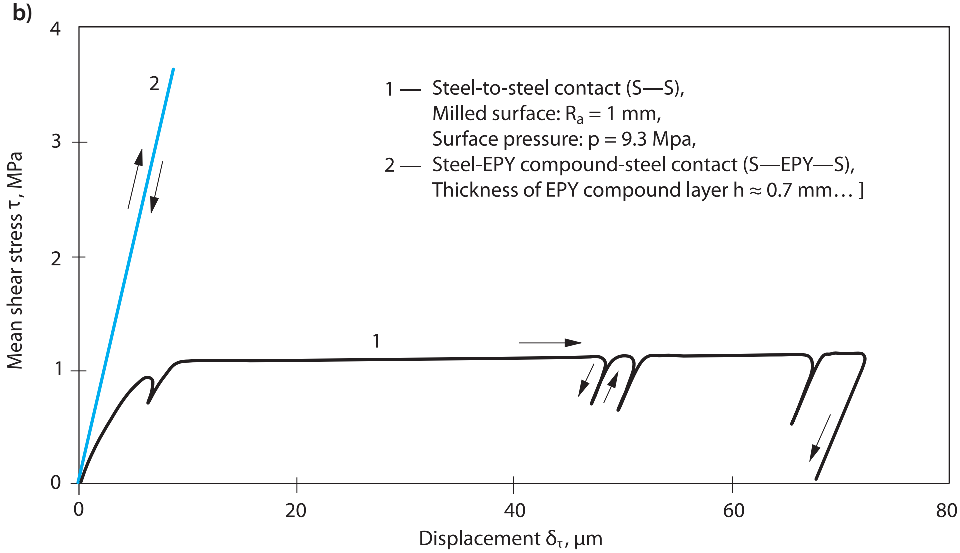


Fig. 8.6. Schematic drawing of a model bolt joint (a) and its static characteristics under constant normal load and slowly increasing load tangential to joint surfaces (b)

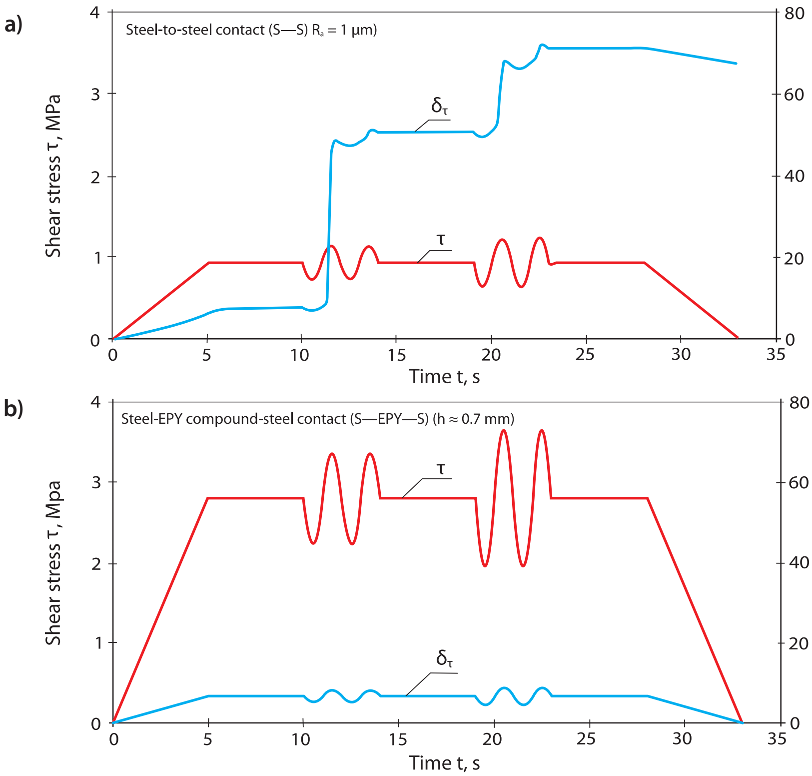


Fig. 8.7. Dynamic characteristics of a model bolt joint: a) of direct contact; b) with a thin layer of the compound

little tangential elastic displacement only, which disappeared completely after the removal of tangential load (Fig. 8.7b). Lack of even low sliding is very advantageous for the joint, as fretting and abrasive wear do not occur. As a result, we benefit from high durability of bolt joint and its better operation in service, resulting from much higher effective friction coefficient in the contact between compound and metal, in comparison with a contact between two metals.

8.2. Research on models of holding down bolts fit in the compound

Fitted bolts are applied in the seating arrangements of main and auxiliary shipboard machinery in order to transfer considerable forces acting in directions tangential to the supporting surface of the mounted machine, which applies in particular to main engines. Boring and precise reaming of the holes for fitted bolts, especially in case of cast compound foundation chocks, is difficult and costly. In order to avoid these difficulties, a concept of fitting the holding down bolts in the chocking compound has been developed. For that purpose, the holes in foundation and bedplate should be made bigger than the bolt diameter by abt. 2 mm. Next, after the engine is aligned and loosely-fitting bolts are inserted, liquid compound is poured into chock moulds, also filling the gaps around bolts in the holes in foundation and the engine's bedplate. However, any practical application of this method required appropriate laboratory testing.

The tests were first conducted on the model of a foundation joint presented in Fig. 8.8. The holes in joined elements 1, 2 and 3 had their diameters bigger by 2 mm than the diameter of bolt shank (5). In order to prevent adhesion between the bolt and the compound, the bolt was covered with a release agent (Silform AR1). When the model was positioned in such a way that the axis of the bolt was vertical with its nut on the top, and when the appropriate mould was arranged *in situ*, two chocks of dimensions 100 × 100 × 40 mm were cast in the model including also the compound sleeves between the bolt and the respective plates. Filling the spaces

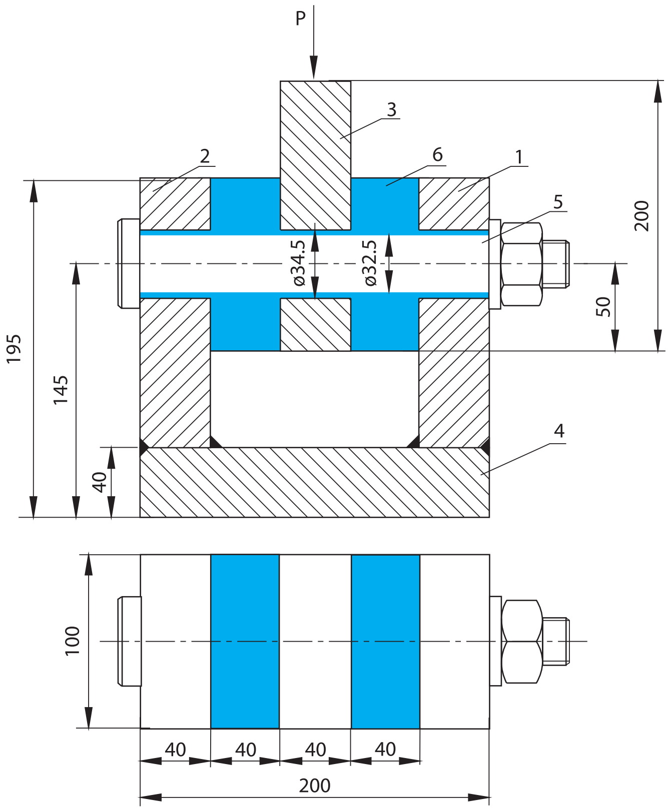


Fig. 8.8. Model of a foundation bolt joint with the bolt fitted in the compound

between the bolt and the walls of the holes in plates was executed only by action of the hydrostatic pressure of liquid compound column.

When the compound cured, a model of a "double" bolted joint was ready. Half of the model simulated the real foundation joint subjected to tangential force. The model was loaded in the compression testing machine. Under the force P = 190 kN, cracks appeared on the flanks of the chocks. The test was interrupted when the force P reached 211.2 kN. The force required to remove the bolt was equal to 48 kN. The maximum value of pressure exerted on the compound layer in the plate holes amounted to 159.4 MPa. When the bolt was removed, it was observed that the compound sleeve of 1 mm thickness filled the space between the bolt and walls of the holes in plates completely and was not damaged (no crushes or cracks). In the place where force P was exerted, permanent bolt deflection equalled 1 mm.

The test proved that:

— the compound filled the gap (about 1 mm in height) between the bolt and the walls of the hole, completely;

— the joint with the bolt fitted in the compound can transfer considerable transverse loads;

— it is possible to disassemble the joint even after some permanent bolt deflection.

Another test was performed on holding-down bolt shank fitted in the compound according to Fig. 8.9, in order to check its performance. The shank was fitted in the hole of steel disk eccentrically, so that the maximum thickness of the compound sleeve was 1.5 mm and the minimum one was 0.5 mm.

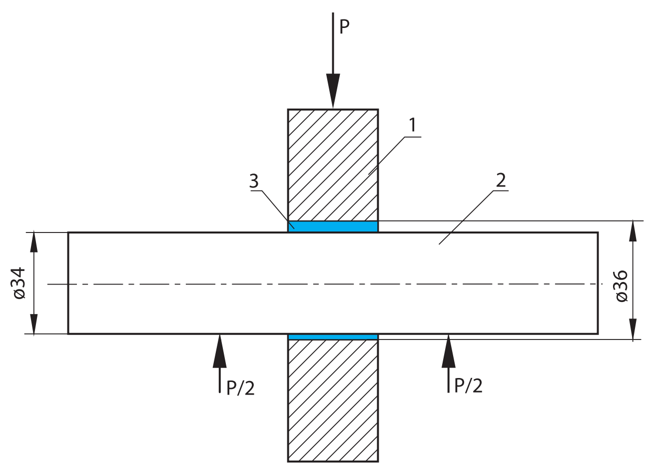


Fig. 8.9. Schematic loading diagram for the bolt shank seated in the compound: 1 — steel disc, 2 — bolt shank, 3 — compound layer

Liquid compound was poured into the gap between the bolt shank and the wall of a steel plate, placed vertically. The shank was covered with a thin layer of a release agent. The test was performed on two models. In one, the thinnest layer of the compound (0.5 mm thick) was compressed, and in the other — the thickest layer (1.5 mm) was tested. Compression test on the first model was stopped when the force reached 260 kN, and on the other model — at 200 kN. The test was stopped when a permanent deformation (bending) of the bolt shank was noticeable.

The disk was cut after the test in order to examine the state of the compound layer. The compound filled the gap completely providing the desired tight fit for the bolt shank. Compression stress (250 and 192 MPa) arisen during the test did not destroy the compound layer (except for its edges). The cast sleeve of the compound did not lose its tenacity either, and it adhered to the walls of the hole in the plate.

Further tests covered the compression strength of the thin wall sleeve cast and cured in the gap between the bolt and a semicircular pit in a steel support. The tests were conducted as shown in Fig. 8.10. The main aim of the tests was to find out how a thin sleeve made of the compound would behave under very high compression stress.

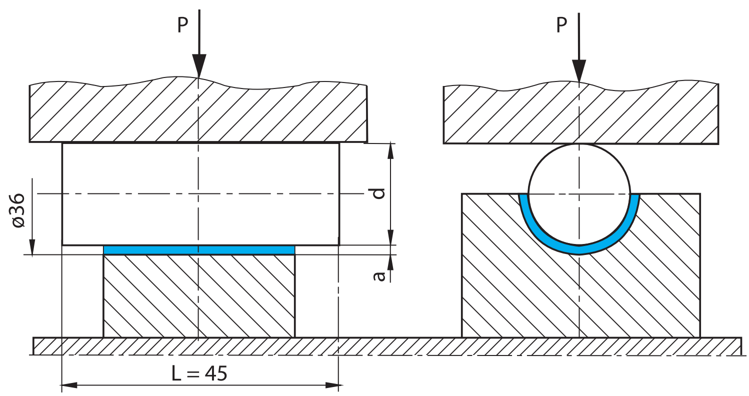


Fig. 8.10. Schematic diagram of compression test of the thin sleeve cast of chocking compound

Specimens prepared for the tests differed in the wall thickness *a* of sleeve made from the compound. The surfaces on supports and bolt shank contacting the compound were covered with a release agent (Siliform AR1). The compound was cast and cured for 10 days at about 18°C. After that, all three models underwent a compression test. The test was performed in a compression testing machine ZD-100. The specimens were subjected to radial force growing from 0 to 1000 kN and distributed on the shank generating line. Compression stress exerted on the compound sleeve ranged from 635 to 694 MPa depending on the diameter of the shank.

For all tested specimens, the compound layer was neither destroyed nor noticeably damaged. There was no outflow of the compound under temporary compression force of 1000 kN either. However, considerable plastic deformations occurred in bolt shanks in the places of their linear contact with the pressing plate of a compression testing machine. The tests proved a high strength of a thin layer of the compound under static compression when cast and cured between two metal surfaces. No significant differences were noticed between the compound layers of 2.1 and 0.1 mm in thickness.

Modeling and numerical calculations of the tested system were also conducted by means of FEM method. To this end, an auxiliary model was selected, as shown in Fig. 8.11. Disregarding boundary effects occurring in the extreme cross-sections of the considered system, a "slice" having the thickness g = 10 mm (Fig. 8.11b) was cut out of it, and plane strain state was assumed. Also, full adhesion between the compound and metal was assumed, that is justified by a high value of friction coefficient (close to 1)and occurrence of high compression stresses in contact area.

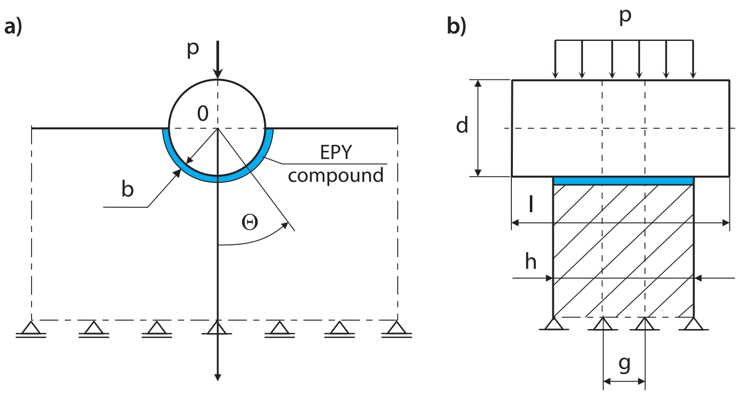


Fig. 8.11. Auxiliary model for determining streses in a thin resin compound layer

The following data were used for the calculations: $E_s = 2.1 \cdot 10^5$ MPa, $\nu_s = 0.3$, $E_t = 5.0 \cdot 10^3$ MPa, $\nu_t = 0.38$, l = 45 mm, h = 30 mm, d = 32 mm, b = 2 mm, $P = 2.08 \cdot 10^2$ N. Value of the force P was so selected as to obtain pressure value related to the area d×g equal to $p_0 = 100$ MPa.

The numerical calculations were performed with the use of MES ANSYS computer software. Polar coordinates frame was selected, as shown in Fig. 8.12. Fig. 8.13 and 8.14 present results of the calculations.

Fig. 8.13 shows distributions of particular stresses acting in the middle plane of the compound layer (for r = 17 mm). Fig. 8.14 presents a collective diagram containing distributions and values of the stresses which occur in the middle plane of the compound layer under action of the force P (as shown in Fig. 8.11)

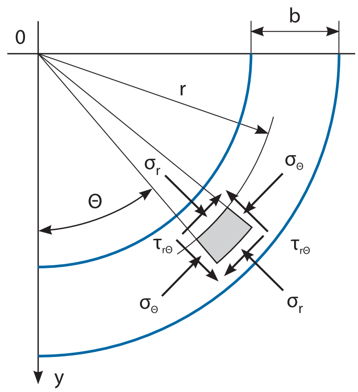


Fig. 8.12. Notation of stresses in the polar coordinates frame

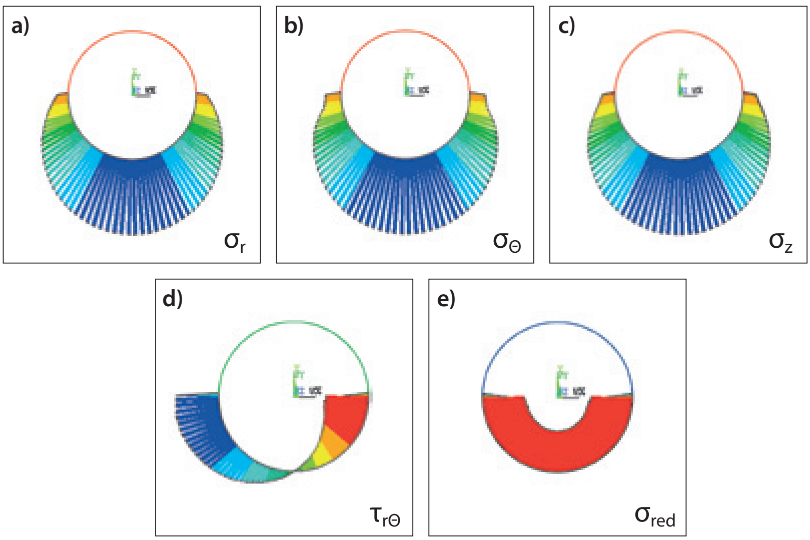


Fig. 8.13. Distributions of the normal stresses (σ_r, σ_Θ, σ_z), tangential stresses ($\tau_{r\Theta}$) and reduced stresses (σ_{red}) in the middle plane of compound layer

of a value which ensured the calculation pressure on the d×g cross-section area, $p_0 = P/d \times g = 100$ MPa. It is worth paying attention that distribution of reduced stresses is almost uniform within the whole compound layer. and their value is much lower than the set calculation pressure p_0 and the maximum values of the normal stress components (σ_r, σ_Θ, σ_z). Due to this fact, very efficient transfer of large external loads is ensured.

The positive results of the laboratory tests and theoretical analysis as well as implementation work fully confirmed that to apply chocking compound to the seating of

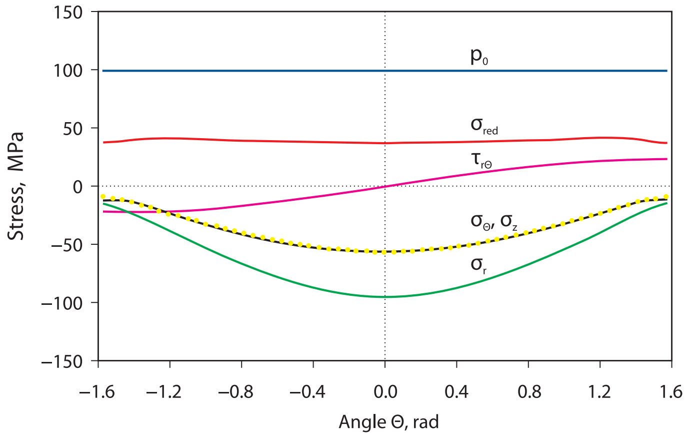


Fig. 8.14. Collective diagram showing distributions of component stresses and reduced stresses occurring in the middle plane of compound layer (in angular coordinate Θ)

the fitted in it holding down bolts of main propulsion engines on ships, is possible. The considered solution regarded novel, has been granted Polish patent [49] and approval certificates from the side of ship classification societies.

8.3. Research on optimum application of EPY compound for the deck machinery seating

8.3.1. Introductory remarks

The permissible compression stress on the compound used in foundation chocks under main marine engines amounts to 5 MPa. Such low permissible stress was determined by classification societies because of the creep susceptibility the compound shows at higher temperatures. As the compression strength of standard specimens made of the compound is 140÷150 MPa, resulting value of compression safety factor is 28÷30. In reality, the strength of the compound in a foundation chock is much higher than in case of standard specimen because the ratio of its bearing surface and height is large. As a result, safety factor value is much greater than 30. For the same reason, the creep of compound foundation chocks is also considerably less than the creep determined from tests of standard specimens of the same material.

Windlasses and mooring winches as well as other auxiliary shipboard equipment installed on the deck or inside the ship do not require such precise aligning as main engines. Therefore, there is no need to apply such excessively high values of the safety factor. As a result, foundation chocks may be smaller and compound strength properties may be used more rationally.

The application of foundation chocks cast of EPY compound instead of steel chocks under windlasses and mooring winches without introduction of any changes in their designs, required special research with taking into account compression pressure much higher than 5 MPa.

The aim of the research was to answer the question whether such compound chocks used under windlasses and mooring winches could safely endure 15 MPa pressure during installation, operational pressure of 30 MPa and short-lasting emergency pressure of 60 MPa in the period t = 30 min. To answer the question, some theoretical analysis was carried out and the experimental tests were conducted on the chock models.

8.3.2. Theoretical analysis

For a specimen with dimensions of 20 mm diameter and 25 mm height subjected to free compression a uniaxial state of stress, disregarding friction, may be assumed. In a real chock a complex state of stress occur, because of limited ability to transverse deformations (except for free edges). The compound in a chock is subjected to three-axial compression, which is favourable for operational conditions and ensures a very high static and fatigue strength. By assuming that a cubicoid element separated imaginatively from a chock cannot be deformed in transverse directions x and y (Fig. 8.15), we can derive the following relation on the basis of the generalized Hooke's law [68]:

$$\sigma_x = \sigma_y = \frac{\nu\sigma_z}{1-\nu} = -\frac{\nu p}{1-\nu} \tag{8.1}$$

where:

p — surface pressure,
ν — Poisson ratio.

By assuming (on the basis of these authors' research) that Poisson ratio of EPY compound ν = 0.376, we obtain:

$$\sigma_x = \sigma_y = -\frac{0.376\,p}{1-0.376} = -0.6026\,p \tag{8.2}$$

Reduced stress in a chock is derived according to the Huber hypothesis [140] from the formula:

$$\sigma_{red} = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2 - \sigma_x\sigma_y - \sigma_y\sigma_z - \sigma_z\sigma_x} \tag{8.3}$$

By substituting respective stress values expressed by pressure p we obtain:

$$\sigma_{red} = 0.397\,p \tag{8.4}$$

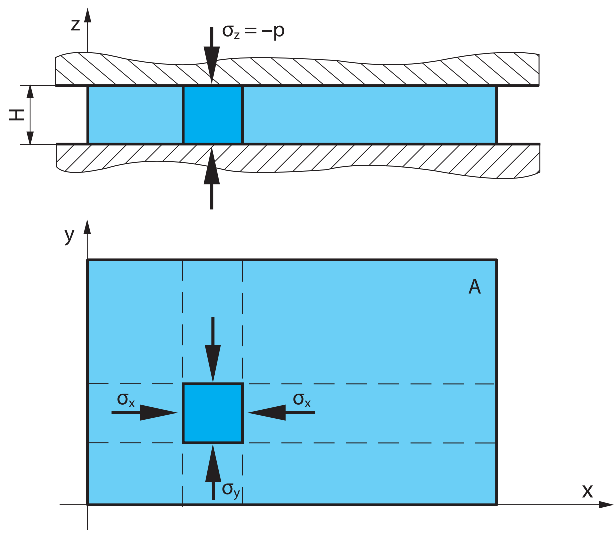


Fig. 8.15. Illustration of stress state in chocking compound

The above presented calculations are a rough approximation only. Reduced stress calculated this way must be lower than a conventional yield point of the compound determined under uniaxial stress. The yield point for EPY compound, $R_{0,2}$, is in the range of 90÷100 MPa. As a result, the calculated pressure acting on chock surface must fulfil the following condition: $p < R_{0,2}/0.397 \approx 2.5\ R_{0,2}$. This provides a 2.5-times greater value of safety factor than that determined for a standard compound specimen tested under simple static compression.

8.3.3. Tests on a windlass foundation chock model

The aim of the tests was to check how a model of an EPY compound foundation chock measuring 100 × 100 × 15 mm (Fig. 8.16) is going to behave within the period of 60 min under the force F = 900 kN generating the pressure p = 90 MPa.

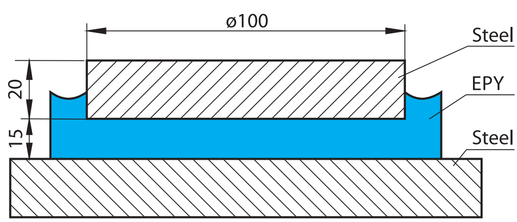


Fig. 8.16. The model of windlass chock tested under surface pressure of 90 MPa

The EPY compound chock was cast *in situ* between two steel plates and cured for 3 days at ambient temperature (about 24°C). Such model of a joint (two steel plates with a chock cast in between) was subjected to the compressive load P = 900 kN in a compression testing machine. The chock was left under the test load (P = 900 kN) for 60 minutes. After that, the load was removed and the chock was thoroughly inspected. No damage and no changes were found in the tested joint. In conclusion, we may state that the pressure p = 90 MPa (1½-times greater than the assumed emergency case pressure) acting for 60 min does not pose any threat to a compound chock cast and cured between two metal plates.

8.3.4. Research findings

On the basis of theoretical analysis based on the calculations and the tests conducted on models, we may conclude that to accept installation stress of 15 MPa, operational stress of 30 MPa and emergency case stress of 60 MPa (acting for 30 min) is safe for the seating of windlasses and mooring winches on foundation chocks made of EPY compound, and it will not produce any adverse effects.

8.4. Research on influence of paint coating on the sagging of shipboard machinery seated on cast compound chocks

8.4.1. Introductory remarks

Contemporary method of ship hull assembling in a berth consists mainly in connecting together smaller or bigger pre-manufactured structural blocks (sections). In order to prevent corrosion, surfaces of the elements are cleaned and covered with one or many layers of protective paint coating which is thick from a dozen or so to about 300 μm.

The traditional installation of machinery on ship foundations with the use of metal chocks requires that the coating must be removed before fitting the chocks to properly cleaned and machined metal surfaces, which is laborious, time consuming and costly.

In present, chocks of chemically cured compound cast *in situ* directly under the machine replaced the traditional metal chocks in the seating of shipboard machinery. Therefore, the question arose whether and how paint coating would influence the quality of the seating. To answer the question, it was necessary to plan and conduct some unconventional tests which would show the influence of paint coating on the contact behaviour of interacting surfaces in real-life conditions in which main engine and auxiliary devices are assembled on ships. The tests were ordered by Szczecin Shipyard S.A.

The main practical aim of the tests was to answer a more specific question: whether, before commencing the assembly of main engine and auxiliary equipment on a ship, paint coating should be removed from load-bearing surfaces of foundations or left there, so the foundation chocks made of EPY compound can be directly cast on the painted surfaces under the machine.

8.4.2. Tested specimens and test stand

The tests were performed on cylindrical specimens cut out from steel plate and coated with anticorrosive paint on one side. Their diameter was equal to 90 mm and the height to 40 mm. The specimens were made and painted in Szczecin Shipyard according to a painting plan for B170/III ships. There were seven specimens, some of them without any coating and some with a single-layer or multi-layer paint coating with thickness ranging from 11 μm to 289 μm. Details concerning paints, number and thickness of coatings are contained in the publications [33, 71]. For every specimen supplied by Szczecin Shipyard, a steel counter-specimen was prepared whose diameter was 90 mm and the height of 46 mm.

In order to attach the instruments measuring contact deformations, holes were drilled, turned and tapped in the specimens (Fig. 8.17). Contact surfaces of the specimens were ring-shaped, and had the nominal area A = 55 cm^2.

A modern servo-hydraulic testing machine of Instron (model 8501 Plus) fitted with special instrumentation was used for the tests. The special computer software

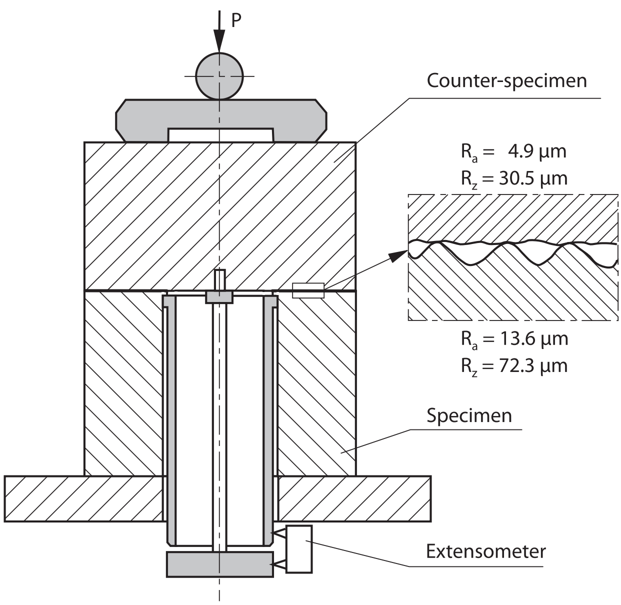


Fig. 8.17. Schematic diagram showing the method of measuring contact deformations and the roughness parameters of specimens

"Wavemaker" managed, according to an assumed plan, the whole control process of loading and recording the resulting data. Measured values of force and contact deformations δ (extensometer indications) were recorded in function of time with an appropriate frequency as ASCII files. The files were transferred to Excel spreadsheet for data processing and graphical presentation of run of the tests and their results.

8.4.3. Testing program, its execution and example results

The tests were carried out in two rounds: first, all specimens and counter- specimens were compressed without the compound (Fig. 8.18a, c) and next, the same was done with specimens having a 1 mm thick layer of EPY compound cast in between and cured (for 48 h in 23°C) (Fig. 8.18b, d). In order to prevent adhesion of specimens, their contact surfaces were covered with a thin layer of release agent (Spray FT 36).

All specimens (with and without the compound) underwent loading to the linearly increasing values of compressive force F and subsequent unloading. Fig. 8.19 through 8.22 present example diagrams illustrating run of the test and its results.

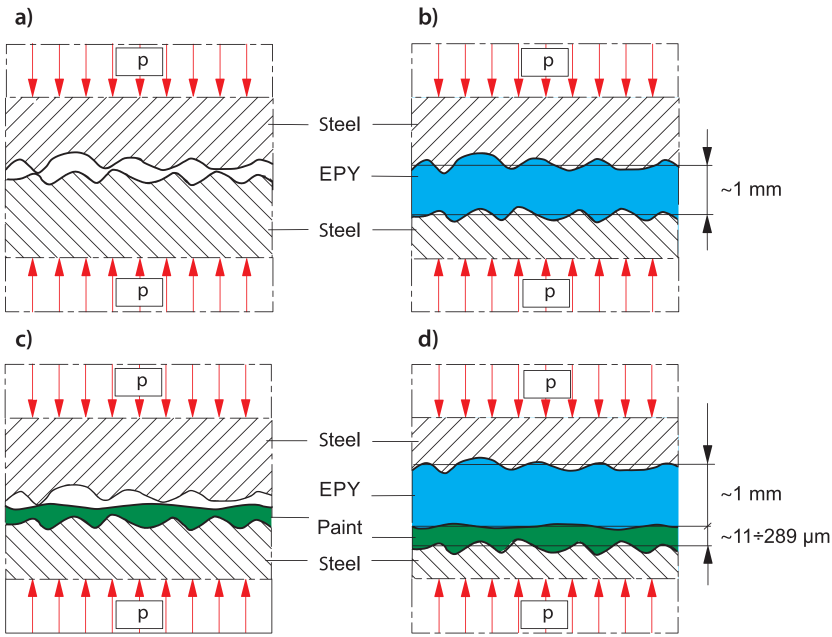


Fig. 8.18. Schematic drawings of tested contact connections: a), b) specimens without paint coating; c), d) specimens with paint coating

Figure 8.19 presents, in function of time, the values of the assumed and exerted surface pressure p and the contact deformations δ_a and δ_b caused by the pressure in specimens without paint coating; δ_a refers to the contact connection without the compound (Fig. 8.18a), and δ_b — to the contact connection with EPY compound (Fig. 8.18b). The shape of the curve δ_a (Fig. 8.19) demonstrates that the relation between contact deformations and surface pressure for specimens without the compound (metal-to-metal) is strongly non-linear. In this case contact deformations (total) are considerable (δ_{amax} = 34 μm) and of elastic-plastic character. Lower points of the curve $\delta_{a,}$ corresponding to zero pressure, indicate plastic contact deformations caused by the preceding maximum loads.

Curve δ_b (Fig. 8.19) presents a time function of contact deformations in specimens with EPY compound (metal-compound-metal). Maximum contact deformations are much smaller (δ_{bmax} = 4 μm), elastic and linear.

The results shown in Fig. 8.19, processed in a way showing the relation between normal contact deformations and surface pressure, are presented in Fig. 8.20. Considerable qualitative and quantitative differences can be observed between contact deformation of specimens without the compound (curves δ_a) and with the compound (curves δ_b). Metal surfaces without any EPY compound, because of their roughness, waviness and shape faults, make contact in a number of "spots" only (Fig. 8.18a). Actual surface pressure is very high and causes considerable plastic deformations of the peaks of uneven spots. As a result, apart from the specimens being brought together in elastic way, there is also permanent closing (so called sagging) of contacting surfaces. EPY compound layer between two surfaces (Fig. 8.18b), filling all the micro- and macro-pits, ensures a tight contact of the surfaces and a uniform load on the whole nominal surface area. As a result, very low values of contact deformations of linear-elastic character, are obtained (Fig. 8.20 — curves δ_b).

Fig. 8.21 and 8.22 show runs and results of analogue tests on specimens covered with four layers of paint coating (289 μm thick in total). The curve δ_a illustrates run of deformations in contact surfaces: metal—paint coating—metal (Fig. 8.18c). Alike as in the case of specimens acc. Fig. 8.18a, the deformations δ_a have large values, non-linear runs and elastic-plastic character. However, the proportions of elastic and plastic deformations are different, moreover, some rheological effects occur in paint coatings (deformation changes in time [36, 143]).

The curves δ_b in Fig. 8.21 and 8.22, which show runs of surface deformations in contact of the kind: metal + paint coating—EPY compound—metal (Fig. 8.18d), are linear. Values of the deformations are very small in contrast to those for the same set of specimens but without a layer of EPY compound, and they are linear and elastic.

Similar results (qualitatively) were achieved for the remaining sets of specimens with paint coatings [36]. The tests proved very favourable influence of EPY compound on deformability of contact joints, both with and without paint coat-

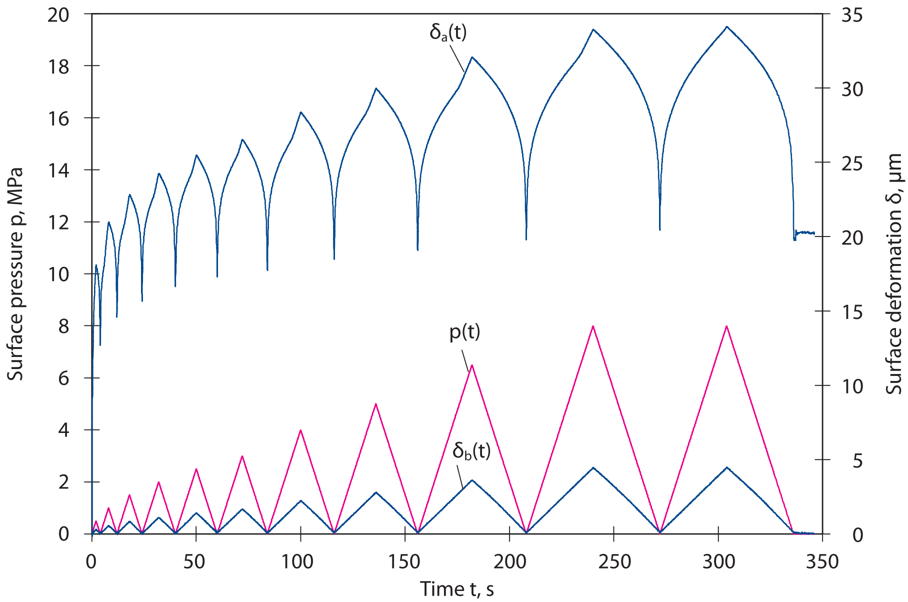


Fig. 8.19. Time runs of surface pressures p and the resulting contact deformations for the specimens without paint coating: δ_a — without the compound, δ_b — with EPY compound layer

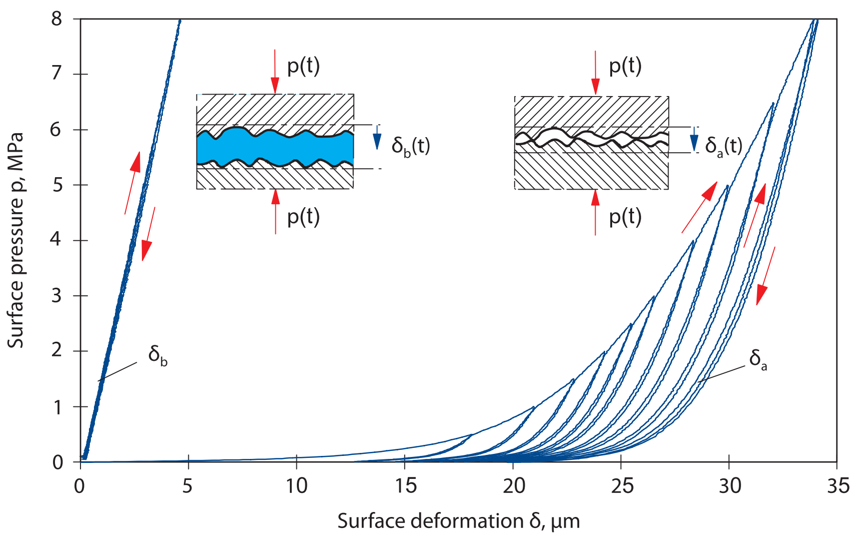


Fig. 8.20. Relation between contact deformations and surface pressure for the specimens without paint coating: δ_a — without the compound, δ_b — with EPY compound layer, under load as in Fig. 8.19

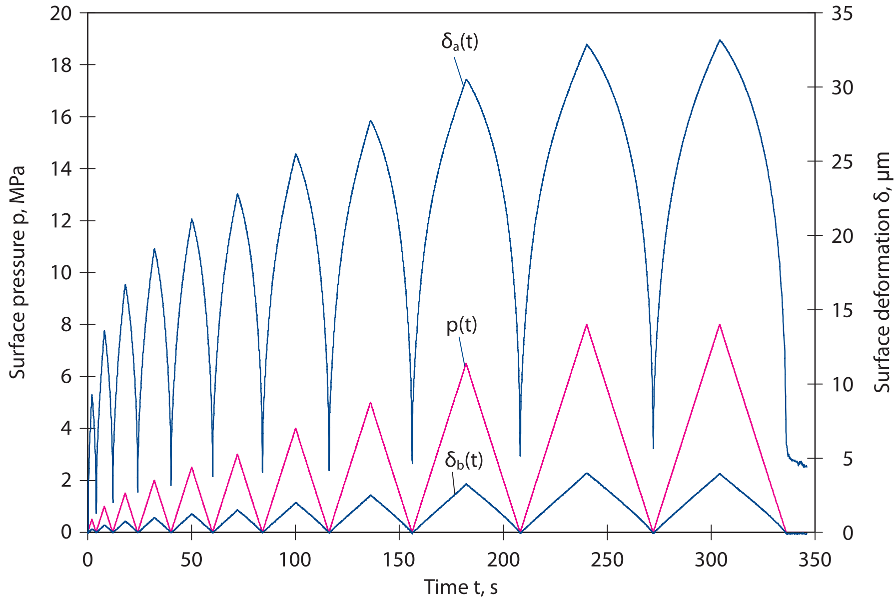


Fig. 8.21. Time runs of surface pressures p and resulting contact deformations for the specimens with four-layer paint coating: δ_a — without the compound, δ_b — with EPY compound layer

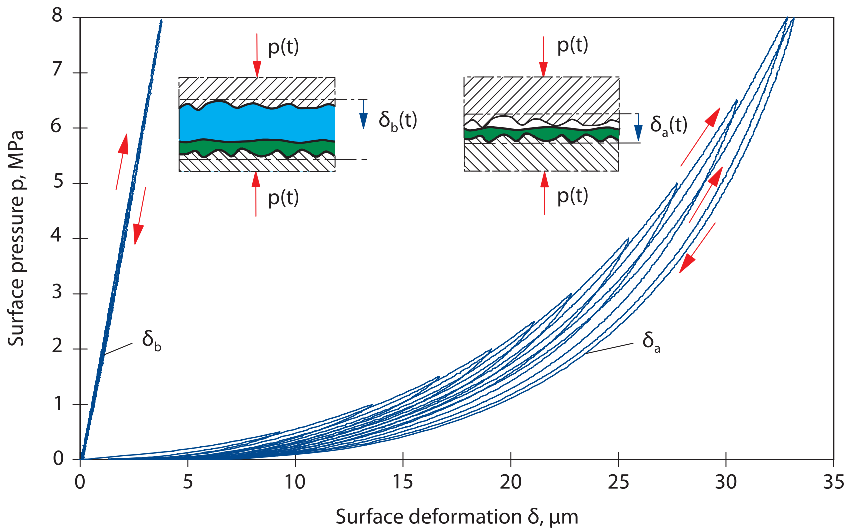


Fig. 8.22. Relation between contact deformations and surface pressure for the specimens with four-layer paint coating: δ_a — without the compound, δ_b — with EPY compound layer, under load as in Fig. 8.21

ings. In case of application of EPY compound the presence of paint coatings 11÷289 μm thick did not show any adverse effect to deformability of the contact joint or its sagging. The contact joints of the same sets of specimens without any EPY compound and with paint coatings showed much greater (7÷10 times) deformability and susceptibility to creeping (also vibration-induced) [143], which results in their sagging.

8.4.4. Conclusions

From the above presented tests, the following conclusions answering the questions put up in the introduction, can be drawn.

In case of seating the shipboard machinery on foundation chocks cast *in situ* from EPY compound, presence of protective paint coating on foundation surfaces does not have any adverse influence on mechanical properties of contact joints between the foundation, chock and bedplate. Neither the type of paint coating nor the number of layers or their thickness (which ranged from 11 to 289 μm) have any practical influence on the tested contact joints. If EPY compound is applied, the characteristics of contact joints for specimens with and without paint coating are almost the same.

In conclusion, there is no justified reason to remove protective paint coatings from the surfaces of foundations before the machines are installed on them. On the contrary: the presence of paint coatings may be beneficial for corrosion protection.

Mechanical characteristics of contact joints between two clean metal surfaces and joints between one clean metal surface and a metal surface covered with protective paint coating differ considerably when there is no EPY compound in between. There are contact deformations and distinctly noticeable creep in a contact joint with paint coating. Therefore, in case the machinery is seated on traditional metal chocks, the removal of paint coating is justified.

8.5. Analysis of construction and model tests of stern tubes seated with the use of chocking compound

8.5.1. Introductory remarks

Technical University of Szczecin has started the research on seating propeller shaft stern tubes with the use of chemically cured compounds as early as in 1976. As a result, a new assembling technology was implemented in Polish shipyards. The first stern tube was mounted this way in 1979 by Ustka Shipyard in B410/2 ship. Since that time, 1637 stern tubes and rudder liners altogether have been mounted on various ships till the end of 2013.

The research and development projects conducted till 1994 concerned stern tubes of relatively small diameters up to 510 mm. Positive experience gained from service of stern tubes installed with the use of the compound gave good grounds for attempts to use the same technology in the assembling of stern tubes of bigger diameters and lengths. Nevertheless, to implement the technology it was necessary to do some additional design analysis and check and elaborate many details of the assembling technology during appropriately programmed model tests in conditions as close to the real ones existing on ships as possible. Such tests were carried out in 1994 by Marine Service Jaroszewicz Co. in close cooperation with the Technical University of Szczecin, Szczecin Shipyard and Gdynia Shipyard. The detailed description of the tests and their results are presented in the report [144] and a short summary is given below.

8.5.2. Aims of the tests

The tests were aimed at:

— analysing the thermal insulation properties of compound layer in an assembled construction in comparison with the traditional technology, and formulating possible requirements concerning cooling;

— analysing thermal deformations of the construction;

— elaborating all details in assembling technology for big stern tubes with the use of EPY compound, and testing them on an appropriate model.

8.5.3. Analysis of thermal insulation properties of a construction system containing EPY compound layer

In order to analyse the thermal insulation properties of a tube system with a EPY compound layer, it was necessary to first determine experimentally the thermal conductivity of the compound. Such research was conducted by the Chair of Heat Engineering at the Technical University of Szczecin [145]. The value of thermal conductivity for EPY compound determined at temperature of 20°C is equal to 0.48 W/mK.

A model of three coaxial tubes (Fig. 8.23) was used for the comparative analysis of thermal conductivity between frame tube, propeller shaft stern tube and EPY compound layer. Boundary conditions of the fourth kind were assumed for the model, i.e. a perfect contact of two elements and temperature equality of both bodies along the surface of contact. A linear model of a specific thermal resistance for a cylindrical wall in radial direction was applied to the comparative analysis of thermal conductivity. The resistance was calculated from the formula:

$$r_{l\lambda w} = \frac{1}{2\pi}\sum_{i=1}^{3}\frac{1}{\lambda_i}\ln\frac{d_{i+1}}{d_i} \tag{8.5}$$

where:

d_i — diameters as in Fig. 8.23,

λ_i — respective thermal conductivity coefficient.

Calculations were conducted for three cases:

1. Propeller shaft stern tube is assembled in compound (as in Fig. 8.23). The following values were assumed: $d_1 = 880$ mm, $d_2 = 960$ mm, $d_3 = 1000$ mm, $d_4 = 1550$ mm, $\lambda_1 = 0.48$ W/mK — for EPY compound, $\lambda_s = 58$ W/mK — for steel. Thermal resistance calculated according to the formula (8.5) was $r_{i\lambda w} = 0.015$ mK/W.

2. Propeller shaft stern tube is assembled by using the negative allowance method (metal-to-metal). The following values were assumed: $d_1 = 880$ mm, $d_2 = 960$ mm, $d_3 = 1000$ mm, $d_4 = 1550$ mm, $\lambda_s = 58$ W/mK. Specific thermal resistance calculated according to the formula (8.5) was $r_{l\lambda w} = 0.016$ mK/W.

3. Propeller shaft stern tube is assembled by using the negative allowance method along a part of its length only; the remaining part was left in the air (20 mm thick layer). The following values were assumed: $d_1 = 880$ mm, $d_2 = 960$ mm, $d_3 = 1000$ mm, $d_4 = 1550$ mm, $\lambda_s = 58$ W/mK — for steel, $\lambda_p = 0.026$ W/mK — for air. Specific thermal resistance calculated according to the formula (8.5) was $r_{l\lambda w} = 0.025$ mK/W.

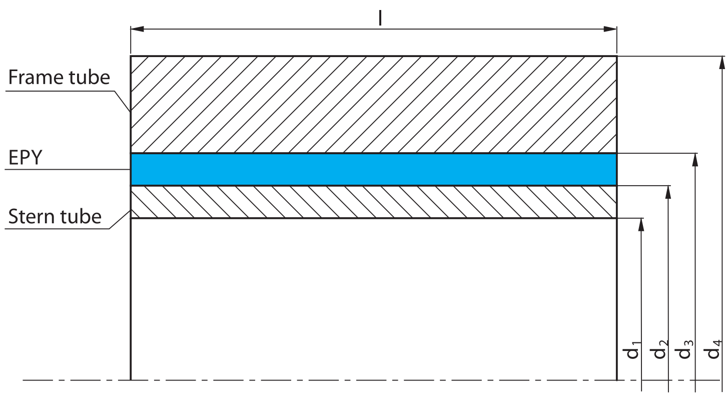


Fig. 8.23. Model of the system: frame tube — propeller shaft stern tube — EPY compound layer

The following conclusions may be drawn from the calculations:

1. Thermal resistance in the radial direction through a cylindrical steel-EPY compound wall is about ten times greater than that for analogue steel-steel wall.

2. Thermal resistance of the wall with air layer is 16.7 times greater than in case where the compound layer is present.

8.5.4. Analysis of thermal deformations

First, a coefficient of linear thermal expansion was determined experimentally for EPY compound at various temperatures. To this end, three specimens were tested in accordance with PN-82/C-89021 standard: “Plastics. Evaluating the coefficient of linear thermal expansion”. Details are presented in the publication [146]. Mean values of the coefficient for various temperatures are given in Tab. 8.1.

Table 8.1. Values of the linear thermal expansion coefficient α_t for EPY compound

$\alpha_{t\,-50}^{\;20}$	$\alpha_{t\;20}^{\;100}$	$\alpha_{t\;100}^{\;150}$
$24.7 \cdot 10^{-6}$, 1°C^{-1}	$40.4 \cdot 10^{-6}$, 1°C^{-1}	$68.3 \cdot 10^{-6}$, 1°C^{-1}

Calculation of the thermal elongation of propeller shaft stern tube

According to the literature [147], in case of very long stern tubes one end must be fitted freely to enable their unimpeded elongation or shortening in changing temperatures.

In order to calculate the maximum movement of propeller shaft stern tube end in relation to the other end in changing temperatures, a simplified model shown in Fig. 8.24 was assumed with input data referring to an unfavourable situation.

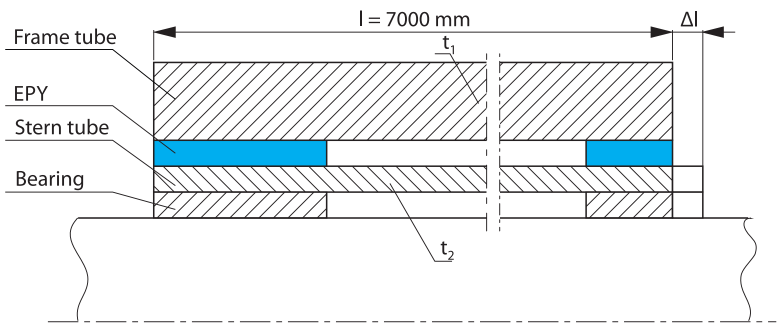


Fig. 8.24. Model for computing propeller shaft stern tube elongation

Stern tube elongation caused by rising temperature was calculated by using the formula:

$$\Delta l = \alpha_s l \Delta t \tag{8.6}$$

where:

α_s — thermal expansion coefficient of steel stern tube,
l — stern tube length,
$\Delta t = (t_2 - t_1)$ — difference of temperatures.

The following values were assumed: $\alpha_s = 12.5 \cdot 10^{-6}$ 1/°C, $l = 7000$ mm, $t_2 = 55$°C, $t_1 = -5$°C. The result of calculations according to the formula (8.6) was:

$$\Delta l = 5.25 \text{ mm}$$

The obtained value is the elongation of a stern tube deforming freely in extremely unfavourable conditions. In reality, difference of temperatures Δt is usually smaller so elongation Δl will also be smaller, respectively.

If the ends of a stern tube cannot move freely, the following longitudinal compressive stresses will occur:

$$\sigma_c = E_s \varepsilon = E_s \Delta l / l = 2 \cdot 10^5 \cdot 5.25/7000 = 150 \text{ MPa} \quad (8.7)$$

where
$E_s = 2 \cdot 10^5$ MPa — Young's modulus for steel.

The change of stern tube outer diameter, ΔD, assuming that D = 1000 mm and deformation is free, is:

$$\Delta D = \alpha_s D \Delta t = 12.5 \cdot 10^{-6} \cdot 1000 \cdot 60 = 0.75 \text{ mm}$$

It should be stressed that the calculated values of thermal elongation Δl and ΔD are caused only by the difference of temperatures $\Delta t = t_2 - t_1 = 60°C$ in stern tube and frame tube and they do not depend on the fact whether the compound is used for the seating or not. Therefore, if the compound is used, the stern tube must have a freedom of movement in its one end, while staying in contact with compound.

In case there is no freedom of mutual longitudinal and radial movement of stern tube and the compound (Fig. 8.25), stresses are expressed by the formulae:

$$\sigma_t = E_t \alpha_t (t_1 - t_2)$$
$$\sigma_s = E_s \alpha_s (t_1 - t_2) \quad (8.8)$$

where:
σ_t — stress in compound,
σ_s — stress in steel stern tube,
$E_t = 4915$ MPa,
$\alpha_t = 40.9 \cdot 10^{-6}$ 1/°C.

For the assumed extreme values: $t_1 = -5°C$ and $t_2 = +55°C$, the following values were obtained for longitudinal and circumferential compressive stresses: $\sigma_t = -11.9$ MPa, $\sigma_s = -150$ MPa.

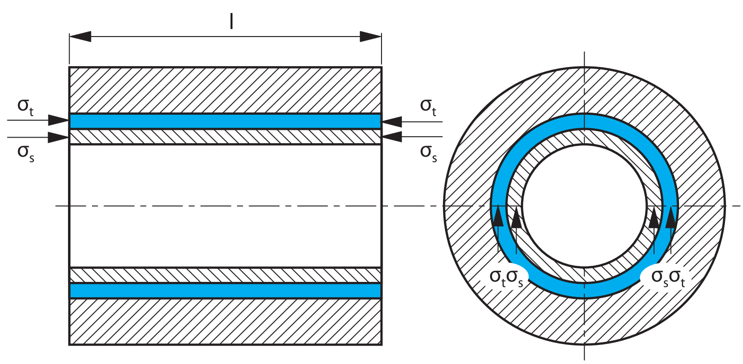


Fig. 8.25. Simplified model for determining thermal stresses in the stern tube system at no freedom of longitudinal and radial displacements

In reality, there is always some (limited) freedom of deformation and movement as well as relatively smaller differences of temperatures $\Delta t = (t_2 - t_1)$. Therefore, the actual values of thermal stresses are usually smaller than those above calculated.

8.5.5. Model tests of a propeller shaft stern tube assembling

The aim of the tests was to check in practice all the details involved in installing a propeller shaft stern tube of a large diameter (about 1 m) with the use of EPY compound. The tests were conducted in Szczecin Shipyard on the model constructed by the Mechanical Department W-2 (Fig. 8.26 through 8.28).

The model of a stern tube (bearing) of a propeller shaft (Fig. 8.27) was made of a steel pipe with a welded seam. A flange was welded at one end. On the outer surface of the pipe, two longitudinal grooves 16 mm wide and 14 mm deep modelling

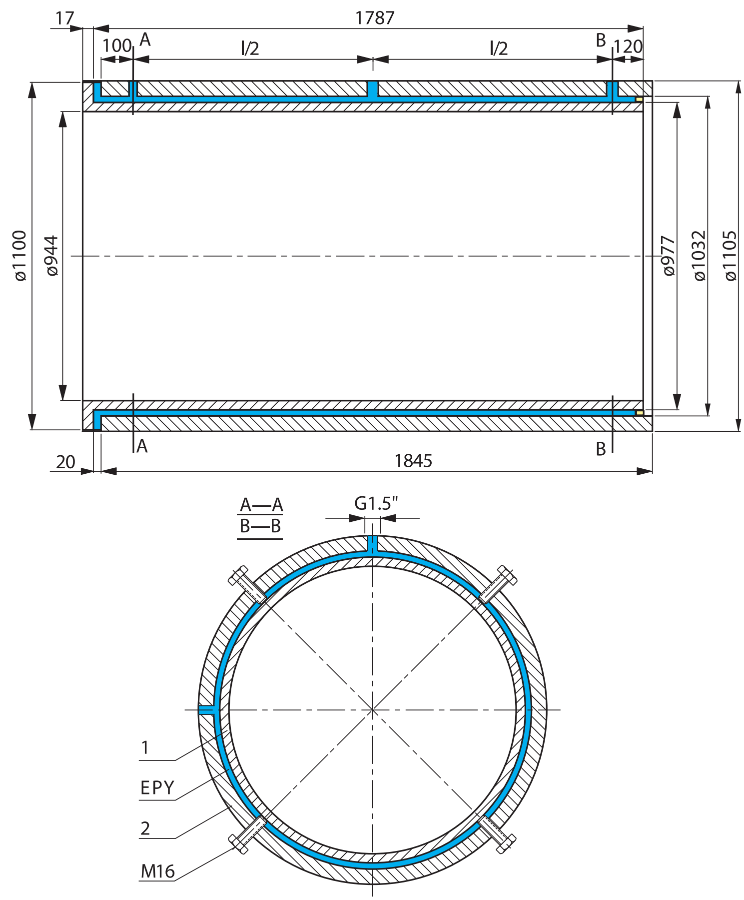


Fig. 8.26. Model of the system of propeller shaft stern tube (1) and frame tube (2) with EPY compound layer in between

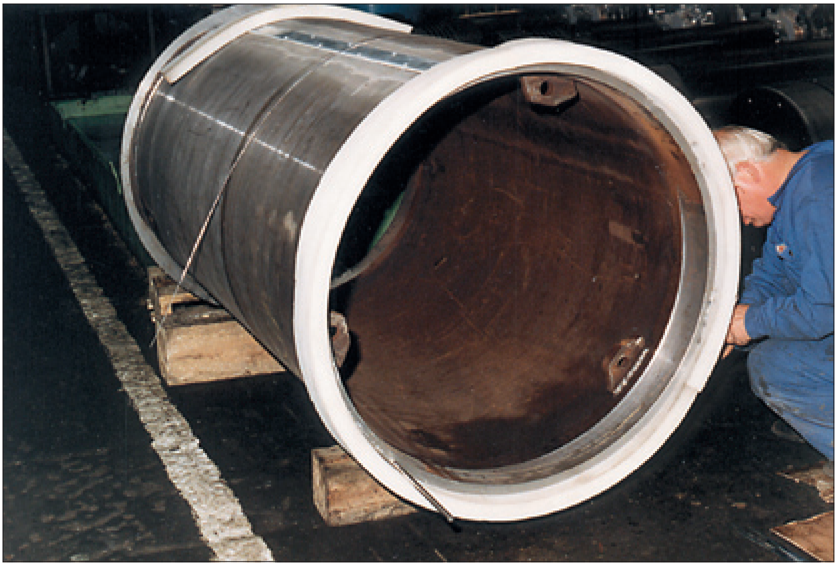


Fig. 8.27. The model of propeller shaft (bearing) stern tube (inner pipe)

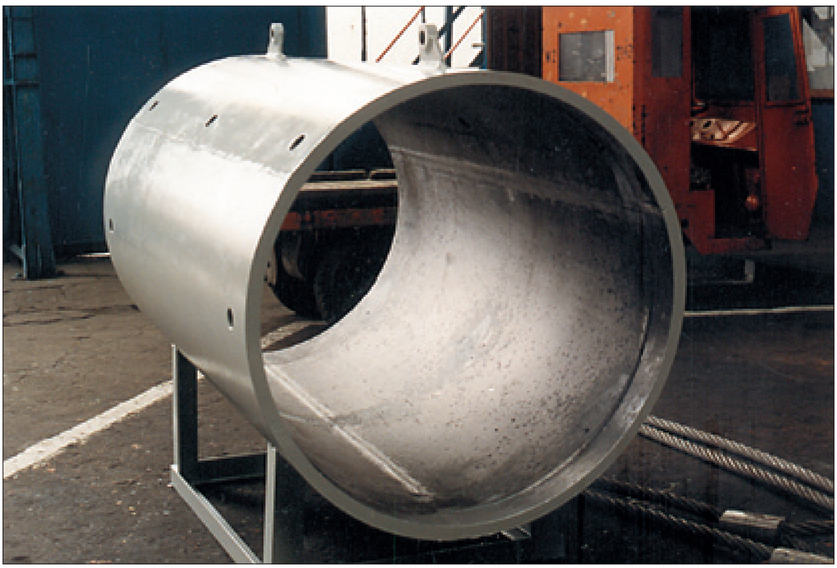


Fig. 8.28. The model of frame tube (outer pipe)

Fig. 8.29. Fore packing made of polyurethane foam and steel band (before mounting)

Fig. 8.30. The model of the assembled system of propeller shaft stern tube and frame tube, fitted with sensors for measuring relative displacements of joined elements

lubricating channels and a groove modelling a channel for oil temperature sensor, were milled. There were three holes of 10 mm diameter, bored through the bottom of oil grooves. Oil grooves were covered with steel slats and sealed with silicone.

The model of a frame tube (outer tube — Fig. 8.28) was made of three steel segments welded together. The pipe had holes for filling and venting, nine inspection openings with 1.5″ threads for plugs and eight holes with M16 threads for adjusting screws (Fig. 8.26). The outer pipe was put on the stand (Fig. 8.28) with inclination angle of 3°45′, the same as on the slipway.

Fore packing was made of polyurethane foam and a steel band (ring) (Fig. 8.29). The inner tube was put into the outer pipe together with fore packing by using a gantry crane.

Basic data:

— volume of space to be filled: $V = 118.7\ dcm^3$,

— mass of EPY compound to be poured into the space:
$M = V \cdot \rho = 118.7\ dcm^3 \cdot 1.59\ kg/dcm^3 = 188.7\ kg$,

— ambient temperature: 19°C,

— temperature of compound before mixing: 28°C,

— temperature of compound before filling: 36°C,

— time of pouring 12.6 kg of compound into a side filling hole (gap g = 20 mm): about 1 min,

— mass of compound poured in during the first stage of pouring:
$M_1 = 10 \cdot 12.6\ kg = 126\ kg$,

— curing time of compound poured in the first stage: t = 5 h,

— time of pouring 12.6 kg of compound through the upper filling hole (gap g = 5 mm): about 5 min,

— mass of compound poured in the second stage: $M_2 = 5 \cdot 12.6\ kg = 63\ kg$,

— total mass of compound poured in: $M = M_1 + M_2 = 126 + 63 = 189\ kg$.

Stern packing was made of polyurethane foam and a steel band (ring) as well. After joining the pipes and installing the stern packing, the sensors (Fig. 8.30) were installed to measure the relative displacement of the pipes while pouring EPY compound into the space between the pipes and also during the curing phase. Special funnels were put into filling holes and overflow holes. The methods used for pouring EPY compound into the model and recording relative displacement of the pipes are illustrated in the photographs (Fig. 8.31). The test, whose final stage is presented in the photograph (Fig. 8.32), provided a wealth of useful information, and proved in particular that:

1. The method used for packing the filled space fully passed the exam of the test during installation, pouring and curing phases.

2. The solution applied for closing the oil grooves prevented the compound from leaking into them.

3. Stern tube (bearing) of a propeller shaft should be inserted to the frame tube axially with the use of special equipment ensuring a controlled movement of the stern tube without any damage to fore packing.

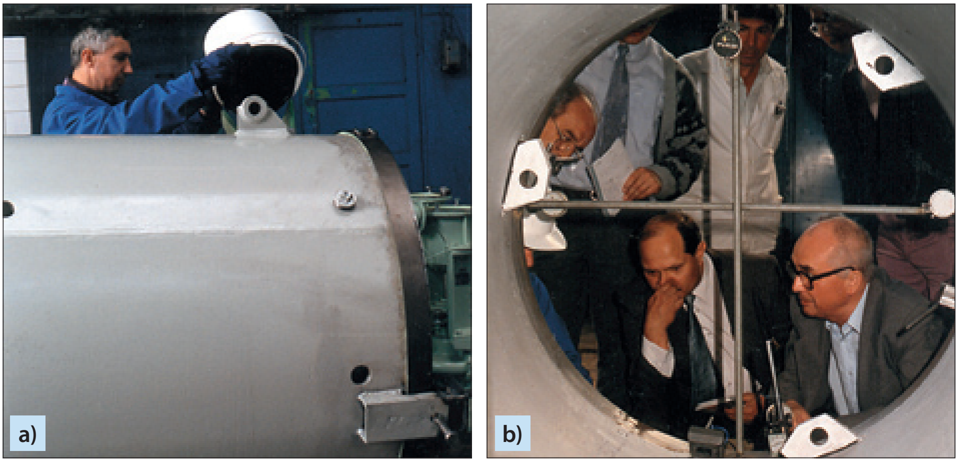


Fig. 8.31. Pouring EPY compound into model (a) and recording the relative displacements of joined elements (pipes) (b)

Fig. 8.32. Final stage of model testing of propeller shaft stern tube assembly (in Szczecin Shipyard)

4. Stern tube should be aligned with adjusting screws to provide its stable position in radial and axial directions.

5. Filling hole (with a diameter of about 40 mm) should be located in the upper part of the frame tube, in the place where compound is the thickest, and its corresponding overflow hole-in the highest place of the filled space.

6. Propeller shaft stern tube should be filled with compound in at least two stages, at a temperature of 20°C.

7. Inspection in control points showed that compound fully filled the space including the places where the layer of compound was thinnest, i.e. amounting 4 mm.

8.5.6. Conclusion

The performed assessment calculations and model testing proved that the propeller shaft stern tubes (bearings) of large diameters (about 1 m) can be installed with the use of EPY compound in real shipyard conditions, and provided a wealth of valuable information necessary to work out the details of assembling process of these units.

8.5.7. Epilogue

Having completed the tests in Szczecin Shipyard, the model of the unit consisting of a frame tube and propeller shaft stern tube with a layer of EPY compound in between was taken to Marine Service Jaroszewicz Co. where it was exposed to weather action for a long time. After seven years, the outer pipe was cut lengthways with a gas torch in a few places, and dismounted (Fig. 8.33).

When the model was dismounted, it was observed that the compound filled the whole space between the pipes, and was coherent and uniform. Metal surface in contact with the compound was not corroded. It proved that the contact of the

Fig. 8.33. Stern tube assembly model (frame tube and propeller shaft stern tube with EPY compound layer in between) during its dismounting: a) gas cutting the outer pipe; b) upper part of the outer pipe, cut-out together with EPY compound layer

compound with metal surfaces is very tight. Its adhesion to metal was lower than its tensile strength, which as a result made it possible to separate big chunks of the compound from the surface.

8.6. Research on possible use of the microwaves for post-curing (additional heating) of EPY compound and foundation chocks cast of it

8.6.1. Introductory remarks

Basic problem encountered in seating any machinery on cast *in-situ* compound foundation chocks is their proper curing. At ambient temperatures lower than 10°C curing process performs too slow. In order to shorten curing time while obtaining the required strength properties, chocks can be additionally heated by using external sources of heat. The most typical method is blowing hot air onto chocks from appropriate heaters; in this way the whole foundation and machinery frame are heated as well. Therefore, it is an arduous and energy-consuming process. In order to overcome the drawbacks, a research was undertaken on a new original method of curing the chocks with the use of microwaves. The aim of the research was to examine the influence of using microwaves for the post curing of EPY compound on its strength properties, as well as possible application of the method to the seating of machines and devices on ships. Detailed descriptions and results of the research are contained in the publications [148÷151]. Only a part of the results is presented below.

8.6.2. Tests on EPY compound specimens

Tests on post curing of EPY compound with microwaves of the frequency f = 2.45 GHz were performed on cylindrical specimens (of 20 mm diameter and 25 mm height) and on full-size models of foundation chocks. Tests on the specimens were done for comparative purposes. Some specimens were cured traditionally and some with microwaves, and then they were subjected to compression tests and creep tests. All specimens used in the tests were cast from the same batch of liquid compound and were cured for 24 h at 23°C. Next, they were divided into seven groups of 10 specimens each. One group was left without additional heating, four groups were additionally heated for 2 h in an oven at temperatures of 60°C, 80°C and 120°C. Then, two groups were post-cured in a microwave oven of 850 W power: one for 2 min (non-stop) and the other — four times for one minute every 5 minutes.

When the specimens cooled down (in about 2 h), a part of them underwent a compression test and the remaining part — a creep test. The compression tests were carried out in accordance with ASTM standard in a 8501 Plus Instron testing machine, the creep tests were conducted in a creep testing machines specially intended for this purpose (Fig. 7.31). The creep tests were performed at a temperature of 80°C and under pressure σ = 10 MPa. Results of the tests are graphically presented in Fig. 8.34 and 8.35.

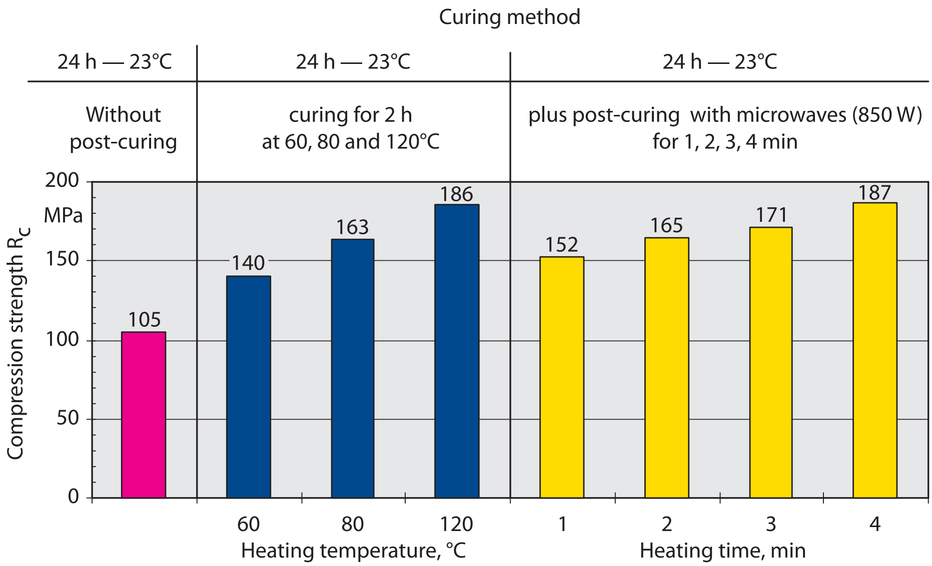


Fig. 8.34. Compression strength of specimens made of EPY compound cured in various ways (traditionally and by using microwaves)

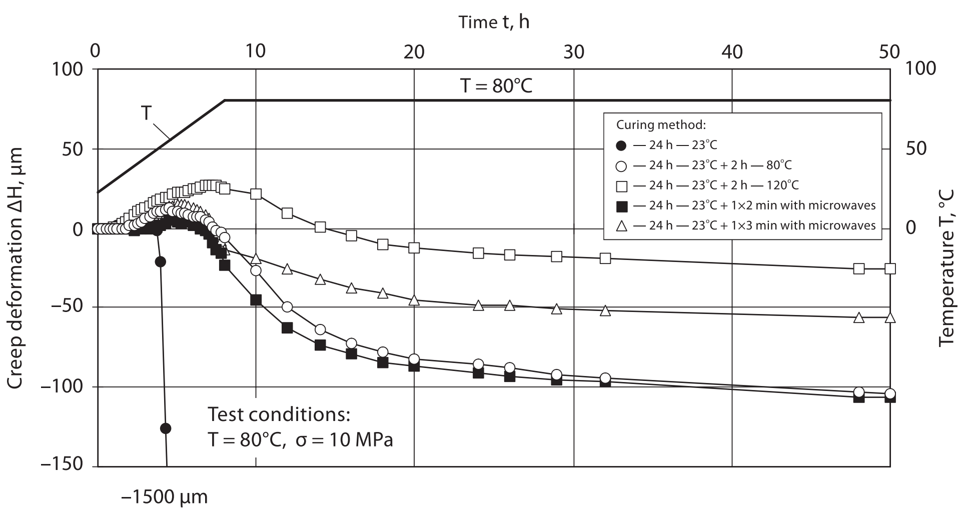


Fig. 8.35. Creep characteristics of specimens made of EPY compound cured in various ways (traditionally and by using microwaves)

Having analysed the results of compression tests and creep tests (Fig. 8.34 and 8.35), the following conclusions may be found:

1. Heating the compound in the oven for 2 h increases its strength. The higher the temperature of heating, the higher the strength. Heating the compound for more than 2 h at any given temperature does not have any considerable influence on the strength of the compound.

2. The additional (post) curing of the specimens in a microwave oven for 1÷4 min produces the same effect as heating them for 2 h in the oven at an appropriately high temperature. What increases the strength of the compound is its maximum temperature. In a microwave oven the temperature of specimens reaches 130÷140°C after about 3 min. Too long exposure to microwaves results in an excessive rise of the temperature in the compound and causes its destruction.

3. There are certain optimum conditions (time and temperature) for the post-curing, which depend on many factors.

8.6.3. Tests on models of foundation chocks

Positive results of the tests on post-curing the compound by using microwaves encouraged these authors to undertake tests on full-size models of foundation chocks. A special device was made for a post-curing with microwaves, which is schematically shown in Fig. 8.36.

Tests were conducted on an axially-symmetrical model of chock, whose drawing is presented in Fig. 8.37. The chock was put on a steel plate and covered with aluminium foil. A microwave antenna was inserted centrally into the hole in the chock. The chock was post- cured 3 times for 5 min about every 5 min. At the intervals, the

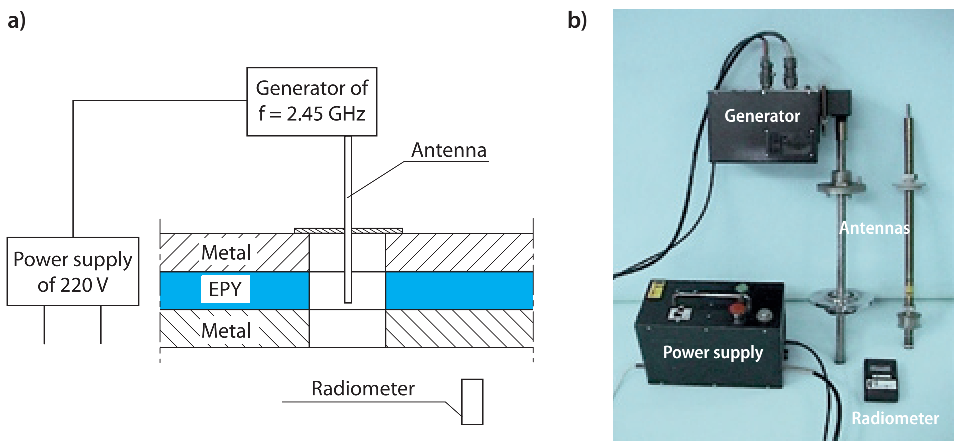


Fig. 8.36. The microwave device for post-curing the compund chocks: a) schematic diagram; b) overall view of elements of the device

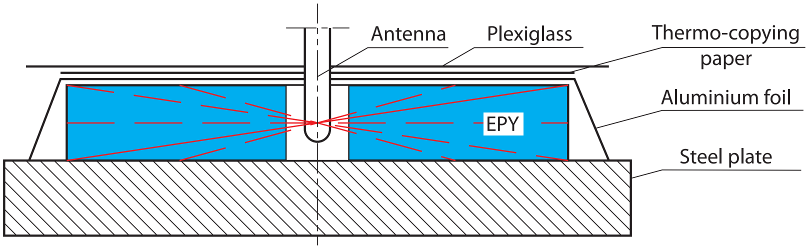


Fig. 8.37. Schematic diagram of microwave emission into the model of EPY compound chock

temperature on the top of the chock was measured with a contact thermometer. After the compound was post-cured and cooled down, a compression test was performed on 30 specimens (of 20 mm diameter and 25 mm height) taken from different places in the chock (Fig. 8.38). Results of the temperature measurements and compression tests are shown in Fig. 8.39

Experimental tests were also performed on a simplified, axially symmetrical model of a foundation joint (Fig. 8.40) made of two steel plates 38 mm thick which simulated the foundation and engine bed-plate. Between the plates, a 30 mm thick chock of EPY compound was cast. The tests were performed on two chocks. Three dial indicators, installed circumferentially on the plates, measured the changes in

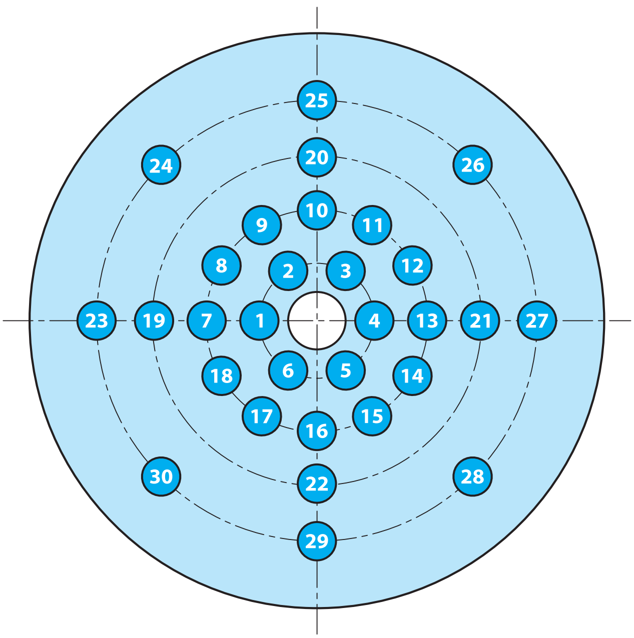


Fig. 8.38. The places in the chock model where specimens were cut out for testing

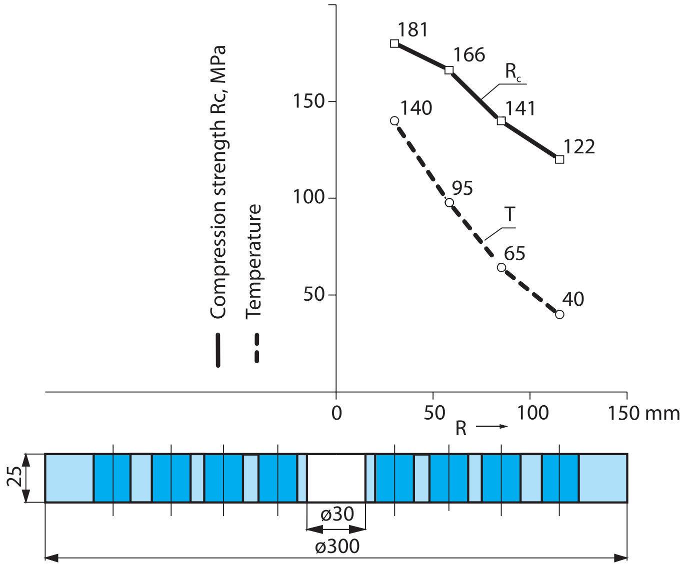


Fig. 8.39. Distributions of maximum values of temperature and compression strength of EPY compound post-cured with microwaves in the foundation chock model

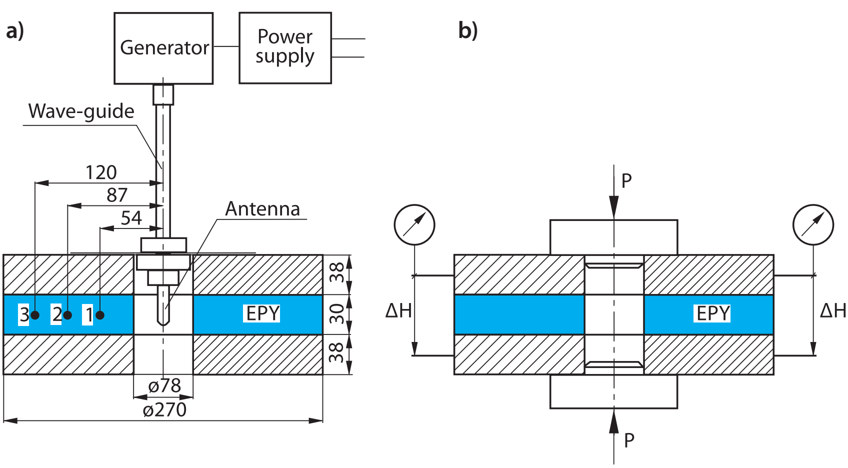


Fig. 8.40. The axially-symmetrical model of a foundation joint with EPY compound chock: a) schematic diagram of microwave post-curing with the marked points where temperature was measured (1, 2, 3); b) schematic diagram of compression test and measurement of changes in height of the chock

Table 8.2. Run and results of tests on models of foundation chock

Run of the tests	T_1, °C	T_2, °C	T_3, °C
Casting the chock №1	19	19	19
Gelation for 3 h	36	36	36
Microwave heating for 4 min at 600 W	101	82	71
Break between heating sessions — 15 min	52	51	47
Microwave heating for 4 min at 600 W	68	69	65
Break between heating sessions — 15 min	50	48	48
Microwave heating for 8 min at 600 W	88	87	74
Load P = 262.5 kN for 5 h at T_o = 39—82°C	ΔH = –0.02 mm		
Casting the chock №2	20	20	20
Gelation for 3 h	36	36	36
Microwave heating for 5 min at 500 W	67	57	48
Break between heating sessions — 15 min	53	50	47
Microwave heating for 5 min at 500 W	65	64	58
Break between heating sessions — 15 min	55	55	55
Microwave heating for 10 min at 500 W	79	71	64
Load P=262.5 kN, for 3 h at T_o = 22—84°C	ΔH = –0.01 mm		

chock height due to compression in strength testing machine, after the post-curing with microwaves was completed. Tab. 8.2 presents the temperature cycles and test results; the temperature T was measured in points 1, 2 and 3 (Fig. 8.40a) after cyclic heating with microwaves; the mean height change ΔH of the chock was measured under pressure *p* while at the same time oil surrounding the chock was heated to a temperature of about 80°C. The pressure exerted on the chock and the increase of ambient temperature correspond to the real conditions in which the engine is started and operated.

8.6.4. Major conclusions

1. The role of microwaves is mainly to heat the compound. The process occurs inside the compound in its entire volume and is very fast. A temperature of 100°C and a high compression strength are reached within a few minutes. Too long exposure to microwaves causes overheating and destruction of the compound.

2. Weakly cured compound absorbs more microwave energy than a strongly cured one. It means that stronger cured compound is a better conductor of microwaves and the amount of absorbed energy is lower. This matter requires further quantitative research.

3. Tests carried out on the models of foundation chocks produced positive results. They confirmed the possibility of using microwaves for the post-curing of full-size foundation compound chocks and the effectiveness of the device designed for this purpose.

4. Practical shipboard application of the method and the device requires further elaboration of technical details, work safety conditions and choice of the optimum parameters of the microwave post-curing process (power, periods of microwave emission and intervals between them).

5. Prospective shipboard application of microwave post-curing of compound chocks may significantly reduce the time and energy used for seating the machines in comparison with the presently used thermal process of post-curing of the chocks.

8.7. Strength tests on holding down bolts anchored in concrete with the use of EPY compound

Installation of anchor bolts with the use of polymer composites proves to be particularly advantageous in the repair and modernization works, when it is necessary to replace destroyed bolts or to install new ones in places imposed by constructional changes (for instance in foundation plate).

The aim of the tests described in detail in the publications [152, 153] and presented in short below, was to examine the practical possibility of using EPY compound for the anchoring of bolts in concrete blocks.

The testing of the load-carrying capacity of bolts anchored in concrete by means of EPY compound was conducted on models (Fig. 8.41) with three types of bolts, whose forms and dimensions are given in Fig. 8.41b, c, d.

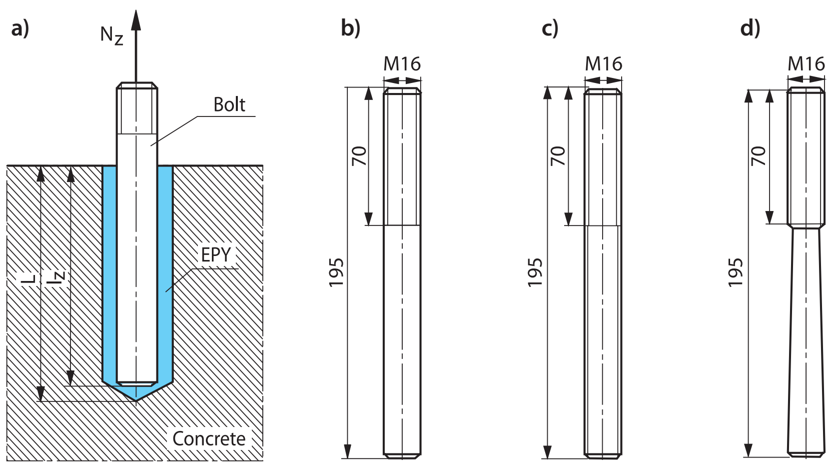


Fig. 8.41. Schematic drawing of the bolt anchoring in concrete (a) and foundation bolts with differently shaped anchoring parts: with smooth cylindrical surface (b), with helical groove (c), with conical surface (d)

Diameters and depth of bolt holes were as follows: D = 18 mm and L = 130 mm and the length of anchoring was l_z = 125 mm. Bolts were driven out of concrete by means of a hydraulic press. Mean values of measured forces N_z (load-carrying capacity of anchor), taken at the beginning of the destruction of anchored bolts shown in Fig. 8.41b, c, d, equalled respectively 64, 57 and 59 kN. Having analysed the differences between the values, one may state that they result from the natural spread of data and the errors of the measuring method, but not from the influence of bolt shape along the anchoring length [152]. However, the shape of a bolt along the anchoring length influences considerably its destruction process, which is demonstrated below. Load-carrying capacity of a bolt anchored directly in concrete, calculated in accordance with Hilti catalogue [154], amounted to N_{zb} = 16 kN.

Bolts anchored in concrete by means of the compound were also subjected to torsional moment rising until their torsional strength was exceeded, which happened at torsional stress of $\tau_{śr}$ = 393 MPa. Anchors were not destroyed. Bolt fractures occurred beyond the length of bolt anchoring.

The model used for the test of adhesion between the bolt and the compound (or between bolt and concrete) is presented in Fig. 8.42. The term "adhesion" means the resistance of an anchored bolt when pulled out [152]. The test was performed by using 8501 Plus Instron testing machine. Example diagrams demonstrating the run of the test and its results are presented in Fig. 8.43. They correspond to the model of

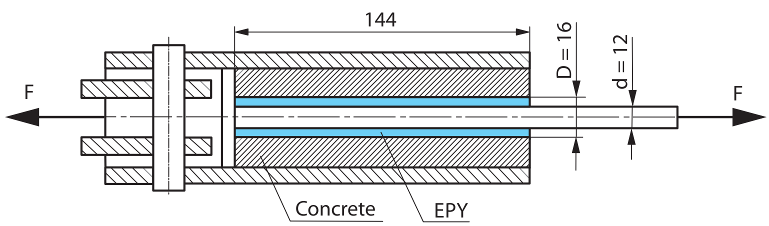


Fig. 8.42. Anchor bolt model for testing its adhesion to resin compound

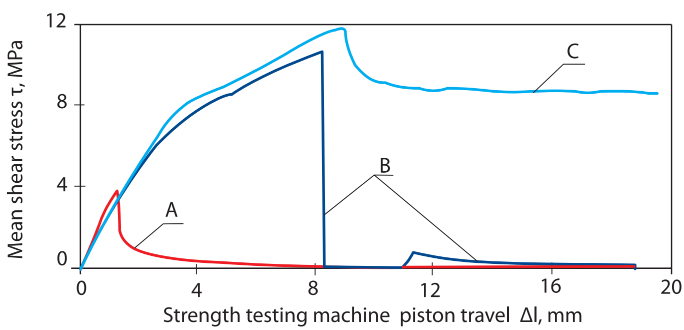


Fig. 8.43. Diagrams of pulling the bolt out of concrete (A) and resin compound (B and C)

the following dimensions: D = 16 mm, d = 12 mm, and l_z = 144 mm. Curve A (Fig. 8.43) refers to a bolt of cylindrical anchor length sunk directly in concrete, and curves B and C — to a bolt with cylindrical or tapered anchor length sunk in EPY compound, respectively. For the three anchored bolts used for comparison purposes, shear stress τ was calculated as a relation of the tensile force F to the shear cross-section area A_τ. The maximum values of shear stresses in case of bolt anchored in the compound are similar and about three-time higher than maximum stress values determined in pull-out test on bolt anchored directly in concrete. In case of the bolt with cylindrical anchor length, destruction of the joint is sudden (curves A and B in Fig. 8.43). The

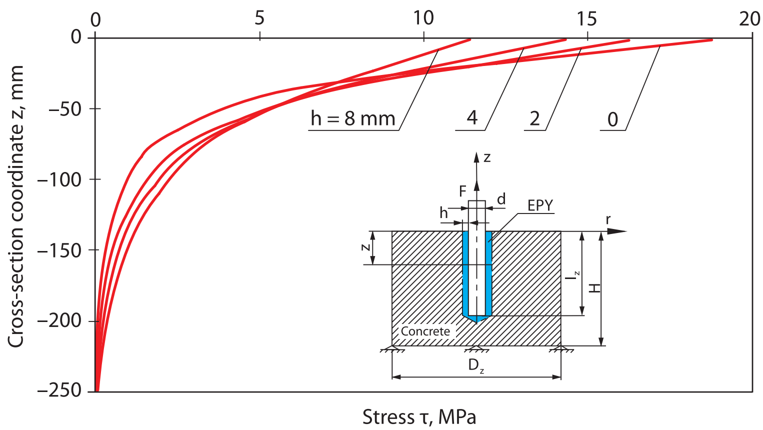


Fig. 8.44. Shear stress distributions on compound layer surface contacting the bolt over anchoring length area

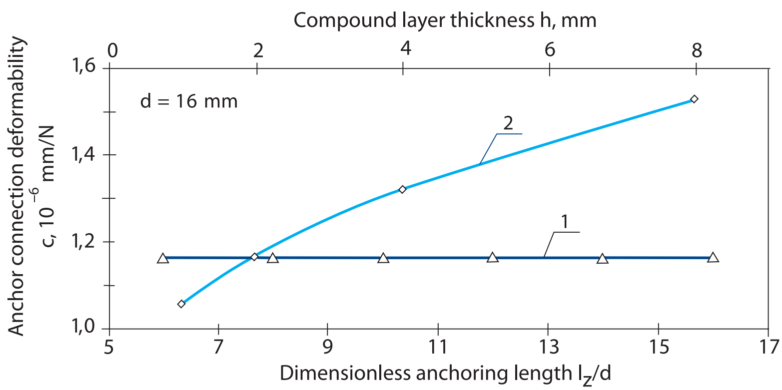


Fig. 8.45. Relation between deformability of the anchor connection and its dimensionless anchoring length (curve 1) and compound layer thickness (curve 2)

bolts with tapered anchor length do not lose all their load-carrying capacity at once (curve C in Fig. 8.43) which prevents the bolts from failures with serious consequences.

Apart from the experimental tests, also the numerical computations were done by using the finite elements method (FEM). Data taken from the experiments [152, 153] was used in the computation. It was assumed that there was perfect adhesion on the contacts between steel and concrete, steel and compound and also concrete and compound. The results of computations are presented in a graphical form in Fig. 8.44 and 8.45.

Shear stress τ in a layer of compound (or concrete at h = 0 mm) touching the anchor surface decreases as the distance from a considered bolt transverse cross-section to concrete surface increases (Fig. 8.44). Maximum values and the rate at which stresses decrease depend on the compound layer thickness. Therefore, it is the thickness of the compound layer that considerably influences maximum values of shear stresses.

Figure 8.45 presents the relation between anchoring deformability and the relative anchoring length (l_z/d) and the compound layer thickness. For a given thickness of the compound layer (h = 2 mm), the anchoring deformability calculated as the ratio of the displacement of the anchored bolt cross-section at the concrete surface and the force effecting such displacement, does not depend on the anchoring length l_z if its value is higher than 6d (Fig. 8.45, curve 1). While at a given anchoring length (for example l_z = 256 mm), anchoring deformability increases when the thickness of the compound layer increases (Fig. 8.45, curve 2).

The performed tests proved good strength properties of foundation bolts anchored in concrete with the use of EPY compound. Their load-carrying capacity is about three times higher than that of bolts anchored directly in concrete. The optimum anchoring length (giving the highest load-carrying capacity) may be assumed equal to l_z = 8d. The shape of the bolt anchoring shank (smooth cylindrical surface with a spiral groove or a tapered shank) has little influence on ultimate load-carrying capacity of the anchoring, but it has some influence on the anchoring damage process. In case of a smooth cylindrical surface, the damage is sudden and brittle in character. However, in case of a tapered shank the loss of load-carrying capacity takes some time and is of elastic-plastic character, which may give some protection against an immediate collapse.

8.8. Research on adhesion between EPY compound and foundation bolt shank

8.8.1. Introductory remarks

For repair of reinforced concrete foundations and modernization of seating arrangement of large reciprocating compressors, and lately also for installation of new such objects, foundation bolts anchored in special polymer compounds are more and more commonly used (Fig. 8.46a). This method has many significant technical and operational advantages in comparison with the traditional method of anchoring foundation bolts in concrete.

In this process adhesion of compound to steel and concrete plays an important role. It should be so high as to make it possible to transfer static and dynamic loads acting onto a given system, safely and without violating its integrity. To know the adhesion and factors on which it depends is crucial not only for designing and manufacturing foundation bolt joints but also in modelling and dynamic analysis of seated objects, which — in a contemporary manner [105÷111] — should be considered to be integral systems consisted of machine, its foundation and fastening arrangement.

Research tests on adhesion, presented in literature [155], and also in preceding own publications [152, 153], have been of a global character and dealt with adhesion of concrete or resin compound to steel bar or bolt shank of a rather large anchoring length.

The main aim of the below presented research was to develop an appropriate method and to determine magnitude of adhesion related to unit area of contact surface between EPY compound and shank of steel foundation bolt, as well as walls of hole made in concrete. Comprehensive tests in this range were conducted in the frame of the research project described in [156]; only a part of their results are presented in this section.

8.8.2. Research on adhesion between EPY compound and shank of steel foundation bolt

8.8.2.1. Test method and specimens used in the tests

Phenomenon of adhesion should be meant in general [155] as a resistance which occurs in a layer of compound or concrete being in contact with steel bar while attempting to pull it out from the surrounding material. The factors governing the adhesion phenomenon are in general as follows [155]:

- adhesion, i.e. intermolecular attraction occurring in contact of two materials;
- mutual catching on uneven areas of contact surfaces of both materials;
- friction occurring in contact of both materials;
- chemical bonding of both materials.

In spite of that a lot of attention has been paid so far to the issue of adhesion between concrete and steel, there is today no satisfactory theory concerning this problem, nor standard recommendations determining a testing method as well as criteria for qualitative and quantitative assessment of results of such tests, are at one's disposal.

Tests on concrete or compound adhesion to steel reinforcing bars or foundation bolt shanks are usually performed for their definite anchoring length l (Fig. 8.46b), and the length is so chosen as not to cause their breaking [155]. In such cases very non-uniform shear stress distribution over contact surface of two materials occurs in the system in question, which is illustrated schematically in Fig. 8.46c [157].

The limiting shear stress R_p, called also the adhesion stress [155], is usually taken as an adhesion measure, which is derived from the formula given in Fig. 8.46c; where

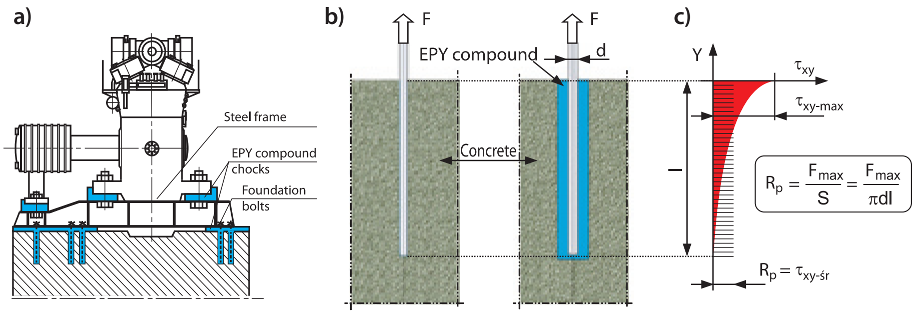


Fig. 8.46. Modernized seating arrangement of a motor-driven compressor (GMVH-12) with the use of EPY compound (a), schematic diagram of classical test on anchored bolt adhesion (b) and distribution of shear stresses occurring in the anchor connection (c)

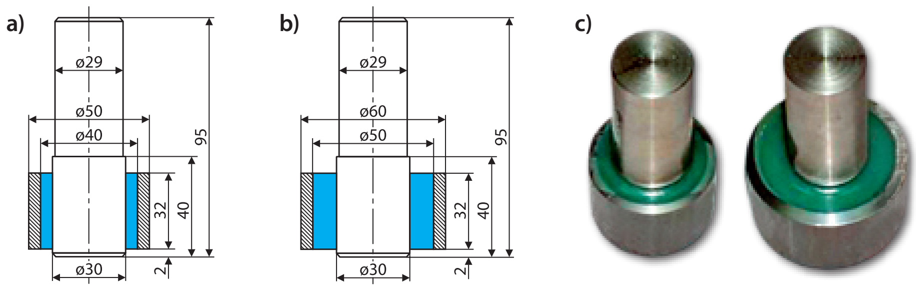


Fig. 8.47. Specimens used in the tests on adhesion between EPY compound and steel bolt shank: a) and b) schematic drawings and main dimensions of the specimens; c) overall view of the specimens

F_{max} stands for a value of force at which a given joint was damaged, and S — contact surface area between a steel element and a considered anchoring material.

The adhesion stress R_p determined this way represents mean value of the adhesion, which significantly depends on the joint length l. However it does not sufficiently describe physical phenomenon of adhesion which is independent of the length l and determines real shear strength of the joint, related to unit area of contact surface.

In order to examine a real (specific) adhesion of EPY compound to steel foundation bolt shank, experimental tests were carried out on specimens representing small parts of the joint. Fig. 8.47a and b shows schematic drawings and main dimensions of the specimens and Fig. 8.47c — their overall view. They are axially symmetrical, consisted of a steel shank and sleeve, as well as a ring cast of EPY compound, filling the gap between the steel elements. The selected diameter of the shank (30 mm) corresponds to that of foundation bolts used for large reciprocating compressors. A relatively low length of the compound-shank connection (equal to 32 mm, i.e. close to its diameter) was so selected as to obtain approximately uniform distribution

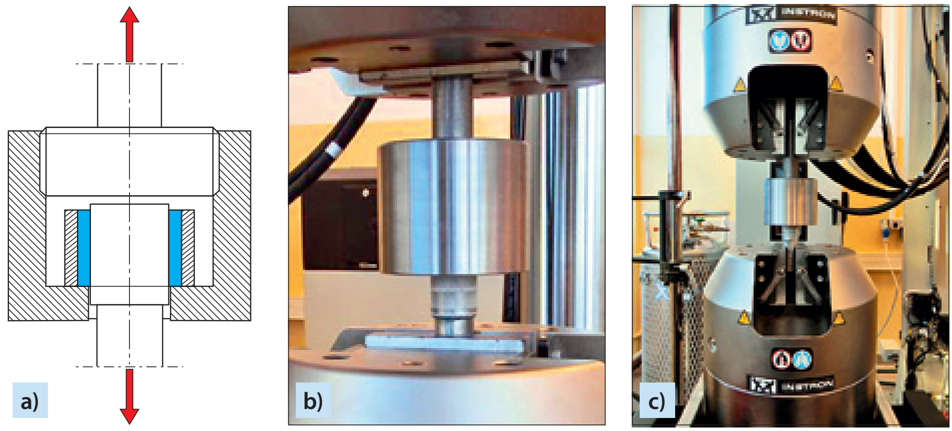


Fig. 8.48. Schematic diagram of the test on pulling-out the shank anchored in the compound (a) and its execution by using a strength testing machine (b, c)

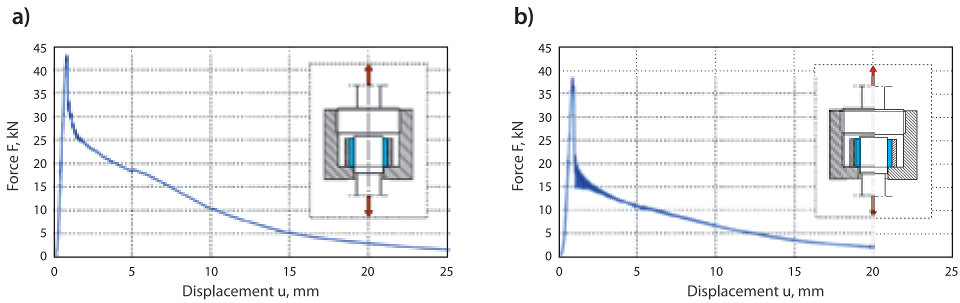


Fig. 8.49. Exemplary curves illustrating runs and results of the tests on pulling-out the shanks anchored in EPY compound: a) for the specimen of ø30/ø40×32, b) for the specimen of ø30/ø50×32

Table 8.3. Results of tests on adhesion between EPY compound and steel obtained from the tests on pulling out the shank from the compound

Specimens of the dimensions: ø30/ø40×32			Specimens of the dimensions: ø30/ø50×32		
Specimen №	F_{max}, kN	R_t, MPa	Specimen №	F_{max}, kN	R_t, MPa
1	42.66	14.14	1	37.88	12.38
2	31.26	10.36	2	41.35	13.71
3	37.36	12.38	3	25.71	8.52
Mean value	37.09	12.29	Mean value	34.98	11.54

of shear stresses over the joint length. The tested shanks were made of 45 steel by turning and had roughness parameters of their surfaces, as follows: R_a = 5.26÷6.43 μm, R_z = 25.30÷31.67 μm. After cleaning and degreasing their surfaces intended for being in contact with the compound, the shanks were concentrically inserted into steel sleeves and poured around with liquid mixture of EPY compound and hardener. Curing process of the compound was conducted at room temperature of 22÷23°C. The adhesion tests were performed after its curing for 5 days.

8.8.2.2. Run and results of the tests on specimens with smooth shanks

The tests were conducted with the use of INSTRON (model 8850)servo-hydraulic testing machine. It was assumed that force exerted onto a given joint will be increasing with a constant speed of the machine's head, v = 1 mm/min (usual in material compression tests) not only until the tested joint is damaged, but up to the instance when the shank sticks out from the compound completely.

Fig. 8.48 shows schematic diagram and run of the test of pulling-out the shank anchored in the compound, executed by means of the testing machine. Runs of the tests are illustrated by diagrams shown in Fig. 8.49, and their results are contained in Tab. 8.3.

As results from analysis of the diagrams (Fig. 8.49), damage of the tested connection of steel shank with the compound is generally effected by shear stresses occurring on contact surface between the two materials. The fast, linear and uniform rise of the load till its maximum value and then its sudden drop show that damage of the joint (due to shear stresses) appears almost simultaneously over the entire contact surface of shank and compound. When the cohesion between shank and compound is lost, the tested joints do not lose completely their load-carrying capacity due to occurrence of a rather large friction resistance in them. The resistance decreases which is associated with gradual shifting out the shank from the compound and smoothing the contact surfaces due to friction.

The quantitative results of the tests, collected in Tab. 8.3, comprise values of the damaging force F_{max} and the adhesion R_p, derived from the formula given in Fig. 8.46c. The results show a rather large spread. For the tested specimens they may be compared to the result for a compound layer 5 or 10 mm thick. The observed differences are contained within spread intervals of the determined parameters.

Mean values of the adhesion (about 12 MPa) determined in the tests, as well as its maximum value (R_{pmax} = 15.67 MPa) are evidently lower than shear strength of EPY compound for which R_t = 40÷52 MPa. Appropriate implementation of the strength properties of this compound (higher than for concrete) makes it possible to significantly improve load-carrying capacity of foundation bolt anchoring in this compound by shaping surface of their shanks properly.

Some experimental tests were arranged to check possible solutions of a high importance for engineering practice. Their run and results are presented below.

8.8.2.3. Tests of adhesion between EPY compound and shanks with cut grooves

In order to additionally prevent bolt anchored in the compound against pulling out, it is possible, instead of applying a retaining nut (commonly used but troublesome in practice) placed at lower end of shank, to shape shank surface in such a way as to increase adhesion effects and more effectively implement strength properties of the compound. It particularly concerns shear strength of shank, which is much higher than its adhesion to a relatively smooth steel surface. Such approach is often used for reinforcing bars dip in concrete, by introducing appropriate ribbing of bar surface. For foundation bolts the treatment can be easily implemented by cutting some grooves in bolt surface. Some experimental tests were made to examine such solutions.

Three series of specimens of 3 pieces each were prepared for testing. Shanks of the specimens were milled (roughly) to get them 30 mm diameter and then cut circumferential grooves in their contact surfaces. Shapes and dimensions of the grooves as well as an overall view of the shanks with cut grooves are shown in Fig. 8.50.

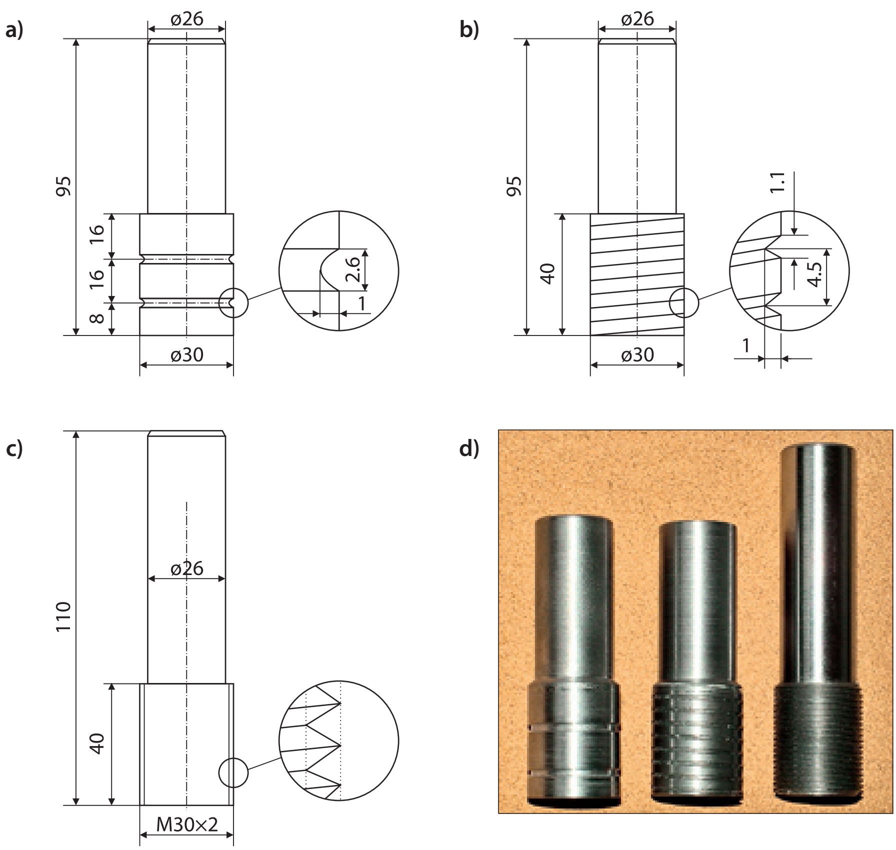


Fig. 8.50. Shanks of the specimens having cut grooves intended for the adhesion testing

The shanks prepared this way together with steel sleeves, after exact cleaning and degreasing their contact surfaces,, were put on support steel plates (ensuring their mutual centring) and poured around with liquid EPY compound mixed in advance with hardener. When the compound is cured at room temperature (22÷23°C), pull--out tests on the shanks anchored in the compound were conducted. Schematic arrangement of such test and its run is shown in Fig. 8.48.

Fig. 8.51 shows runs of particular tests in the form of exemplary diagrams achieved from testing machine. Quantitative results of the tests are collected in Tab. 8.4.

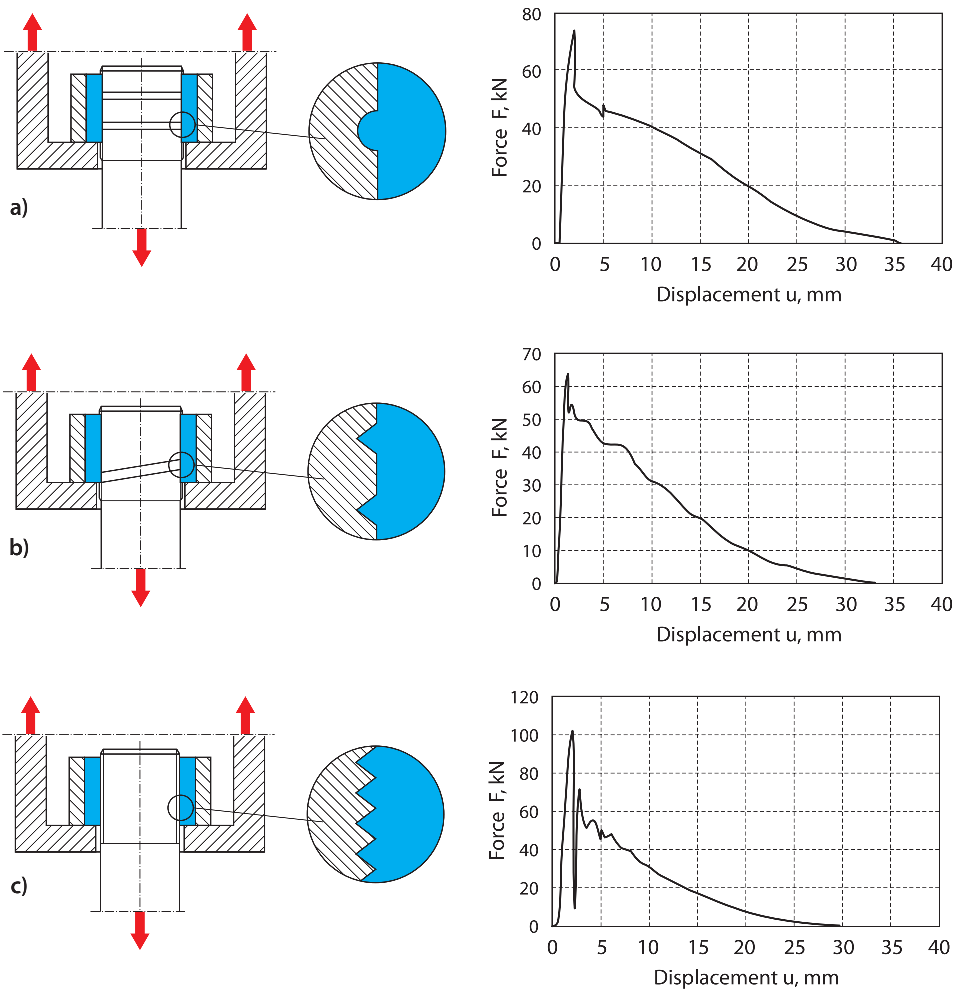


Fig. 8.51. Schematic diagrams and exemplary result curves of the tests on pulling steel shanks having surface grooves of various shapes, out of EPY compound

Table 8.4. Results of tests on adhesion between EPY compound and steel shanks with various form grooves cut on their surfaces

Shanks with two circumferential grooves			Shanks with a helical groove			Shanks with the thread M30×2		
Specimen №	F_{max}, kN	R_p, MPa	Specimen №	F_{max}, kN	R_p, MPa	Specimen №	F_{max}, kN	R_p, MPa
1	73.48	24.36	1	64.16	21.27	1	115.3	38.23
2	75.60	25.07	2	66.56	22.07	2	101.9	33.78
3	77.62	25.74	3	63.52	21.06	3	107.2	35.54
Mean value	75.57	25.06	Mean value	64.75	21.40	Mean value	108.1	35.85

Analyzing the diagrams presented in Fig. 8.51, which illustrate runs of the tests on pulling particular shanks out the compound, one may generally state that they are qualitatively very similar. The similarity consists in a fast rise of load, violent run of damage of the joint and its further significant load-carrying capacity resulting from a relatively high friction drag. This is shear stress acting on the nominal contact surface (cylindrical) between shank and compound, which decides on damage of the joint. The friction drag occurring later, decreases, which is associated with the gradual shifting-out of the shank from the compound and the smoothing of contact surfaces under friction. Tab. 8.4 showing quantitative results of particular tests, comprises values of the damaging force F_{max} as well as the adhesion stress R_p, derived from the formula given in Fig. 8.46c. The nominal contact surface area between shank and compound was $S_n = \pi \cdot 30 \cdot 30 = 3014.4$ mm^2, and the shear surface area in specimens with two circumferential grooves was $S_1 = \pi \cdot 30 \cdot 2.6 \cdot 2 = 489.8$ mm^2, i.e. equivalent to 16.25% of the nominal contact surface area; in specimens with spiral groove — $S_2 \approx 7\pi \cdot 1.1 \cdot 30 = 725.34$ mm^2, i.e. equivalent to 24.06% of the nominal surface area, and in threaded specimens — practically equal to 100% of the nominal contact surface area. The specimens with one small spiral groove, despite the larger ratio of shear surface area and the nominal contact surface area (equal to 24.06%), showed lower strength than the specimens with two circumferential grooves, having the relative shear surface area equal to 16.25% of the nominal one.

8.8.2.4. Comparison of tests on adhesion of compound to smooth shanks and those with cut grooves

Fig. 8.52 shows results of all the adhesion tests, both concerning smooth shanks and shanks with grooves cut on their surface. As results from comparison of the test results for particular kinds of specimens, there are significant quantitative differences between them. There was revealed a favourable influence of grooves cut out in shank surface on drag forces generated during the tests on pulling the shanks out from the compound. By relating the connection strength of the specimens with cut grooves to that of the specimens with smooth- turned shanks, the relative increase in

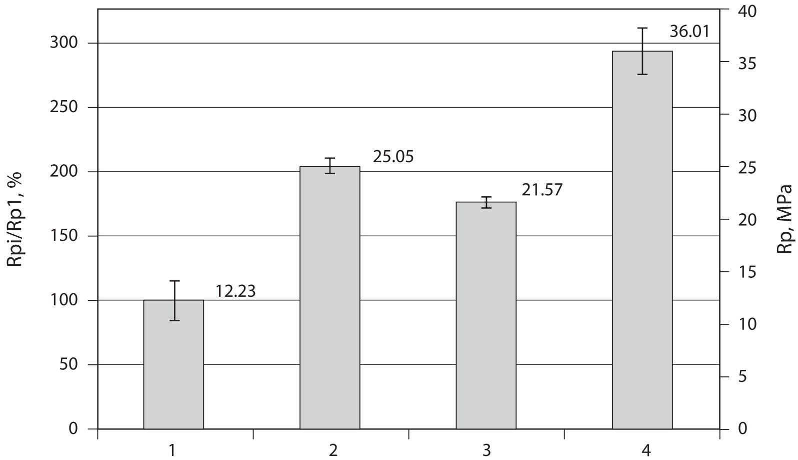


Fig. 8.52. Comparison of the adhesion R_p between EPY compound and steel shanks with smooth milled surface and those having surface grooves; 1 — smooth milled shank; 2 — shank with two ring grooves; 3 — shank with a spiral groove; 4 — shank with M30 × 2 mm thread

mean values of the connection strength ranging from 174.6 to 291.5%,were obtained. The highest, almost threefold rise of the connection strength was reached for the threaded shanks. The rise is caused by the greater shear strength of the compound than its adhesion stress to steel shank (nominally smooth). The compound filling the grooves on shank surface produces catches which resist pulling the shank out. The catches must be cut by shank during its shifting out to make shank pulling out from the compound possible. The greater the ratio of shear surface area and nominal (cylindrical) contact surface area between shank and compound the greater the strength of joint. However the relation is not simply proportional. Shape and location of the groove have also an influence.

Attention should be also paid to the significantly lower spread of test results (Fig. 8.52), manifested by the shanks with cut grooves in relation to the shanks of smoothly turned surface.

8.8.3. Tests on adhesion between compound and concrete

8.8.3.1. Specimens used for the tests

The tests of adhesion between EPY compound and concrete were carried out on specimens shown in Fig. 8.53. They represent some, rather short shank segments of foundation bolt anchored in concrete block with the use of the compound (Fig. 8.46). The specimens constitute an axially symmetrical system of steel elements, concrete and compound which are in close contact to each other. The segment length *l* was assumed very small, equal to bolt shank diameter only, so

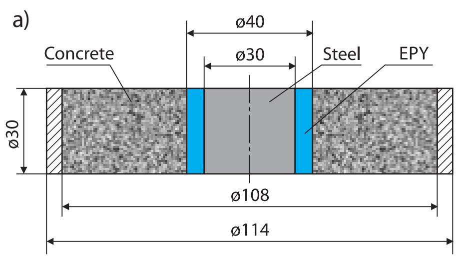


Fig. 8.53. Specimens for the tests on adhesion between EPY compound and concrete

as to obtain a uniform distribution of shear stresses over contact surface area between compound and concrete.

During preparation of the specimens care was taken to maintain proper similarity to conditions occurring in real systems. First, special moulds for casting concrete rings were prepared. They comprised steel rings (ø108/ø114×30 mm) and segments of plastic pipe, having outer diameter of 40 and 50 mm, respectively. Three moulds were made for each of the diameters. The moulds were properly sealed and filled with cement mortar. After concrete solidifying for a few hours the plastic pipes were carefully removed without violating integrity of concrete. Hardening the concrete was carried out under a wet fabric (dampened many times) and plastic sheet for about two months. Simultaneously, a cylindrical specimen (ø59×67 mm) was cast of the same cement mortar to check compression strength of the concrete. The test yielded the following result: $R_c = 27.58$ MPa.

After appropriate solidifying the concrete rings, steel cylinders (ø30×30 mm) representing segments of foundation bolt shanks (Fig. 8.54), were inserted to holes of the rings. Then the space between steel cylinder and concrete ring was filled with

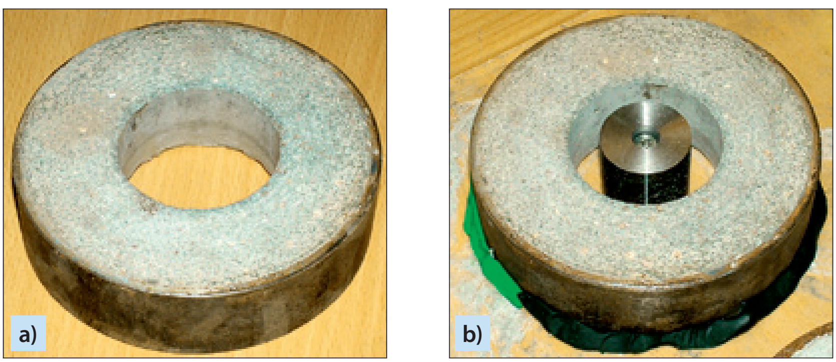


Fig. 8.54. Concrete disc after its curing (a), and with inserted steel cylinders (b), prepared for pouring with the compound

liquid mixture of EPY compound and hardener. Six such specimens, including three with 5 mm thick compound ring and three with 10 mm thick compound ring, were prepared. Pouring the compound into the specimens and curing it was carried out in room temperature of 22 ±1°C. The compound was cured for 72 h (while only 24 h period was required).

8.8.3.2. Run and results of the tests

The tests on adhesion between compound and concrete were conducted in 8850 INSTRON testing machine aided by a special computer controlled program. It guaranteed that all the tests were carried out in the same way. Fig. 8.55 shows a schematic diagram of running the tests in practice. The method of pulling the compound out of concrete by using a steel punch was applied for practical reasons. For sufficiently short connections the method is equivalent to the drawing-out method, that was proved in the preceding research [157].

Diameter of the punch was so selected as to reach an almost uniform distribution of shear stresses over contact surface between compound and concrete. To this end, numerical FEM calculations were performed first. Value of damaging shear stress, which determines, in this case, the adhesion of compound to concrete, R_p, was calculated with the use of a simple formula given in Fig. 8.46, where F_{max} stands for the maximum compression force damaging a given joint, and $S = \pi dl$ — contact surface area between compound and concrete, over which shear stresses act.

Eventually, the compound-concrete adhesion tests were conducted with application of a steel punch of 36 mm diameter — for the specimens of ø30/ø40×30 mm, and that of 46 mm diameter — for the specimens of ø30/ø50×30 mm. Fig. 8.56 shows shear stress distribution along compound-concrete contact length in case of application of the punch of 36 mm diameter. The distribution is almost uniform along the entire length of contact between compound and concrete.

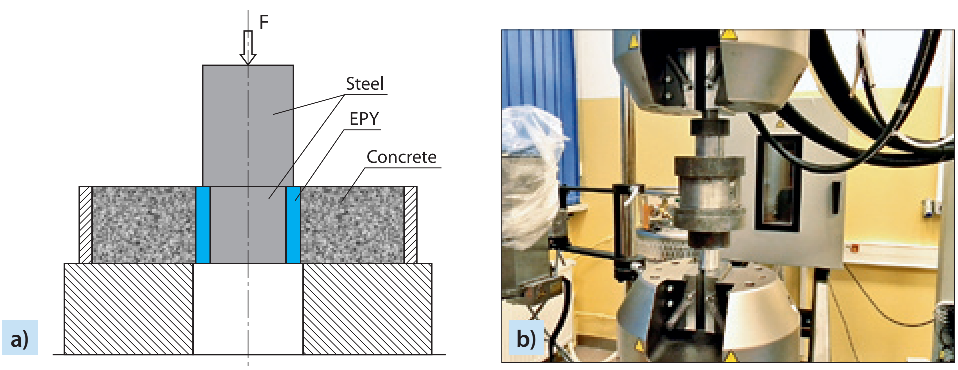


Fig. 8.55. Schematic diagram (a) and execution of the tests in a strength testing machine (b)

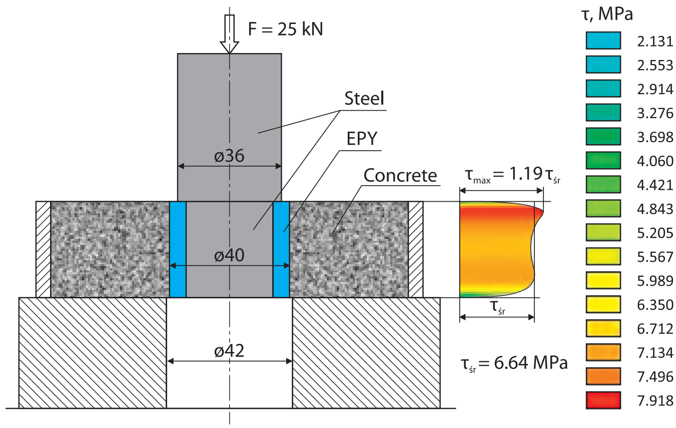


Fig. 8.56. Shear stress distribution along compound-concrete contact length for punch of 36 mm diameter

Table 8.5. Quantitative results of the tests on adhesion between EPY compound and concrete

Specimens of the dimensions: ø30/ø40×30			Specimens of the dimensions: ø30/ø50×30		
Specimen №	F_{max}, kN	R_p, MPa	Specimen №	F_{max}, kN	R_p, MPa
1	102.26	27.12	1	113.94	24.18
2	94.73	25.13	2	128.32	27.23
3	85.83	22.77	3	125.17	26.56
Mean value	94.27	25.00	Mean value	122.48	25.99

The tests were carried out not only till the instance when the load carrying capacity of a given joint has been exhausted and the joint damaged, but also till the full pulling of the compound out of the concrete. Each test was performed at two travel speeds of testing machine piston: first for 5 min at the speed v = 1mm/min, and next for 3 min at v = 10 mm/min. The speed was automatically switched over during run of the test. The speed v = 1 mm/min was selected the same as that used in standard compression tests of materials. Next, after damaging the joints, a greater speed was applied to shorten the time necessary for complete separation of connected elements. Runs of the tests are presented in Fig. 8.57 and their quantitative results — in Tab. 8.5. which contains values of the damaging force F_{max} for particular specimens and values of the adhesion R_p calculated from the formula given in Fig. 8.46c.

8.8.3.3. Analysis of the results

Analyzing the obtained test results one may generally state that the damage of the direct connections between compound and concrete results from action of shear

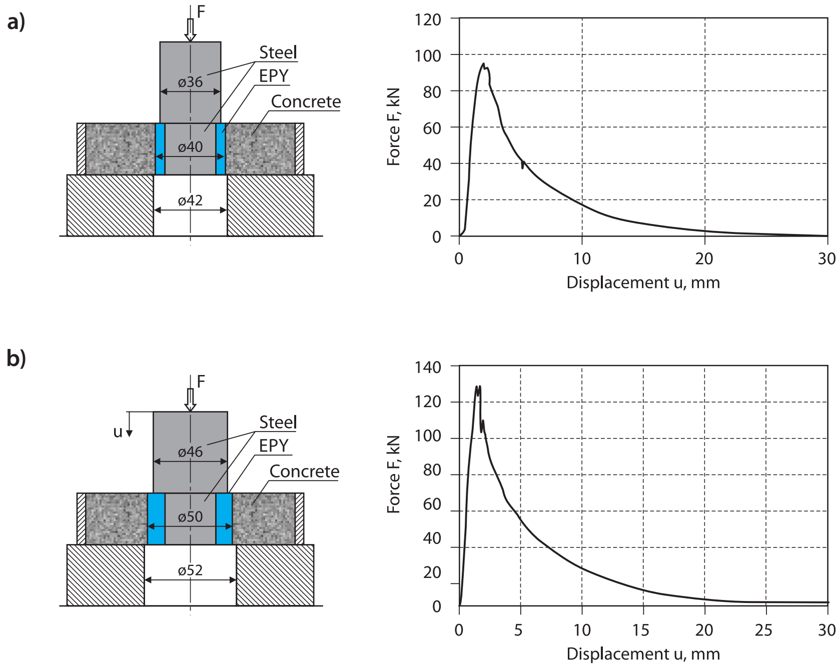


Fig. 8.57. Schematic diagram and results of the tests on adhesion between EPY compound and concrete: a) for the specimens of ø30/ø40×30 mm dimensions; b) for the specimens of ø30/ø50×30 mm dimensions

stresses which occur in contact between the mutually connected materials. The fast, approximately linear rise of load up to its maximum value and then its sudden drop show that the damage of the connection runs very fast over the whole contact area between compound and concrete. Even when the adhesion between compound and concrete is lost the connections do not lose at all their load carrying capacity owing to a relatively large friction drag occurring in them. The drag decreases because the compound is moved out gradually of the concrete and the surfaces are smoothed due to friction.

Fig. 8.58 shows a picture of the specimen after its damage. The mutually connected elements, both concrete and compound, maintained their integrity during the test and after it. The damage of the connection between compound and concrete, resulting from shear stress action, distinctly occurred always on the side of concrete. This is confirmed by a undamaged thin concrete layer stuck to compound and lack of it on surface of the hole in concrete. Therefore it may be supposed that for a higher class of concrete a greater value of adhesion would be reached. However the issue requires appropriate experimental tests to prove it.

Fig. 8.58. Picture of a specimen after its damage

The achieved mean values of the damaging force F_{max} depend on diameter of hole in concrete and are proportional to the hole surface area S. The calculated mean values of the adhesion R_p amount to 25.00 and 25.99 MPa, respectively, and are practically the same for the connections with the smaller and greater thickness of compound layer equal to 5 and 10 mm, respectively. The observed differences are comprised within result spread intervals.

8.9. Experimental tests on models of foundation chocks made of steel and EPY compound

8.9.1. Introductory remarks

Foundation bolt joints of heavy machines and devices constitute, both structurally and materially, complex mechanical systems. According to the classical classification [158], as well as the rules of classification societies which supervise building process of sea-going ships [97], the joints in question are numbered among the category of *rigid structural connections* (in contrast to *flexible connections*). It concerns not only foundation bolt joints with traditional steel chocks but also novel ones with chocks cast of special polymer compounds. Such classification is purely conventional as it simplifies real conditions and makes this way correct understanding and solving contemporary scientific and engineering problems on the seating of heavy machinery on foundations, more difficult. This especially deals with machines and devices which generate large dynamic forces and vibration.

In real systems for fastening machines and devices to foundations, both made of steel and concrete, complex phenomena of deformation, vibration, friction and strength occur. As results from practice, they very often have significant impact not only on reliability and service life of the seating itself but also on performance of the entire system formed of a machine, its foundation and a given fastening system.

Looking from the side of the complexity of the discussed phenomena, one should consider and analyze the fastening system as a deformable mechanical arrangement consisted of many mutually interacting elements. A single bolt joint connecting machine bed plate with its foundation is an authoritative representative of such system. Foundation chock which is an integral part of joint elements, plays important role in the joint. The chock together with holding down bolt form a complex structural unit of determined strength and dynamic features which depend on many various factors. As results from the tests, in such complex structures an important influence on their performance under load is associated not only with geometrical and material features of their components but also to a large extent contact phenomena occurring in their connections. The phenomena just decide very often on strength, reliability and service life as well as dynamics not only of a given structural joint but also to a large extent of the entire system in which it participates.

In order to understand, formulate and solve contemporary problems on strength, dynamics and reliability of foundation bolt joints it is necessary to precisely recognize physical phenomena occurring in them. To achieve this knowledge appropriate experimental tests are needed. Such investigations were suitably planned and conducted in the framework of a special research project financially supported by Polish Ministry of Science and Higher Education. A detailed description and results of the research are presented in the report on execution of the project [156]. In this chapter only some results of the research are discussed.

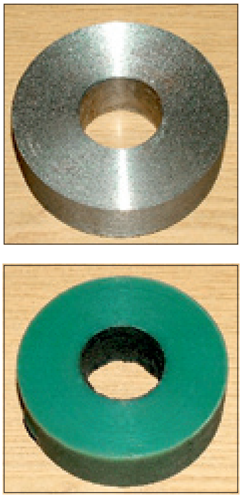
The research was aimed first of all at the determining of characteristics of normal deformations of foundation chock compressed between two flat metal surfaces with taking into account not only chock material deformation (as usual procedure in its modeling and calculating) but also contact deformations occurring in contact between the chock and metal surfaces exerting compression load on it. Such tests were carried out on special models of a traditionally used steel chock and a novel one, cast of EPY compound. The obtained results were analyzed and compared, and relevant conclusions were finally formulated.

8.9.2. Models of foundation chocks and a way of conducting the tests

The tests were carried out on simplified, axially symmetrical models of foundation chocks with taking into account appropriate conditions of their manufacturing and loads which occur in real foundation bolt joints of many machines and technical facilities. The models were made of steel and EPY compound. They had form of a ring (Fig. 8.59a) whose internal diameter was $D_w = 30$ mm, external diameter $D_z = 80$ mm and height $H = 25$ mm.

The experimental tests were conducted by using a 8501 Plus INSTRON servo-hydraulic testing machine. Fig. 8.59b shows a schematic drawing of the test stand.

a)



b)

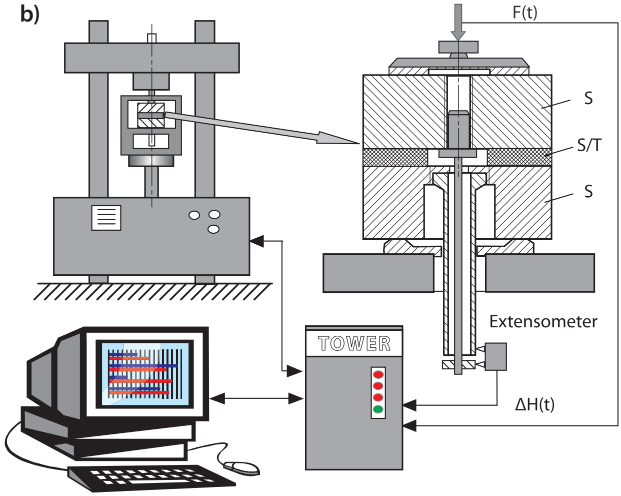


Fig. 8.59. Models of foundation chocks intended for the testing (a) and schematic drawing of a test stand for testing their deformations under normal loads (b)

The tested chock was placed between two flat face surfaces of steel discs which represented segments of steel foundation and bed-plate of seated machine (Fig. 8.59b). The face surfaces of steel discs exerting compression on a tested chock, were machined by milling and had the roughness parameters: $R_a = 13.50 \div 14.53$ μm, $R_z = 5.20 \div 59.59$ μm, which are approximately equivalent to those met on real surfaces of metal foundations and bed-plates of seated machines.

The system formed this way, consisted of the steel foundation chock and two steel disc surfaces being in contact interaction with it, was placed into a special instrumentation and subjected to several compression tests. In the tests a specialty WAVEMAKER software for dynamic testing, inherent in the testing machine, was used. Dynamic tests are specific in that all input and output quantities are considered in function of time. By using the software were prepared detailed programs of several tests aimed at conducting selected load cycles differing in time runs and range of exerted force. Computer control over given load cycles ensured their high exactness and repeatability.

Closing-up distance between face surfaces of steel discs exerting compression on a given chock was assumed to be a measure of its effective deformation. This way, not only material deformations of the chock (of the height H), but also contact deformations occurring on two contact surfaces between chock and compressing elements, were taken into account. In case of real chocks the contact surfaces are those of foundation (steel in this case) and bed plate of a seated machine. In the considered system it was strived to ensure possibly uniform pressure distribution as well as measurement of mean values of the effective chock deformation ΔH, resulting from the exerted pressure (i.e. sum of chock material deformations and contact deformations). The deformations were measured by means of an Instron extensometer. Fig. 8.59b shows schematically how they were measured.

8.9.3. Execution and results of the tests on steel chock

The tested chock of the dimensions 30 mm inner diameter/80 mm outer diameter ×25 mm height, was made of St3 common steel. Its contact surfaces were turned, and their roughness parameters were kept within the ranges: $R_a = 4.67 \div 6.04$ μm, $R_z = 23.28 \div 33.22$ μm. The chock was put between two steel discs (Fig. 8.60) representing machine bed plate and its foundation, and then subjected to several compression tests differing in run and load range. The whole scope of the tests is presented in the report [156]. Only some of the tests are discussed below.

First, compression tests of the chock were conducted under loads linearly varying in time according to the scheme of even-armed triangle with gradually increasing height. Runs and values of loads which were set and executed by testing machine, as well as deformations generated by them are presented in Fig. 8.61 in the form as achieved directly from the measurements. Speed of the force increasing and decreasing in loading and unloading phase was v = 10.8 kN/s, which resulted in the increasing and decreasing of mean compressive stresses in the chock at the rate of 2.5 MPa/s.

As results from the tests (Fig. 8.61), the distinctly nonlinear runs of the deformations ΔH(t) correspond to the linear runs of loads, F(t). During the first loading of the tested system its deformations are elastic-plastic. At the third and further load cycles (not exceeding preceding maximum values) the deformations are almost elastic. Fig. 8.61b and 8.62 demonstrate it distinctly.

The rather significant permanent deformations formed in the tested system during the first loading cycle with increasing force, may be explained by occurrence of plastic deformations of the roughness peaks on mutually interacting surfaces of particular components of the tested system. The deformations may sometimes play a significant role during assembling structural units of precise machines and devices. However, elastic deformations occurring in connections of this kind, numbered among the group of *rigid joints*, show distinctly that they are not perfectly rigid. This highlights complex physical phenomena which occur in such connections. The deformations significantly influence deformation characteristics of bolt joints as well as flexibility (rigidity) of the whole system in which they are placed. Hence they must be taken into account in modeling and static and dynamic analyzing the machines. It especially concerns analyzing vibrations which occur in large reciprocating compressor systems where their fastening systems usually are the weakest links and generate many troubles in service [105÷111].

Fig. 8.62 shows an expanded diagram of stabilized deformation characteristics of the steel chock in the tested system. In this figure the deformation characteristics

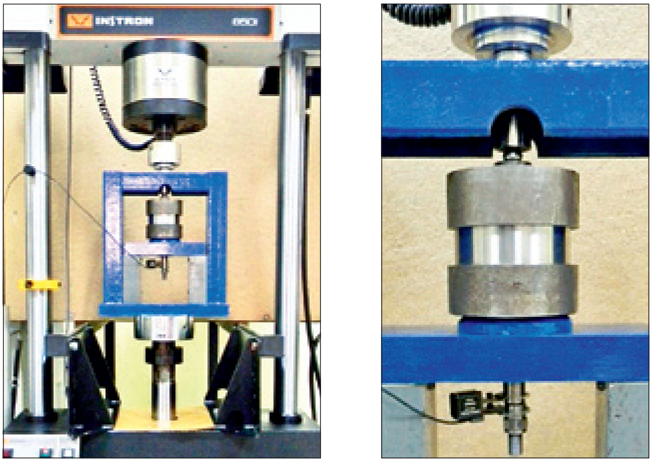


Fig. 8.60. Execution of the tests on the steel chock in 8501 Plus INSTRON strength testing machine

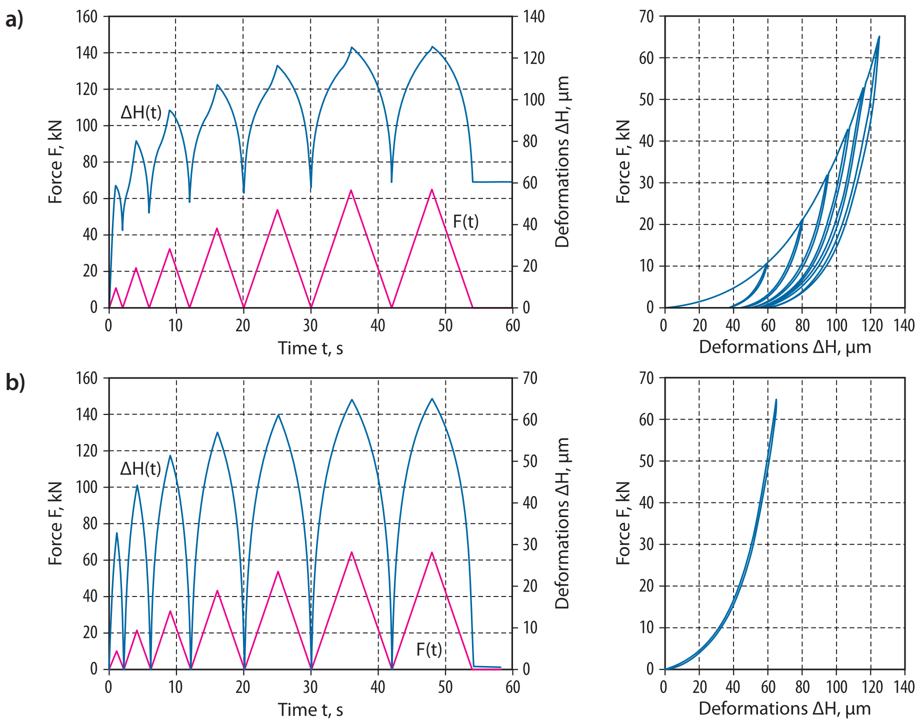


Fig. 8.61. Time runs of the applied compression loads F(t) and the resulting deformations ΔH(t) for the first (a) and the third (b) cycle of the same loads; the right-hand-side drawings present the same test results in the F–ΔH coordinate frame (subsequent peak values of surface pressure are: $\sigma_i = 2.5, 5.0, 7.5, 10.0, 12.5, 15.0$ MPa)

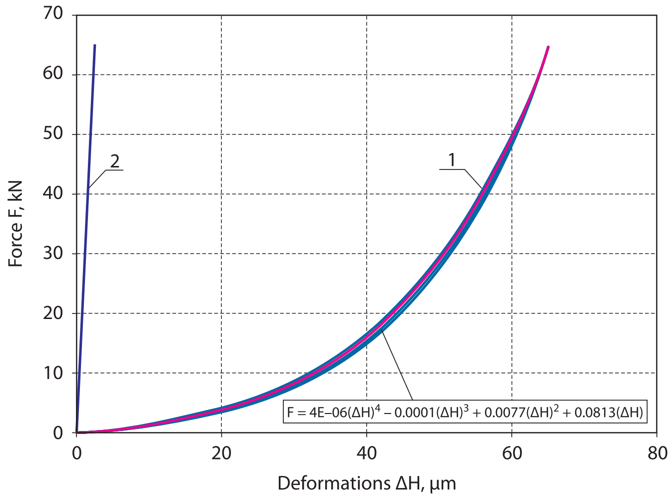


Fig. 8.62. Sabilized characteristics of deformations for the tested system with steel chock: experimentally determined (curve 1); calculated acc. Hooke's law for uniaxial compression (straight line 2)

of the tested chock, included for comparison, were calculated in accordance with Hook's simple low:

$$\Delta H = \frac{FH}{SE} = \frac{\sigma H}{E} = \frac{15 \cdot 25}{2{,}1 \cdot 10^5} = 0.001785 \text{ mm} \tag{8.9}$$

Material deformations of steel chock are a linear function of loads and, at given values of the loads (important from the point of view of engineering practice), they constitute only a very small part of the total deformations of the tested system. Contact deformations occurring on contact surfaces of elements, having nonlinear elastic runs, are dominating. They practically immediately fade at all after unloading the chock (Fig. 8.62). It shows that the tested system is very stable.

Elastic flexibility of the system depends on current load and decreases as the load increases. The small hysteresis loop observed in the system (after its stabilization) results from friction which occur as a result of contact between surface unevenness peaks.

In the next experiments, load runs have two different sinusoidal form: of a constant mean value and three different amplitudes, and three different mean values and a constant amplitude. Time runs of the so selected loads and resulting deformations are shown in Fig. 8.63 and 8.64. They concern the stabilized system.

The tested system distinctly exhibits stable, nonlinearly elastic features and responses to harmonic excitations by non-harmonic runs of deformations. The deflections are non-symmetrical in relation to equilibrium state and distinctly depend on mean value and amplitude of excitation force (Fig. 8.63 and 6.64).

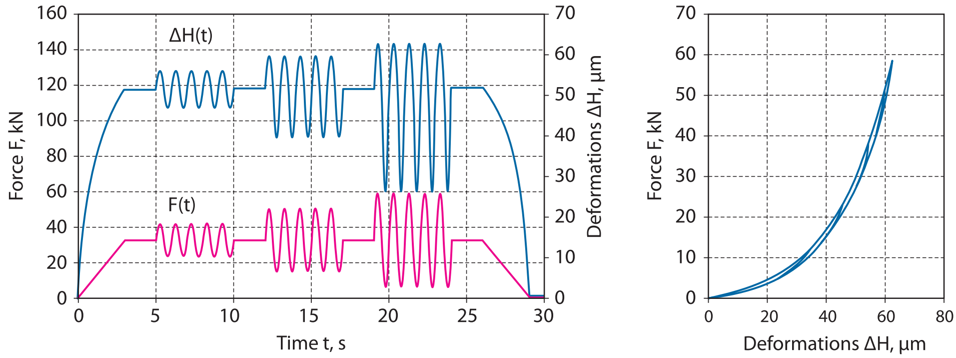


Fig. 8.63. Time runs of sinusoidally varying force of the constant mean value ($\sigma_{śr}$ = 7.5 MPa) and varying amplitude (σ_a = 2, 4, 6 MPa) as well as the resulting deformations; the right-hand-side drawings present the same test results in the F–ΔH coordinate frame

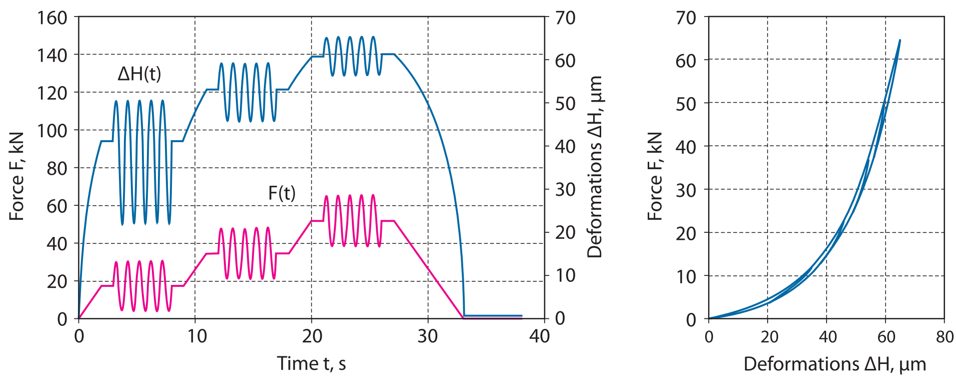


Fig. 8.64. Time runs of sinusoidally varying force of the different mean value ($\sigma_{śr}$ = 4, 8, 12 MPa) ($\sigma_{śr}$ = 7.5 MPa) and the constant amplitude (σ_a = 3 MPa) as well as the resulting deformations; the right-hand-side drawings present the same test results in the F–ΔH coordinate frame

8.9.4. Execution and results of the tests on the chock cast of EPY compound

The identical tests as for the steel chock system were also carried out upon the chock made of EPY compound for comparison purposes. The chock was not machined. It was cast *in situ* between steel discs which represented segments of foundation and bed plate of machine. Fig. 8.65a shows a cast mould specially prepared for manufacturing the chock.

Chock casting conditions were assumed the same as in practice. The chock was cast at room temperature of 22 ±1°C and cured at least for 48 h at the same temperature. The so prepared system was subjected to the same tests as those earlier carried out on the steel chock system. Results of the tests are presented in Fig. 8.66÷8.68.

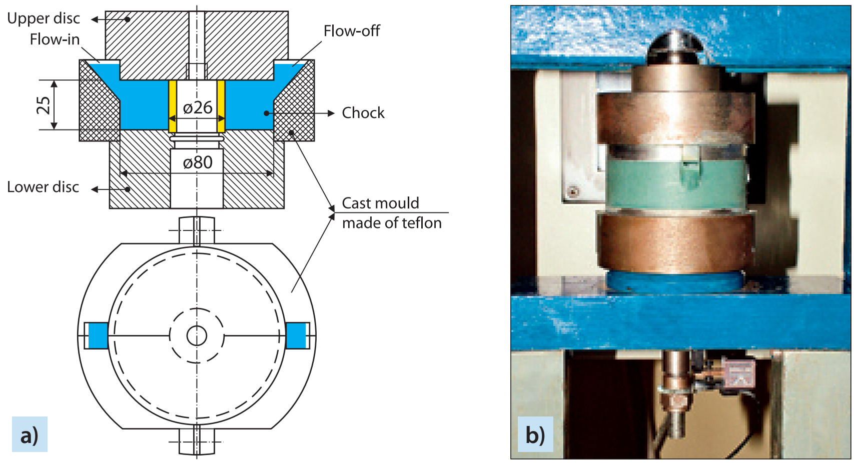


Fig. 8.65. A cast mould for EPY compound foundation chock (a) and execution of the tests on the so obtained system by using strength testing machine (b)

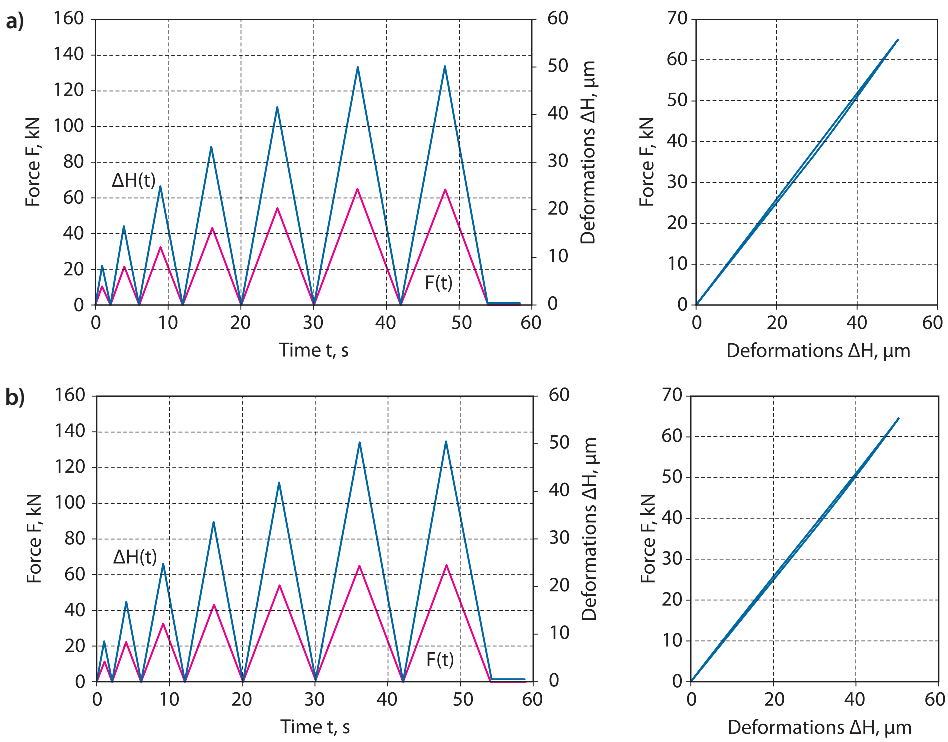


Fig. 8.66. Time runs of the applied compression loads F(t) and the resulting deformations ΔH(t) for the first cycle (a) and the third cycle (b) of the same loads; the right-hand-side drawings present the same test results in the F–ΔH coordinate frame

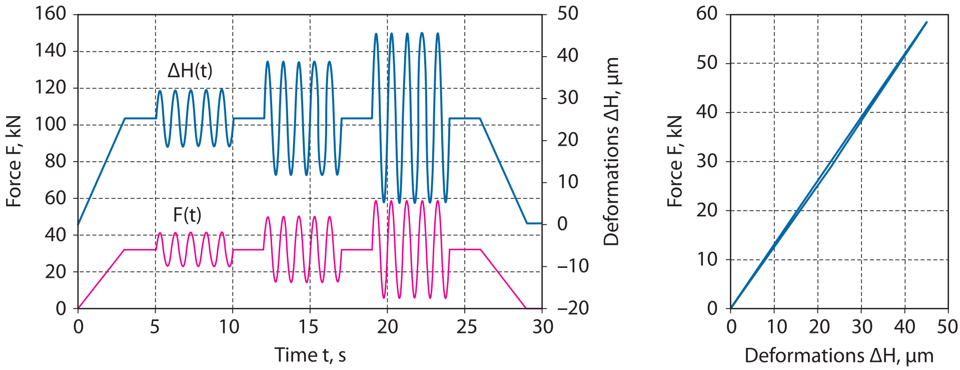


Fig. 8.67. Time runs of sinusoidally varying force of the constant mean value ($\sigma_{śr}$ = 7.5 MPa) and varying amplitude (σ_a = 2, 4, 6 MPa) as well as the resulting deformations; the right-hand-side drawings present the same test results in the F–ΔH coordinate frame

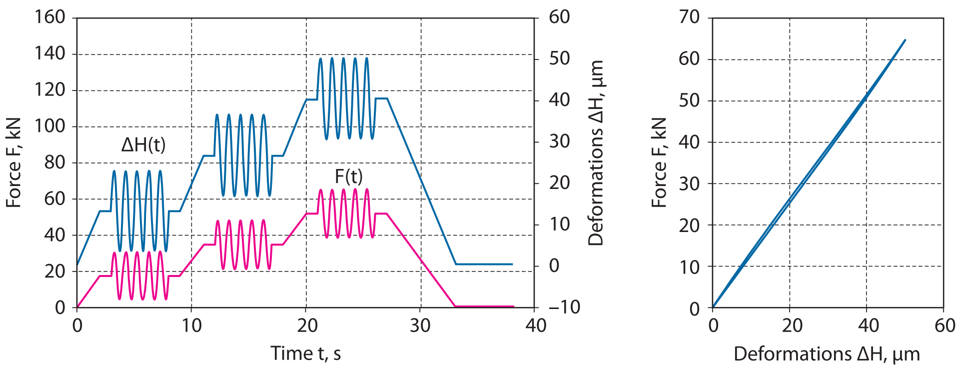


Fig. 8.68. Time runs of sinusoidally varying force of the different mean value ($\sigma_{śr}$ = 4, 8, 12 MPa) ($\sigma_{śr}$ = 7.5 MPa) and the constant amplitude (σ_a = 3 MPa) as well as the resulting deformations; the right-hand-side drawings present the same test results in the F–ΔH coordinate frame

Fig. 8.66 shows time runs of linearly varying loads (according to the scheme of a triangle of gradually increasing height) and resulting deformations.

Behaviour of the tested system containing resin compound chock was fundamentally different from that of the steel chock system which was previously tested. In this case distinctly linearly elastic relations occur between loads and deformations. The deformations are practically the same at the first, second, third and successive load cycles. The system behaves stable from the very beginning. In this case the measured values of the deformations ΔH entirely result from chock material deformations. The cast chock precisely sticks to all macro- and micro- unevenness spots on steel disc surfaces and no noticeable effects of contact deformations (characteristic for two machined contact surfaces) can be observed. Therefore it may be deemed that the real contact surface area is equal to nominal one. The conclusion is of a significant practical importance for transferring mechanical loads. Effective value of experimentally determined modulus of elasticity for the tested chock (Fig. 8.66), is equal to:

$$E_{EPY} = \frac{\Delta\sigma}{\Delta\varepsilon} = \frac{\Delta\sigma \cdot l}{\Delta H} = \frac{15 \cdot 25}{0{,}050} = 7500\ \text{MPa} \tag{8.10}$$

Notice: The determined value of the modulus is greater than its catalogue value (E = 4915 MPa) obtained from standard compression test on resin compound specimens (of 20 mm diameter × 25 mm height) having machined face surfaces. In such case additional contact deformations which decrease real value of the modulus, usually occur. Value of the modulus, determined on longer specimens by measuring their deformations with the use of an extensometer, is much greater and amounts to 7000÷8000 MPa (see Chapter 7, section 7.15.2).

Fig. 8.67 and 8.68 present results obtained for the system tested under compression force of the same sinusoidal runs as used for the steel chock system. They show that the tested system behaves in a linear elastic mode. The deformations, alike the excitation force, have harmonic runs and their amplitudes are proportional to force amplitudes. After the unloading of the system, the deformations fade to zero. The system remains fully stable.

8.9.5. Comparison of the test results and conclusions drawn from the tests

Fig. 8.69 presents normal deformation characteristics experimentally determined for the steel chock system (Curve 1) and that for the EPY compound chock (Straight line 2). The figure also shows material deformation characteristics derived from the classical Hook's formula (Straight line 1'). A large qualitative and quantitative discrepancy of the obtained results can be observed.

In the steel chock system, contact deformations which are nonlinearly elastic and have multifold greater values than chock material deformations, play decisive role within the range of loads important for practice. They result from significant deformations of the peaks of uneven areas of interacting surfaces. Real contact surface area, because of its roughness, waviness and shape errors, represents, in such connections, only a very small percentage of their nominal contact surface area. It strongly influences performance of the connections under load.

The chock cast of resin compound exactly sticks to all uneven areas of metal surfaces. There are no noticeable contact deformations characteristic for contact of two machined metal surfaces. Values of deformations measured in such system result entirely from chock material deformations. They are linearly elastic and their values well comply with the deformations calculated according to Hooke's formula. Hence they are easy to model and analyze theoretically.

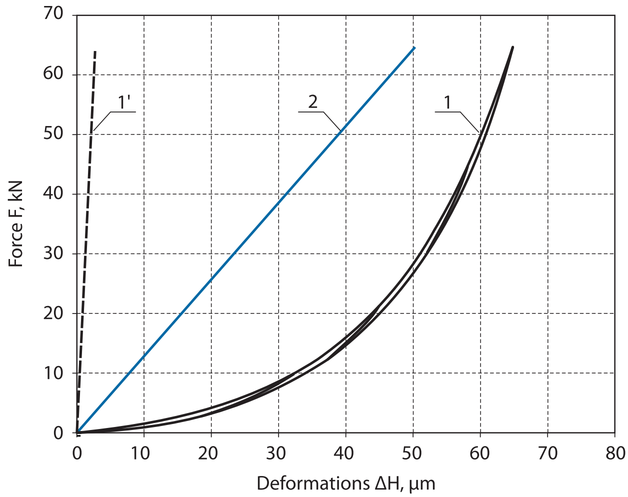


Fig. 8.69. Comparison of normal deformation characteristics determined for the tested foundation chocks

The determined deformation characteristics facilitate to understand and scientifically highlight why the chocks cast of resin compound fulfill their tasks better than steel ones. The basic technical merit of resin compound foundation chocks is their exact sticking to rough metal surfaces. It guarantees a favourable distribution of loads over the whole nominal contact surface area, consequently, ensures correct work, high reliability and service life of such connection. From the performed tests the following general conclusion may be drawn: — the foundation bolt joints, both with metal chocks and cast compound chocks, should not be considered perfectly rigid in their analyzing and modeling as they have distinct deformation characteristics greatly dependent on a kind of foundation chock, which seriously affect quality of operation (vibration), reliability and service life not only of the fastening systems but also the whole system in which they participate.

8.10. Research on characteristics of structural friction and relative displacements in foundation bolt joints both with steel chock and EPY compound chock

8.10.1. Introductory remarks

Foundation bolt joints of machines are loaded not only by forces parallel to bolt axis, resulting from weight of seated object, assembling tension in bolts and service loads, but also by significant transverse forces. They must be so designed and manufactured as to cause the transverse forces (tangent to support surfaces) to be fully transferred by friction forces occurring in the joints ($N\mu > T$, where N stands for normal force, T — force tangent to support surface, and μ — friction factor). If friction forces in a bolt joint are too small, micro-slips leading to its destruction, will occur in it.

The research in question was aimed at experimental determination of characteristics describing structural friction and relative transverse displacements of joint elements, for foundation bolt joints with traditional steel chock and novel one cast *in situ* of polymer compound, as well as at making comparative analysis and assessment of the two solution.

A comprehensive research on this issue resulting from current needs was carried out in the framework of the research project N N502 194938. Its detail description and results are contained in the content-related report on the project [156]. In this chapter are presented only some results of the research as well as conclusions drawn from it, both of scientific and practical nature.

8.10.2. The selected systems and a way of their manufacturing

For executing the planned tests special bolt joints were designed and manufactured. They were properly prepared for fastening in testing machine and adjusted for transferring reversible transverse force. The joints (Fig. 8.70) consisted of two

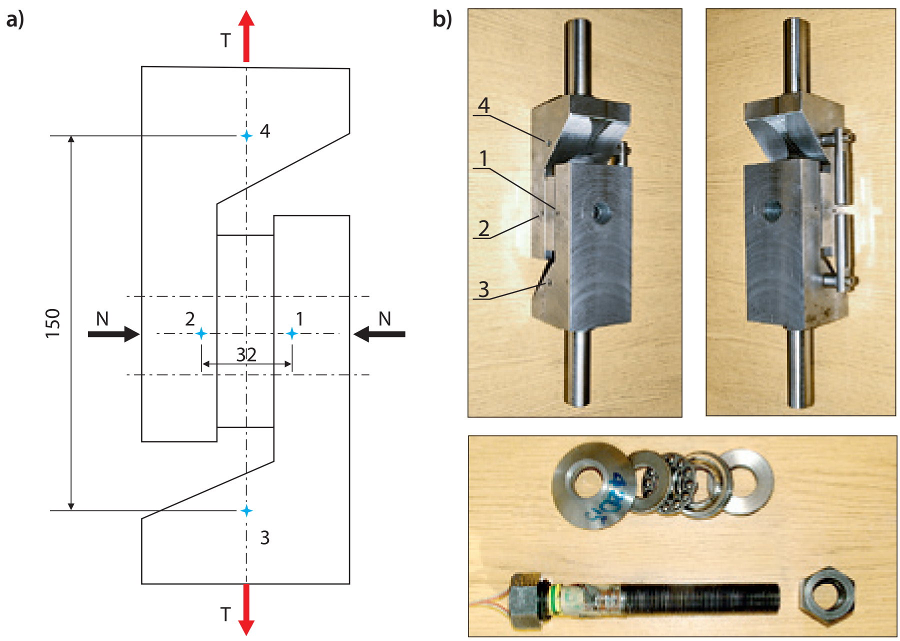


Fig. 8.70. A bolt joint for the testing of structural friction characteristics as well as tangential displacements (transverse to bolt's axis): a) schematic test diagram with marked points where relative diosplacements were measured, b) overall view of the prepared joint elements and the bolt with glued strain gauges for measuring the force in the bolt

mutually connected steel elements of high rigidity, a square spacer washer placed between them (of 80 mm sides and 20 mm thickness, having central hole of 24 mm diameter), as well as a M20×1.25 threaded bolt with nut. In the steel elements to be connected, cylindrical holders for their fixing in testing machine jaws, were placed. The chock was a replaceable element. The tests were carried out first on the joint with steel chock traditionally used in seating heavy machines, and next on the joint with chock cast (in situ) of polymer compound (EPY) — the most often applied today in practice. The bolt together with electric resistance strain gauges bonded on it was properly calibrated to be used as a force meter in the process of exerting tension to the bolt and controlling it during the tests. Under the nut, a special spring washer and an axial ball bearing with a spherical washer (NSK Bearings 52204U) were inserted to ensure that the loading is applied axially to the bolt.

The tests were carried out with the use of a to-date 8850 INSTRON servo-hydraulic testing machine. Its heads (Fig. 8.71a) are fitted with hydraulically clamped jaws, that makes it possible to apply the load to a tested joint reversibly with crossing zero in a smooth manner.

INSTRON special extensometers (Fig. 8.71) were used for measuring displacements between joint elements of the tested system. On side surfaces of joint elements relative displacements were measured in two places marked 1 and 2, and 3 and 4

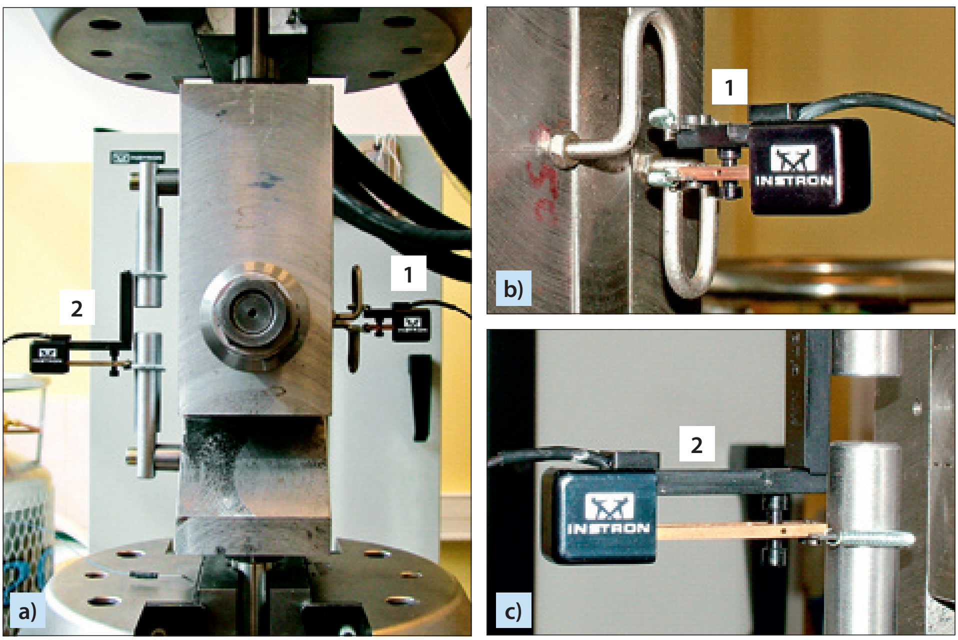


Fig. 8.71. Execution of the tests by using 8850 INSTRON strength testing machine and extensometers for measuring relative displacements between the measurement points (indicated in Fig. 8.70)

in Fig. 8.70a. The extensometer 1 in Fig. 8.71 (of 10 mm reference length) measured relative displacements of joint elements in the points 1 and 2 located in the same transverse line in the middle of the joint (where bolt axis is placed, Fig. 8.70a). The displacements are of local character and generally result from non-dilatational strains of joint elements, contact tangential deformations as well as micro-slips which occur in contact of mutually interacting surfaces of the chock and joint elements. The extensometer 2 in Fig. 8.71 (of 50 mm reference length) measured changes in mutual distance between the points 3 and 4 located in a rather large distance to each other (l = 150 mm), in the line complying with load direction (Fig. 8.70a). The displacements are of a global character. They results from material axial deformations of this part of the joint which is contained between the above mentioned points, non-dilatational strains of the joint elements, contact tangential deformations as well as micro-slips which occur in contact of mutually interacting surfaces of the chock and joint elements.

In the tests was used WaveMatrix INSTRON professional software (v. 1.5.318) intended for the dynamic testing, installed in the testing machine. The software constituted a basis for preparation of detail loading programs and computer control of their execution with a very high precision and repeatability, as well as for the processing of measurement results and editing them in various forms. The dynamic tests are characteristic in that all input and output quantities are considered in function of time. The tests in question were carried out first for the joint with traditional steel chock and next for the joint with cast EPY compound chock.

8.10.3. Execution of the tests on the joint with steel chock and their results

Contact surfaces of mutually connected elements were milled and their measured roughness parameters had the following values: $R_a = 2.47 \div 2.51$ μm, $R_z = 13.40 \div 13.50$ μm. Contact surfaces of the washer (20 mm thick) were turned and had the following values of roughness parameters: $R_a = 2.29 \div 3.60$ μm, $R_z = 11.69 \div 17.25$ μm.

The assembling tension force applied to bolt was N = 51700 ±200 N, producing the tension stress σ = 199.7 MPa in the bolt and the mean pressure p = 8.69 MPa exerted on the washer. Fig. 8.72 shows execution of the tests in the strength testing machine.

Several experiments were performed in accordance with various, computer-controlled loading programs. Their detail description and results are contained in the report [156]. In this chapter only selected results of the research are presented.

The diagram presented in Fig. 8.73 shows characteristics of relative displacements between the measurement points 1 and 2. It was obtained as a result of slowly increasing loading and unloading (to zero) cycle of the tested joint when only a set value of relative displacements between the measurement points 1 and 2 (measured with the extensometer 1 in the load acting direction) was reached. After the unloading to zero the loading cycle was repeated up to reaching a next set displacement value. The last, fifth unloading cycle did not ended at zero. It smoothly passed from tension to compression exerted to the tested joint. The compressive loading was continued as long and in such a way as the initial state (null values of deformations and force) has been reached (Fig. 8.73).

Fig. 8.72. Execution of the tests on the bolt joint with steel chock by using 8850 INSTRON strength testing machine

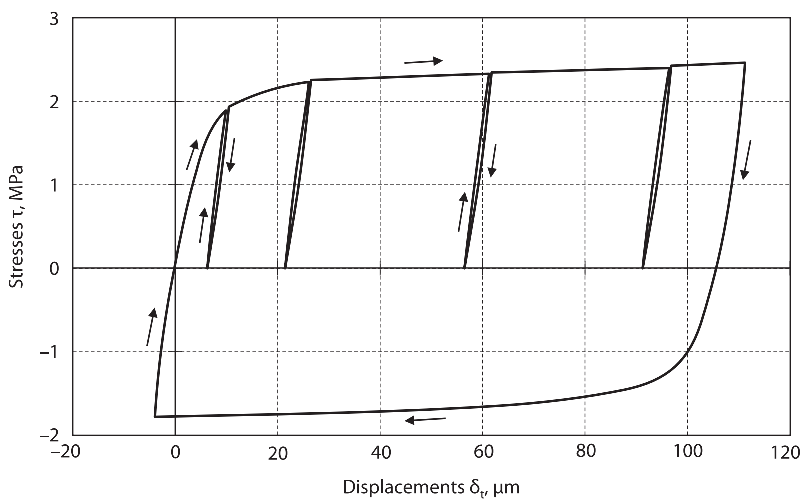


Fig. 8.73. Characteristics of relative displacements measured between points 1 and 2 (in the direction of load action) during the gradually increasing loading and then unloading of the tested bolt joint, expressed in function of the mean shear stresses τ acting on the chock ($N = 51700 \pm 200$ N; $p = 8.69$ MPa)

Fig. 8.74 highlights a mechanism of occurrence of the relative displacements δ_t between the points 1 and 2, measured with the extensometer 1, and resulting from the set force, T, tangent to contact surfaces. In this case the measured relative displacements δ_t result from the elastic non-dilatational strains γ in material of joint elements ($\delta_t' = \gamma h$), contact tangential deformations as well as micro-slips of contacting surfaces.

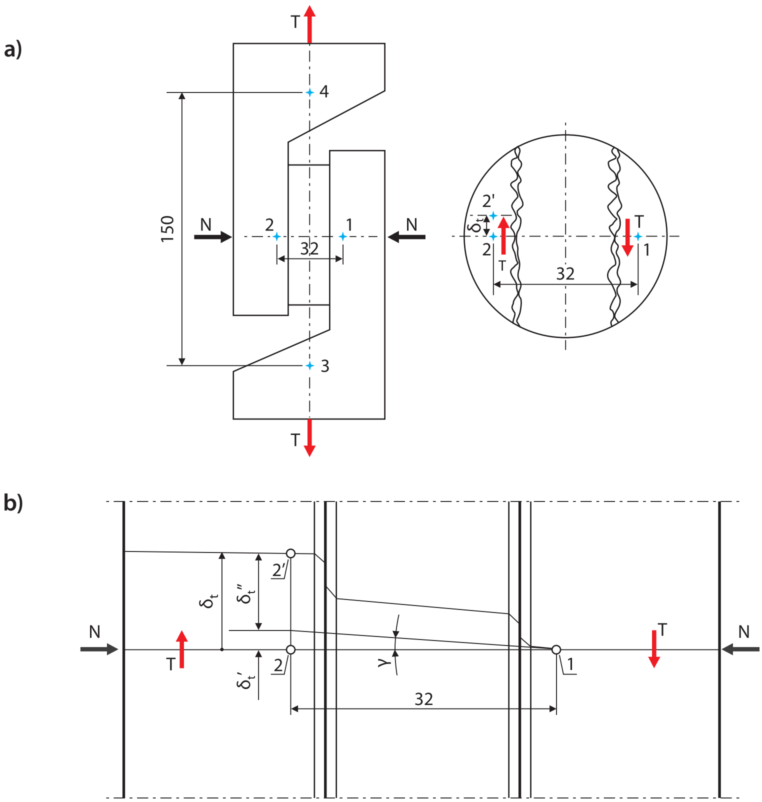


Fig. 8.74. Denotation of the measurement points 1 and 2 on joined elements (a), and schematic diagram which explains mechanism of occurrence of the relative displacements δ_t between these points, caused by the forces T — (b)

Fig. 8.75 presents structural friction characteristics (in rest) for the tested bolt joint. As results from it, development of static friction force is accompanied with certain micro-displacements which are elastic only to a small extent. In this case are dominating micro-slips which may reach significant values before breaking the contact and triggering a macro-slip (Fig. 8.75). Values of elastic tangential contact deformations (tangent contact deformability) can be easily determined in any point of the characteristics by unloading and repeated loading of a given joint. For set normal pressure tangent contact deformability is constant. It depends however on values of the pressure. During the unloading and repeated loading (Fig. 8.75) the system behaves elastically until reaching such point in the diagram, from which the unloading process has started. When the point is reached and the loading process is continued, successive micro-slips are produced under a very small increase of force. During the unloading and repeated loading process very small elastic hysteresis loops occur, distinctly visible in Fig. 8.75.

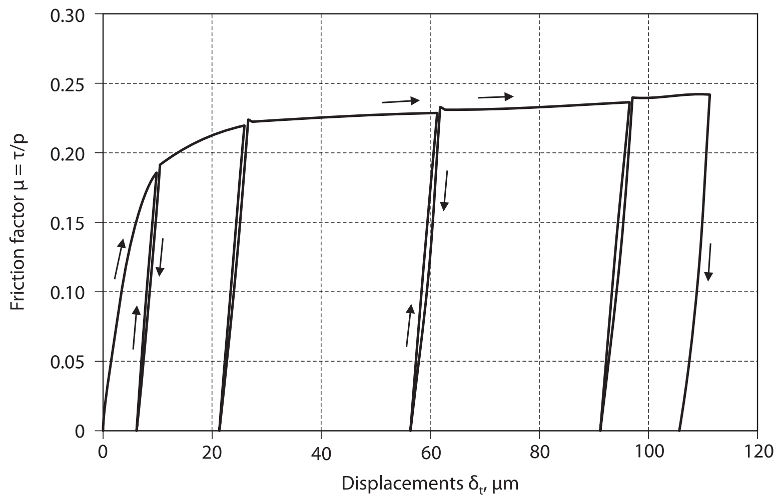


Fig. 8.75. Characteristics of structural friction and resulting elastic tangential contact deformations and micro-slips in the tested bolt joint (under the pressure p = 8.69 MPa)

Notice: In the above described experiments the tested joint was not loaded up to "breaking the contact" for fear of damaging the costly extensometers.

In another experiment, behaviour of the system was tested for a selected program of relative displacements between the measurement points 1 and 2 (Fig. 8.76a), controlled by the extensometer 1 (Fig. 8.71). Fig. 8.76b presents the selected program of relative displacements having sinusoidal form.

Under the displacement program, the testing machine fitted with the software for conducting dynamic tests (Istron VaveMatrix) has to automatically choose and produce appropriate loads for reaching the set relative displacements between the points 1 and 2. Effects of fulfilling the task are presented in Fig. 8.77. Diagrams shown in this figure present time runs of the relative displacements δ_t between the points 1 and 2, and of the force which generated the displacements. It may be clearly observed that the system is non-linear and runs of the force greatly differ from sinusoidal runs of the displacements. Attention should be paid to very high exactness in producing

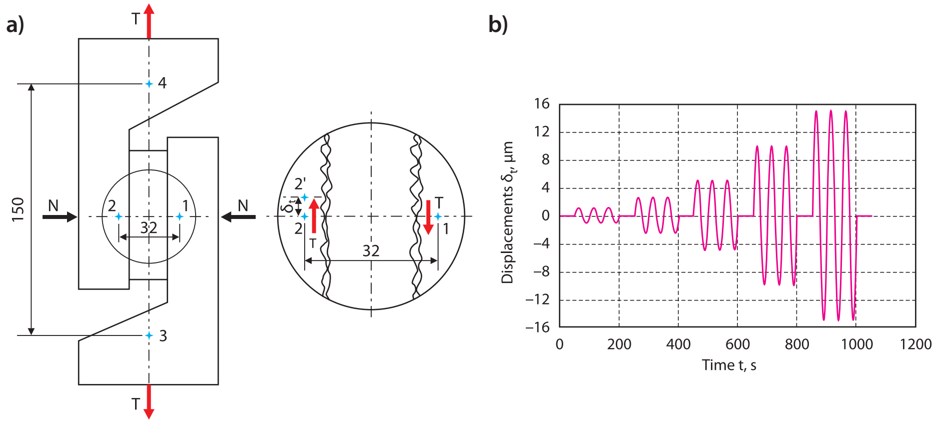


Fig. 8.76. Schematic diagram of the tested system (a), and the programmed time run of relative displacements between the measurement points 1 and 2, of the subsequent amplitudes $\delta_a = 1, 2.5, 5, 10$ and 15 μm (b)

the displacements (of amplitudes reaching 1÷15 μm only) as well as to an irregular, complicated time run of the force which generated the displacements.

Fig. 8.78 shows the measurement results, the same as shown in Fig. 8.77, but in the δ_t—τ, coordinate frame, where τ stands for tangential stresses occurring in the contact ($\tau = T/S$, where S — contact surface area between chock and joined element). In this figure can be also observed hysteresis loops which occur during generation of the set relative displacements of sinusoidal form, shown in Fig. 8.77a.

As results from the tests (Fig. 8.78), the system in question behaves linearly-elastically only at very small values of relative displacements and tangential stresses. At greater values of the displacements occur micro-slips producing large hysteresis loops. They demonstrate that an extensive energy dissipation happens due to structural friction. Its positive effect is a significant damping of vibrations, and negative one – an intensive and fast deterioration of the joint. During the process phenomenon of fretting (friction corrosion) and loosening bolt nuts often occurs.

8.10.4. Execution of the tests on the joint with EPY compound chock and their results

Schematic drawing of the joint with cast EPY compound chock is shown in Fig. 8.79. Dimensions of the joint elements and the chock were the same as in the system with steel chock. The EPY compound chock was manufactured under conditions used in practice, described in detail in the publication [156]. The chock cast this way (ready to use) closely adjusts itself to micro- and macro-uneven surface areas of joint elements.

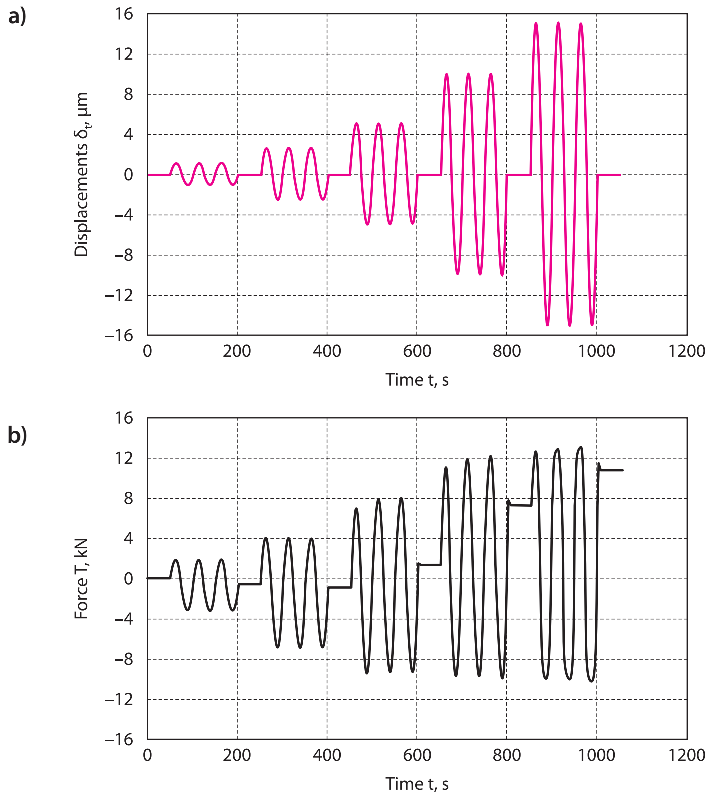


Fig. 8.77. Time runs of relative displacements between the points 1 and 2 (a), and the loading causing the displacements, generated by strength testing machine (b)

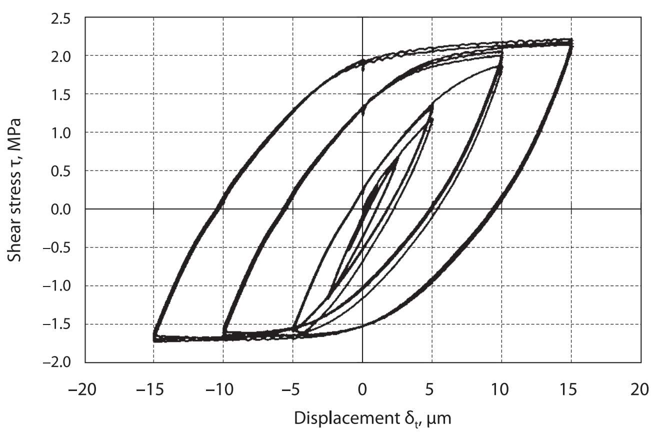


Fig. 8.78. Hysteresis loops occurring under forced sinusoidal displacements of the subsequent amplitudes of 1, 2.5, 5, 10 and 15 μm, measured in the points 1 and 2 of the tested system

After inserting the bolt and its tensioning, several experiments were performed under a little modified loading programs. The same loading programs were not possible to apply because the joint (with resin compound chock) behave entirely different from the previously tested joint with steel chock. The testing conditions were so selected as to distinctly reveal qualitative and quantitative differences in behaviour of both the tested joints.

First, the tested system was loaded and unloaded by applying force whose values were linearly varying with time according to the scheme of even-armed triangles with gradually increasing heights, as shown in Fig. 8.80a. During the tests relative displacements between the points 1 and 2 of the system were measured along the direction of the force T. Results of the experiment are presented in the coordinate frame T—δ_t in Fig. 8.80b. As results from the diagrams (Fig. 8.80), a clearly linear relation between the loading force T and the displacement δ_t between the measurement

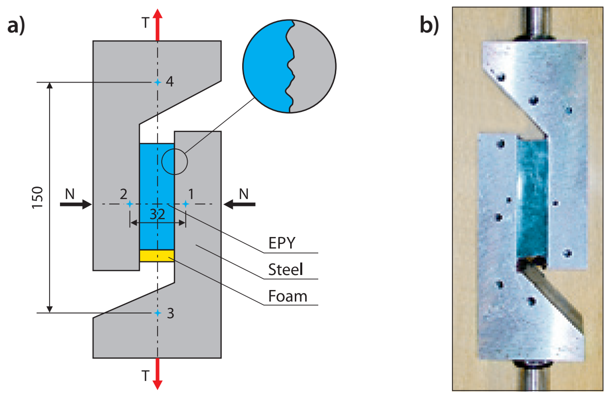


Fig. 8.79. The tested joint with chock cast of EPY compound: (a) schematic drawing, (b) overall view

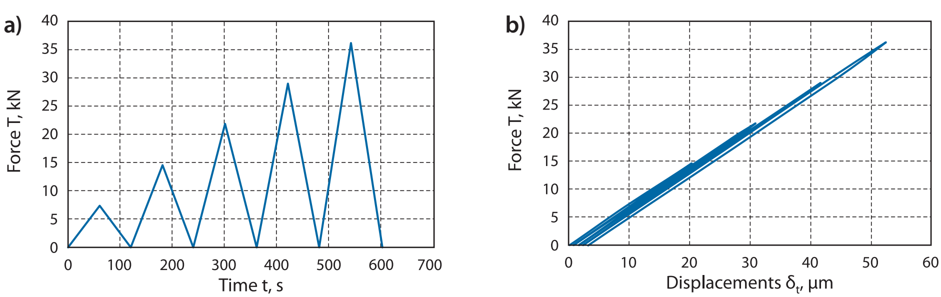


Fig. 8.80. Time run of the force T — (a), and relation between the measured displacements δ_t and the force T — (b)

points 1 and 2, can be observed, and the displacements are elastic at occurrence of only a small hysteresis loop. In this case also the friction resistance continuously equilibrating the force T is linearly dependent on the relative displacements between the points 1 and 2, without any noticeable micro-slips in contact.

In the subsequent experiment the tested joint was loaded by applying the reversible force linearly varying with time, according to the scheme of triangles of increasing height values. Fig. 8.81 shows a manner of conducting the experiment and its results. Fig. 8.81a presents time run of shear stresses (resulting from action of the force T), and Fig. 8.81b — the displacements δ_t generated by the applied load. Very linear relation between the relative displacements and shear stresses can be observed at occurrence of relatively small, sharply ended, elastic hysteresis loops. The characteristics determined for the system in question definitely differ from those previously obtained for the steel chock joint both with regard to its qualitative and quantitative features. In this case the relative displacements δ_t between the measurement points 1 and 2 fully result from non-dilatational strains in material of joint elements and first of all of resin compound chock. The chock tightly sticks to all uneven surface areas of joint elements. Any contact deformations and micro-slips on contacting surfaces, so characteristic for machined contact surfaces in joints, do not occur. It should be stressed that the chock was not glued to joint elements. Contact surfaces of the elements were covered with a layer of an anti-adhesive agent and thus they could be easily split off. The applied tangential load is entirely transferred by static friction forces (without any contact deformations and micro-slips). Owing to the very good adhesion between contacting surfaces, a large effective value of structural friction factor is achieved. In the case in question the factor reached the value μ = 0.8 which was not a limiting one. At this value of friction factor (threefold greater than that occurring in the tested steel chock joint) the system behaves linearly-elastically (Fig. 8.81). An attempt to applying even greater load to the tested system was neglected for fear of possible damage of extensometers due to a sudden rupture of frictional contact.

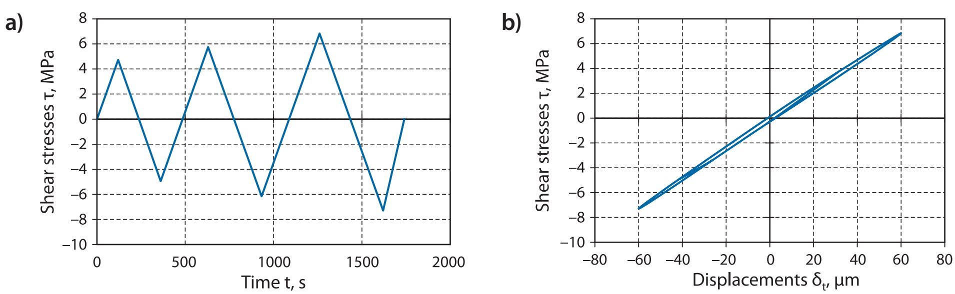


Fig. 8.81. Time runs of the set shear stresses τ — (a), and relation between the measured displacements δ_t and the applied stresses — (b)

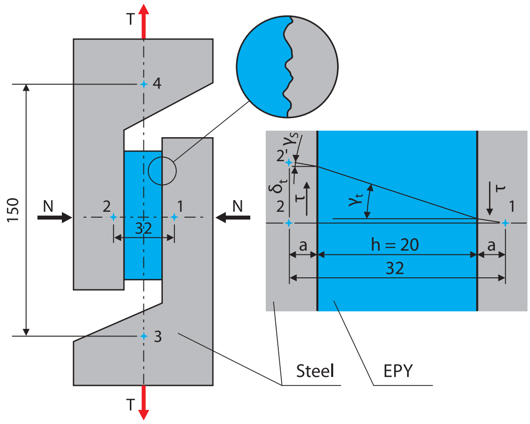


Fig. 8.82. Schematic diagram which explains mechanism of occurrence of the relative displacements δ_t between the points 1 and 2, caused by the forces T in the bolt joint with EPY compound chock

Fig. 8.82 highlights mechanism of occurrence of the relative displacements δ_t between the points 1 and 2, in the considered case. There are significant differences in comparison to the situation presented in Fig. 8.74 showing mechanism of occurrence of relative displacements in the bolt joint with steel chock. In the presently considered joint it was non-dilatational strains occurring in the compound chock, which had a decisive impact on the relative displacements between the points 1 and 2. Owing to the very good sticking of the connected surfaces to each other and the large effective value of friction factor, no tangential contact deformations and micro-slips occurred in the joint in question. The system is stable and behaves linearly elastically even under the load threefold greater than limit loads for the system with steel chock. In the subsequent experiment, behaviour of the system was tested under a selected program of relative displacements between the measurement points 1 and 2, with sinusoidal time run controlled by the extensometer 1 (Fig. 8.71). Conditions for this experiment were identical to those used in the previously conducted tests on the steel chock joint. Fig. 8.83 shows schematically the tested system and the selected program of generating the relative displacements between the points 1 and 2. Fig. 8.84 and 8.85 present results of this experiment. Fig. 8.84 shows respective time runs of the displacements between the point 1 and 2, executed by testing machine, as well as the mean shear stresses τ, acting onto the chock and producing the displacements. A simple, linearly elastic relation between the quantities is clearly visible. The measured displacements between the points 1 and 2 result first of all from the non-dilatational strains in chock material and also, to a very small extent, in joined elements (Fig. 8.82).

Fig. 8.85 shows hysteresis loops revealed in the experiment. They are rather small and illustrate effects of viscous damping which occurs in chock material. On the

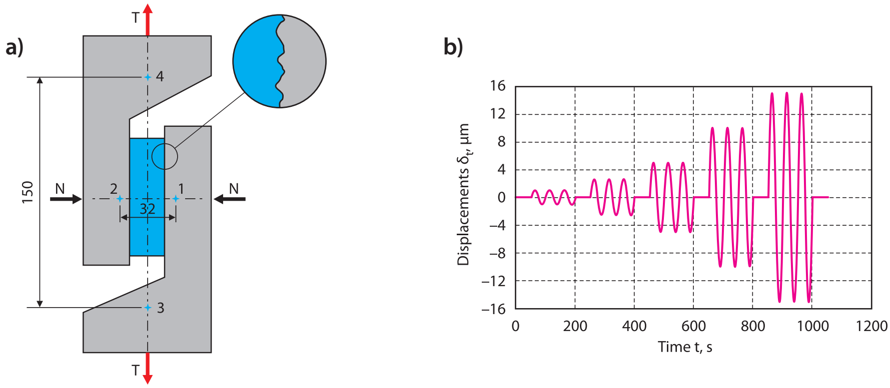


Fig. 8.83. Schematic drawing of the tested system (a), and the programmed time run of relative displacements between the measurement points 1 and 2, (b)

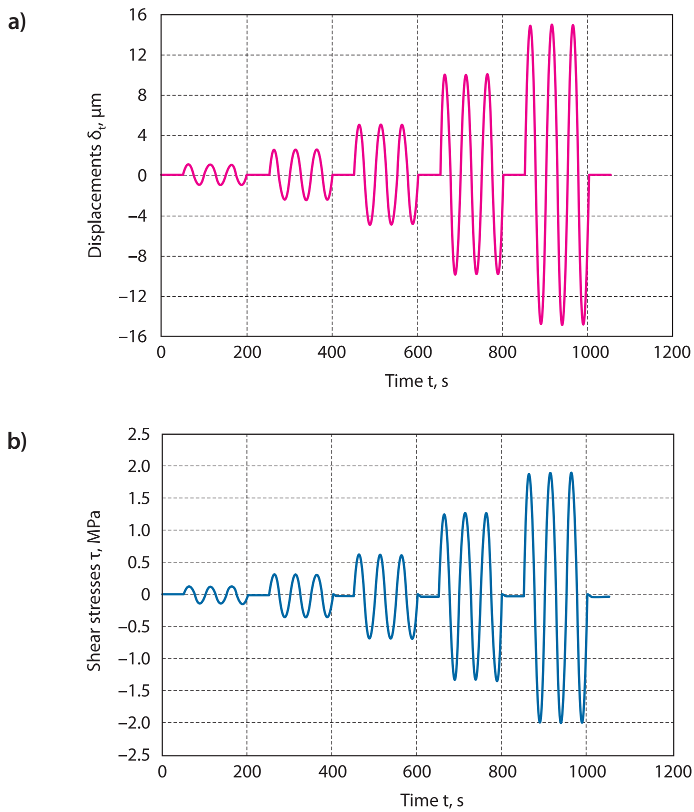


Fig. 8.84. Time runs of the executed dispacements between the points 1 and 2, (a), and the mean shear stresses acting on the chock and generating the displacements (b)

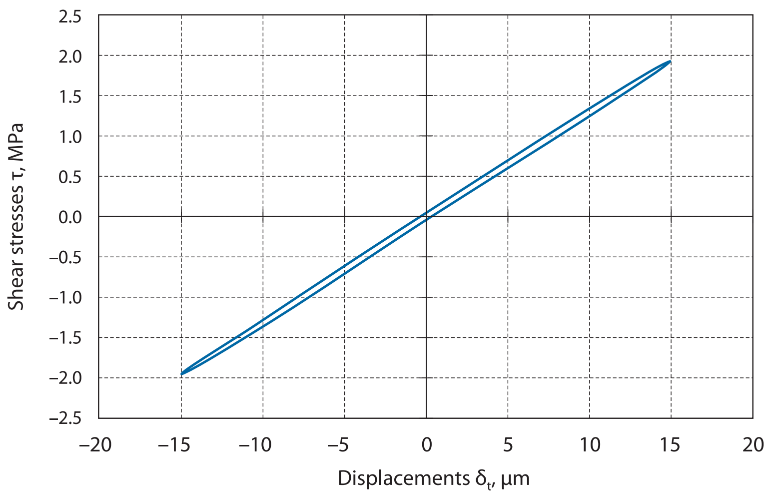


Fig. 8.85. Hysteresis loops determined on the basis of the measurement results shown in Fig. 8.84

basis of the loops, values of the shear modulus G and the loss factor η can be easily determined for the resin compound chock. The following values: $G_t = 2651$ MPa and $\eta = 0.032$ (for the largest loop) were derived on the basis of the relevant calculations presented in the work [156] for the conditions assumed in this experiment. The values are in a good conformity with those determined by using other methods [39].

8.10.5. Comparative analysis of test results for bolt joints with steel chock and EPY compound chock

Only a part of the test results, i.e. these which are collected in below given figures, was taken for comparisons. Fig. 8.86 shows structural friction characteristics for the tested bolt joints with steel chock and that cast of EPY compound, which present the relative displacements of joint elements, measured between the points 1 and 2. Even at first glance, can be observed significant qualitative and quantitative differences in the achieved characteristics. Friction characteristics for the joint with steel chock (Fig. 8.86, Curve 1), is linear from the very beginning. The structural (static) friction resistance which equilibrates external load, is accompanied with significant elastic-plastic micro-displacements. Only to a small extent they result from elastic strains occurring in material of elements and their mutual contact, which are visible during loading and repeated unloading process. First of all they are caused by micro-slips which occur in contact of mutually interacting rough surfaces. The slips appear already at very small load increases and may reach large values before the contact is broken and a macro-slip (kinetic friction) appears.

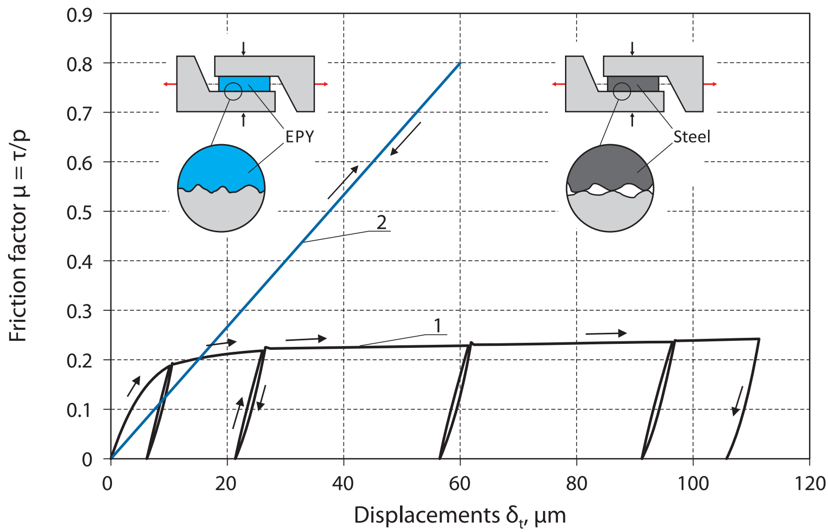


Fig. 8.86. Comparison of characteristics of structural friction and micro-displacements for bolt joints with steel chock (curve 1) and EPY compound chock (straight line 2)

Structural friction characteristics for the joint with resin compound chock are of linear form and elastic character (Fig. 8.86, Straight line 2). Micro-displacements measured in the points 1 and 2, occurring in this case, result from elastic strains in material of joint elements in which mutually interacting surfaces of the elements and the chock tightly stick to each other. Owing to this, neither contact tangential deformations nor micro-slips occur in the joint, despite the loading force is threefold greater than the maximum one acting onto the joint with steel chock.

Maximum value of friction factor, determined for the steel chock, is equal to $\mu_s = 0.24$, and for the resin compound chock — $\mu_t = 0.8$. The latter is 3.3 — fold greater than the friction factor value for the joint with steel chock, and this is not an ultimate value at which friction contact in the joint would be broken. (An attempt to further increasing the force T was stopped for fear of possible damage of extensometers).

In Fig. 8.87 and 8.88 a comparison is made between the dynamic characteristics determined for the bolt joint with steel chock and that with chock cast of resin compound, respectively, at identical kinematic excitations of sinusoidal variability, measured in the points 1 and 2. Amplitudes of the excitations were equal to: 1, 2.5, 5, 10 and 15 μm (Fig. 8.87b, 8.88b). Time runs of the forces generating the set displacements, are shown in Fig. 8.87c and 8.88c, respectively, and the hysteresis loops which then occurred — in Fig. 8.87d and 8.88d.

In the tested system with steel chock, non-linear relations resulting from significant micro-slips in contact occur already at relatively small excitations. They are clearly

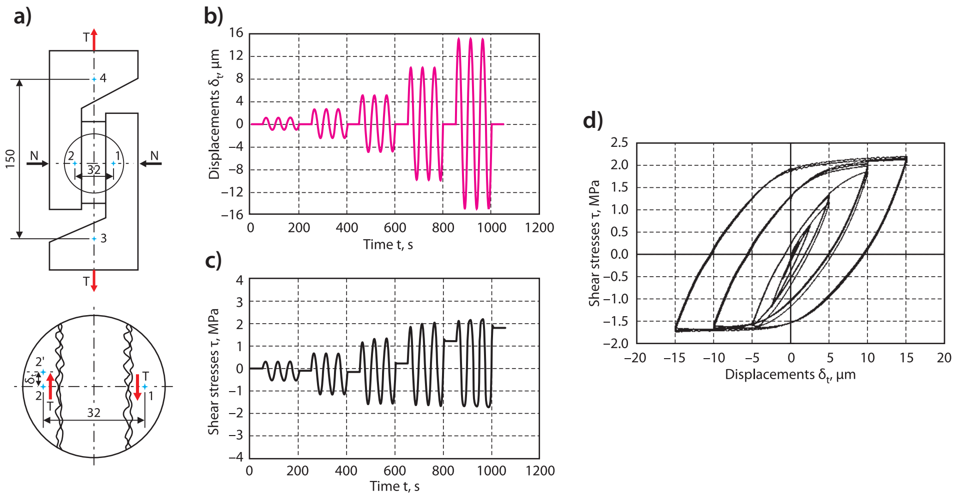


Fig. 8.87. Schematic drawing of the tested joint with steel chock (a), time runs of the dispacements δ_t (b) and shear stresses τ (c), and hysteresis loops occurring in the tests (d)

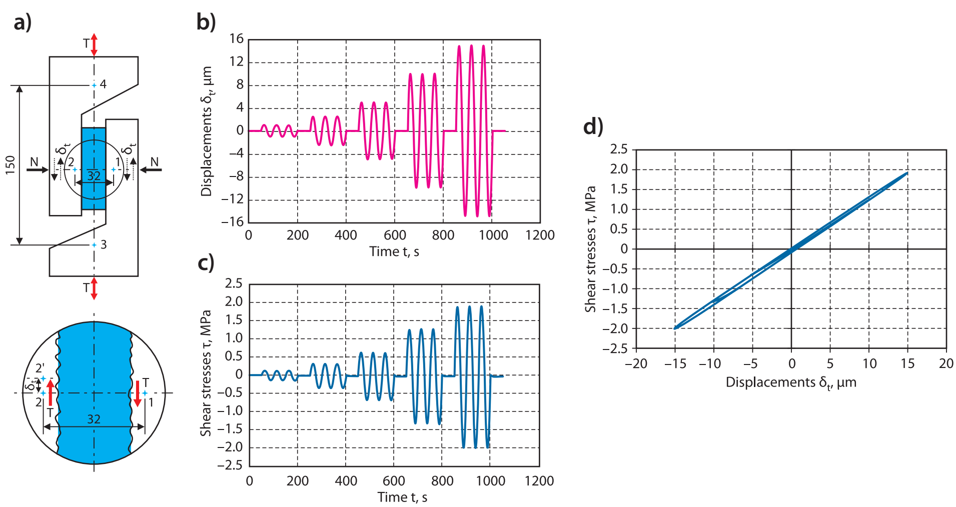


Fig. 8.88. Schematic drawing of the tested joint with EPY compound chock (a), time runs of the dispacements δ_t (b) and shear stresses τ (c), and hysteresis loops occurring in the tests (d)

visible in big hysteresis loops (Fig. 8.87d), where a large work is done by structural friction forces, resulting in effective damping vibrations. However, along with time the uneven surface peaks get worn and friction corrosion usually appears leading to degradation of interacting surfaces and loosening and damaging the joint.

At the same excitations, the joint with resin compound chock performs entirely in a different manner. In this case, simple linear relations between tangential stresses and resulting relative displacements happen within the whole range of excitations. No micro-slips between interacting surfaces occur, and the measured displacements result from linearly elastic deformations of material of joint elements and first of all of resin compound chock. Hysteresis loops are small and manifest damping properties of resin compound. They can be approximated with the use of sharp-ended ellipsoidal forms. It is of a great theoretical and practical importance, because such approximation facilitates modeling and computing such joints and analyzing their influence on dynamic features of the entire complex system as well. Large value of effective friction factor (reaching even 1 sometimes), without occurrence of any micro-slips, guaranties that large tangential forces can be effectively transferred (transversely to bolt axis). Also, in this case no corrosion phenomena occur, which consequently ensures that such joints are capable of reaching high reliability and long service life. The facts were practically confirmed in many objects operating in ultimately harsh conditions (e.g. in shipbuilding). The performed research highlights in a scientific, unambiguous way why the foundation chocks cast *in situ* of an appropriate polymer compound better fulfill their technical tasks than the traditionally used steel chocks. An additional merit of these chocks is that they may be easily manufactured in any place, have good insulation properties against sound and vibration effects and resistance to action of atmospheric factors and various aggressive agents.

8.11. Determination of the states of stress and strain in bolt joints with chocks made of EPY compound and steel

8.11.1. Introductory remarks

Determination of stress and strain states in foundation bolt joint is a very complex task which belongs to the field of contact mechanics of deformable bodies, and which is almost unsolvable with the methods known from material strength science, principles of mechanical engineering and theory of elasticity, unless many simplifying assumptions are made. However, adopting such assumptions as recommended in the VDI guidelines [159] leads to obtaining calculation results straying rather far from reality.

New computation possibilities in the field of complex mechanical systems have been opened by the finite elements method (FEM) combined with application of numerical processing on computers [160]. This method was used here in an unconventional way to determine the stresses and strains generated during the assembling and appearing in service, for two models of a foundation bolt joint of main ship engine. The models differed only in chock material — in one model the chock was made of EPY compound, in the other — of steel.

The aim of the work was:

— to examine the influence of elastic properties (E and ν) of chocking material (EPY compound and steel) on the size of contact area, distributions and values of pressures exerted on the chock and the field of displacements in joint elements;

— to determine the values of stress and strain and the operational characteristics of forces appearing in the bolt under the assumed external load both tensioning and compressing the examined joint;

— to examine the influence of temperature changes on the values of stress and strain generated during the assembling in the analysed bolt joint model with a resin compound chock.

8.11.2. Model of a foundation bolt joint

A simplified axially symmetrical model of a foundation bolt joint was selected for analysis and computations, Fig. 8.89 [161]. Such model is generally applied to bolt joints because of the local character of loading. The model is sufficient for comparative analysis and the fulfilling of aims set for this work. The elements of analysed system (Fig. 8.89), including EPY compound chock, were treated as elastic bodies. The quantities used as input data to numerical computations were chosen so as to correspond to mean values occurring in practice.

A discrete model of joint, which was used for FEM numerical computations is presented in Fig. 8.90. Since the computation and analysis were focused mainly on the contact areas between the bed-plate, foundation and chock (made either of compound or steel), two-nodal joint elements were applied in order to enable the

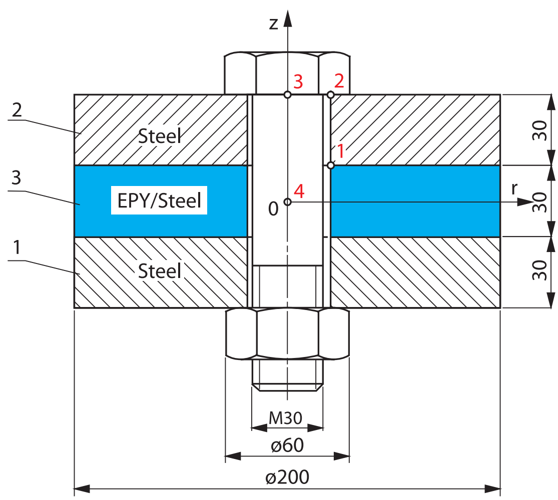


Fig. 8.89. Model of the foundation bolt joint: 1 — foundation plate, 2 — machine bed-plate, 3 — foundation chock (made of EPY compound or steel)

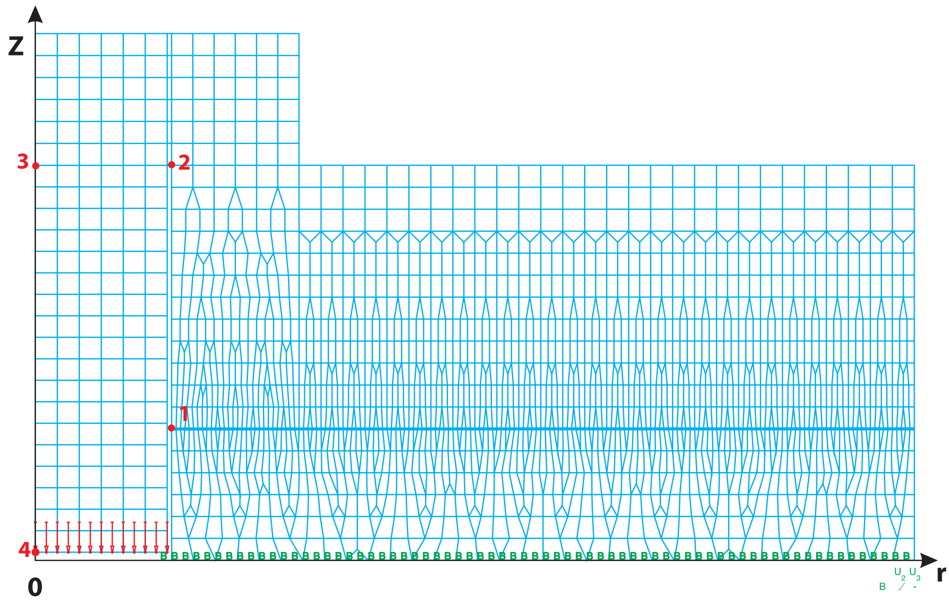


Fig. 8.90. FE model of a bolt joint for calculations by means of MES ADINA software

contacting surfaces to open out and slide. Coulomb friction forces on contact surfaces were taken into account. However, the area in bolt joint lying between the head of the bolt and the bed-plate was simplified by using one-nodal joint elements.

Only one part of the joint was modelled for computations because of symmetry of the system (Fig. 8.90). Finite elements axially symmetrical with respect to Z-axis were used, which significantly simplified the computations.

8.11.3. Determination of the states of stress and strain generated during the assembling

The following values were taken for numerical computations of the model: dimensions as in Fig. 8.89; material constants $E_{st} = 2.1 \cdot 10^5$ MPa, $\nu_{st} = 0.3$, $E_{tw} = 6369$ MPa, $\nu_{tw} = 0.375$; friction factors $\mu_{st} = 0.3$, $\mu_{tw} = 0.8$; bolt pre-tension force $P_o = 150$ kN generating mean surface pressure on the chock $\sigma_0 = 5$ MPa. The set assembly pre--tension of the bolt in the model (Fig. 8.90) was obtained by displacing the middle cross-section of the bolt along Z-axis. (Fig. 8.91).

Fig. 8.92 and 8.93 present the field of displacements along Z-axis and the contact force distribution in the models of bolt joints with a compound chock (Fig.8.92) and a steel chock (Fig. 8.93), respectively.

Fig. 8.94 presents displacements along Z-axis of bed-plate and chock contact surfaces under the pre-tension force $P_o = 150$ kN. In one case, the chock is made of

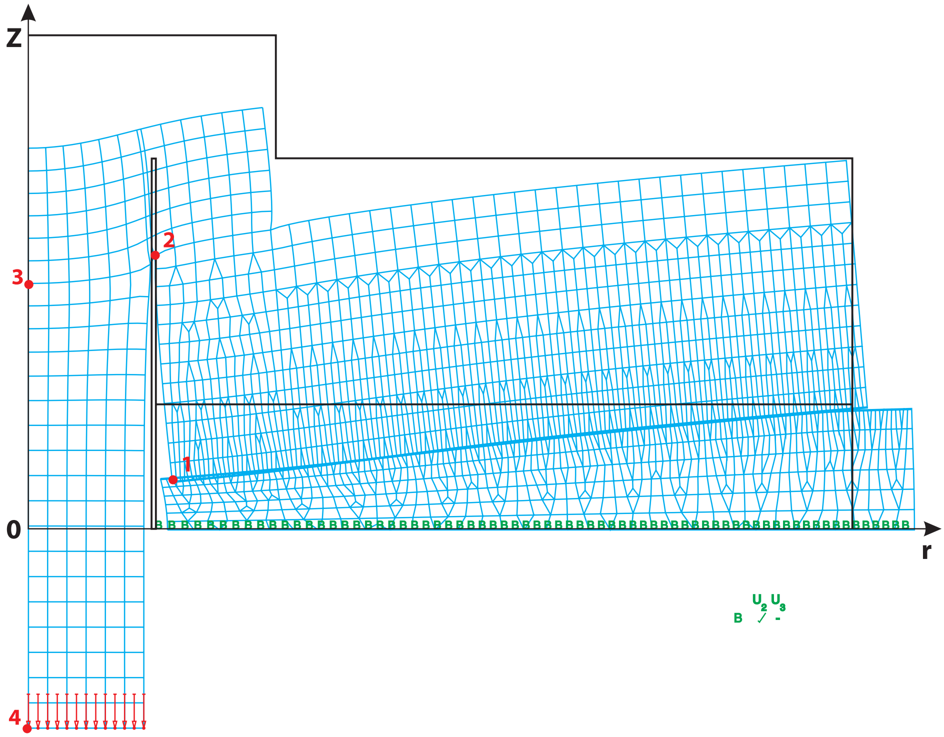


Fig. 8.91. FE grid deformed under the bolt pre-tension force $P_0 = 150$ kN (scale 200 : 1)

the compound, in the other of steel. In the figure, radius R_o defines contact surface area between bedplate and foundation chock. The areas for both chock materials differ significantly. Beyond radius R_o, contact between the bedplate and the foundation chock breaks up (Fig. 8.94). The differences in break-up areas and the surface opening range are distinct, again depending on the material of the chock.

Fig. 8.95 presents the contact force distribution σ_z on the contact surface between the bed-plate and the chock in bolt joints under the pre-tension force $P_o = 150$ kN. In one case, the chock is made of compound, in the other of steel. The maximum value of contact pressure in the case of steel chock is almost threefold higher than the maximum contact pressure exerted on the compound chock, which results from the distribution of pre-tension load on a larger contact surface. The horizontal line in Fig.8.95 indicates a mean computational value of contact pressure ($\sigma_z = 5$ MPa) on the whole nominal contact surface area of the chock and bedplate. Application of compound chocks provides a much better similarity between the actual contact force distribution and the nominal one (assumed for design calculations of foundation chocks).

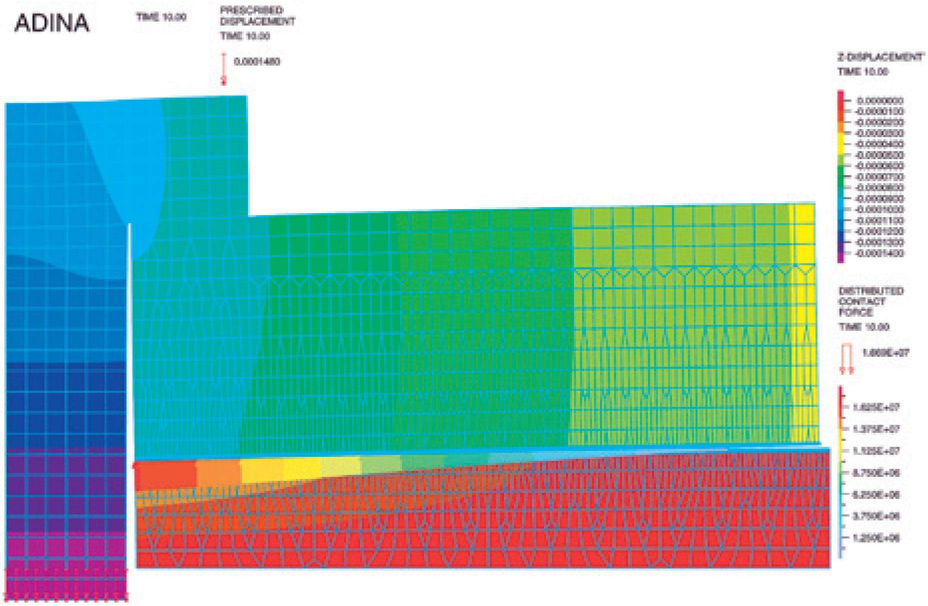


Fig. 8.92. Displacement field in Z-axis direction and contact force distribution in the model of the bolt joint with EPY compound chock

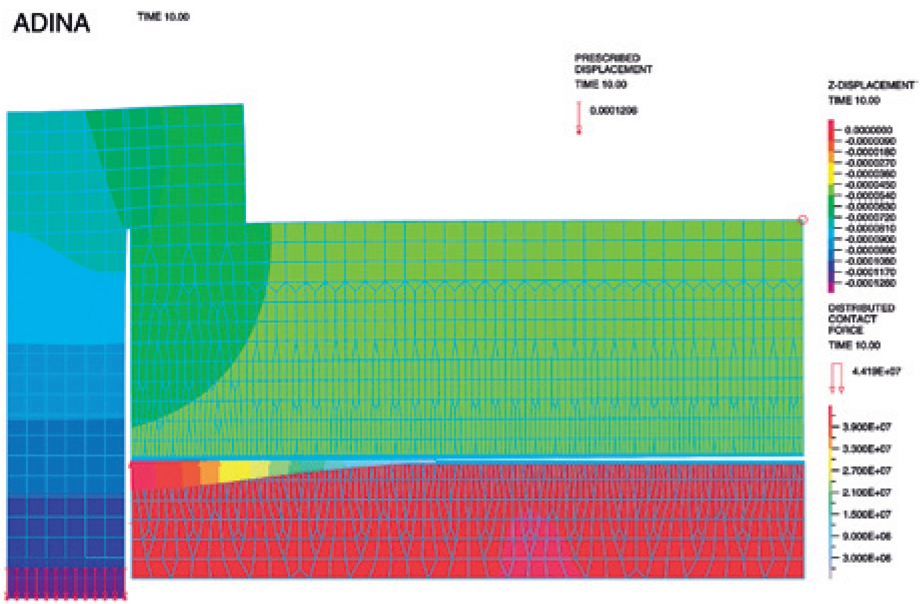


Fig. 8.93. Displacement field and contact force distribution in the model of the bolt joint with steel chock under the external force F = –282.743 kN

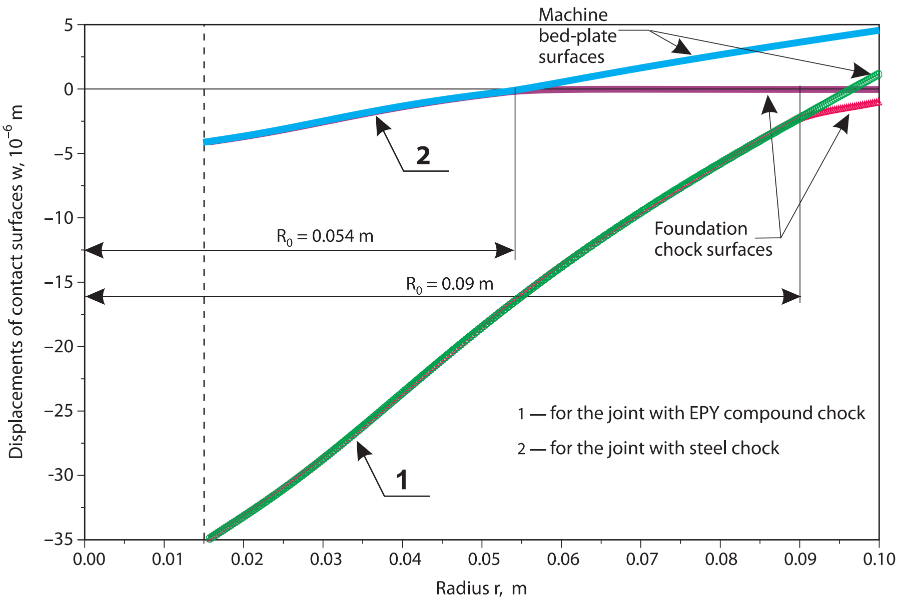


Fig. 8.94. Displacement fields in the direction of Z-axis of contact surfaces between machine bed-plate and chock made of EPY compound (1) and steel (2), under the force P = 150 kN

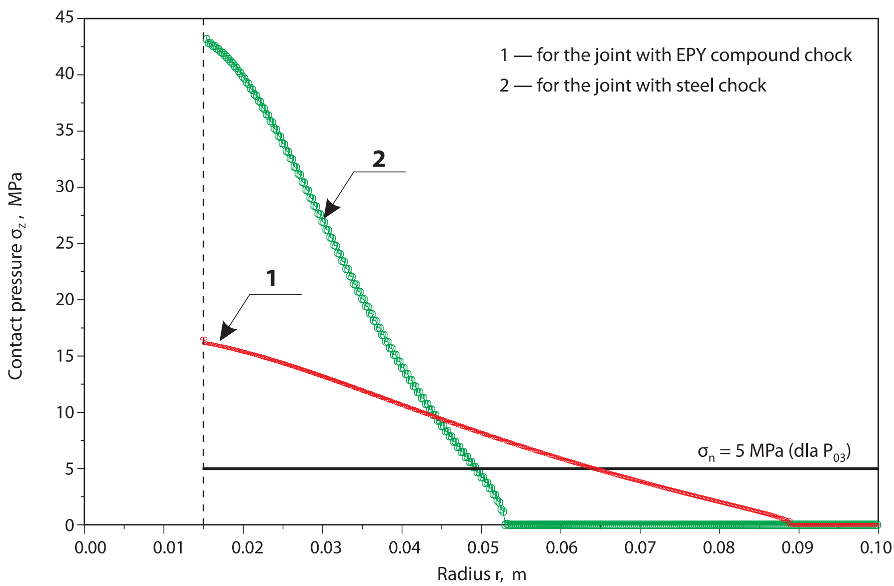


Fig. 8.95. Contact force distributions on contact surface between machine bed-plate and chock made of EPY compound (1) and steel (2), under the force $P_0 = 150$ kN

8.11.4. Determination of the service states of stress and strain and the characteristics of loads in holding down bolts

It is assumed now that the initially tensioned bolt joint is loaded with the external force F distributed uniformly on the circumference of the plates (discs) representing fragments of the bed-plate and the foundation (Fig. 8.96). External force may stretch or compress the examined joint. The values of the external force F used as input data for numerical computations were taken as ranging from –282.743 kN to +282.743 kN in 400 steps. The "minus" sign is assigned to compressing and the "plus" sign to stretching the joint.

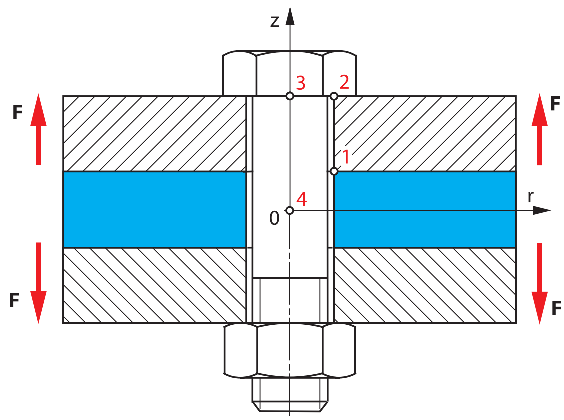


Fig. 8.96. Model of the bolt joint under the external force F

The distributions of forces and displacements of joint elements, determined for the maximum values of external compressing and stretching force, are presented in Fig. 8.97, 8.98 and 8.99, respectively. As can be observed in Fig. 8.97 and 8.98, in the case of the compressing of the bolt joint with a compound chock, the force is exerted on the whole chock more uniformly than in the case of a steel chock. When the joint is stretched by the maximum external force F, the chock becomes completely unloaded and the whole external tension force is transferred by the bolt itself. In such case, the material used for the chock does not make any difference. The fields of displacements in the bed-plate and the bolt are the same in both models of the joint (Fig. 8.99).

Fig. 8.100 presents the relation between the operational force (P) in the bolt and the external force (F) applied to the joint in both models. The computation was done for the values of external force changing from –300 kN to + 282.743 kN. There are three tension ranges in the model with a compound chock (Fig. 8.100, Curve 1). Sufficiently high compressive force provides full contact between the chock, bed-plate and foundation.

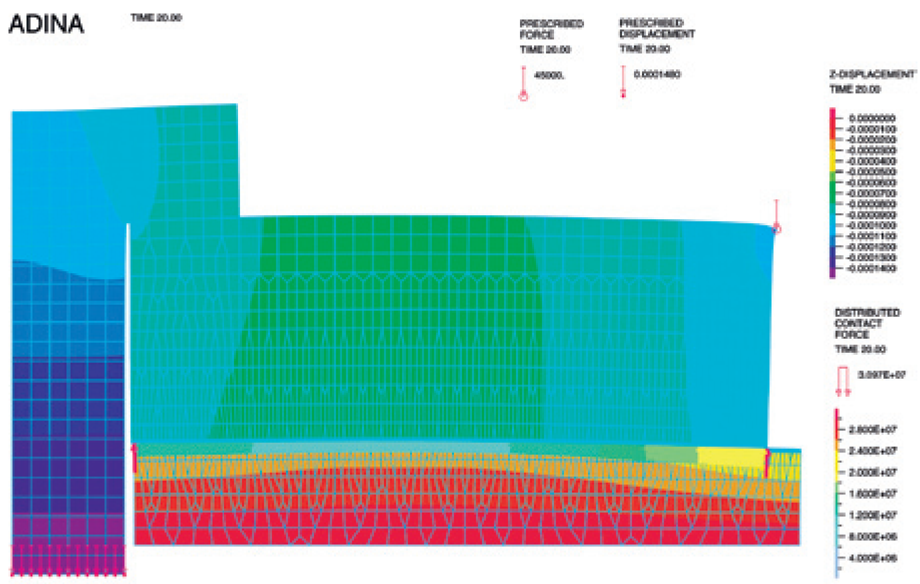


Fig. 8.97. Displacement field and contact force distribution in the model of the bolt joint with with EPY compound chock under the external force F = –282.7 kN

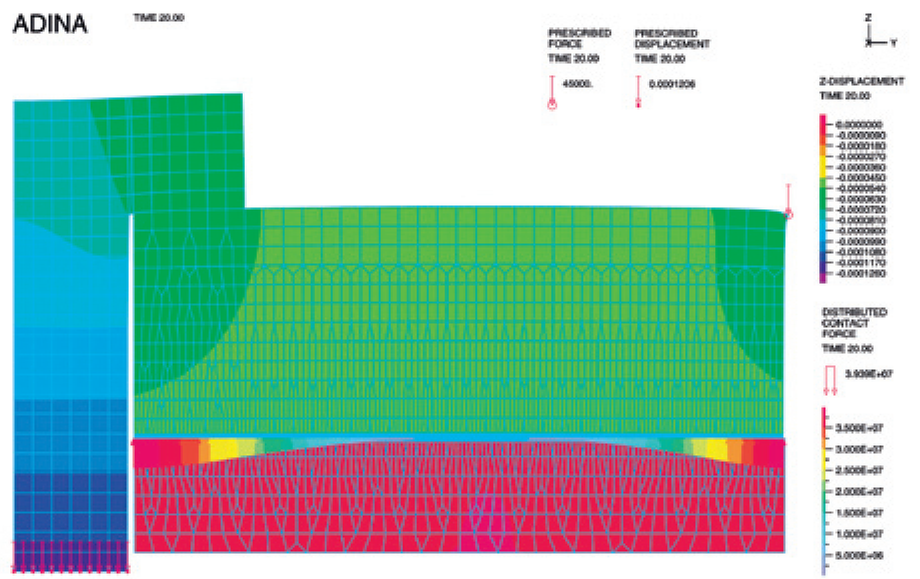


Fig. 8.98. Displacement field and contact force distribution in the model of the bolt joint with steel chock under the external force F = –282.7 kN

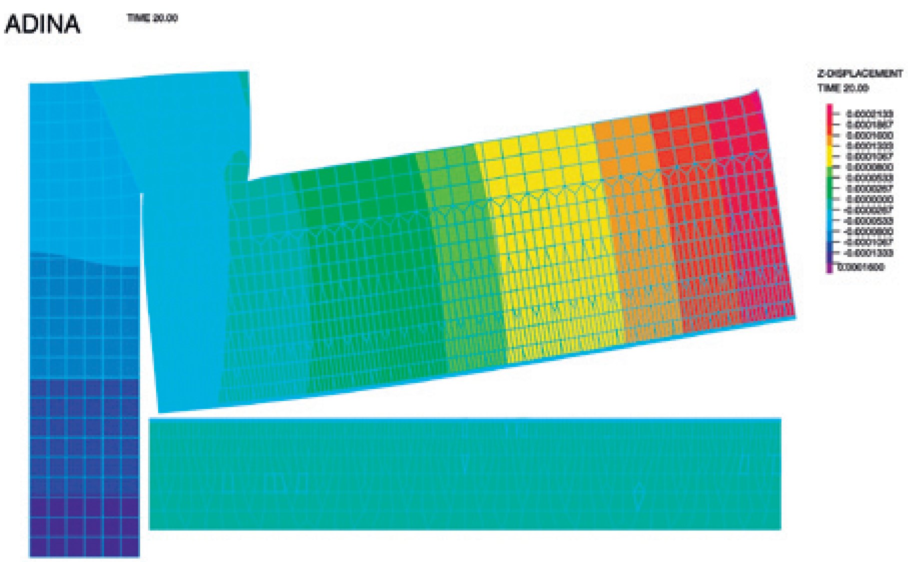


Fig. 8.99. Displacement field and contact force distribution in the models of the bolt joint with chock made of EPY compound and steel under the external force F = +282.7 kN

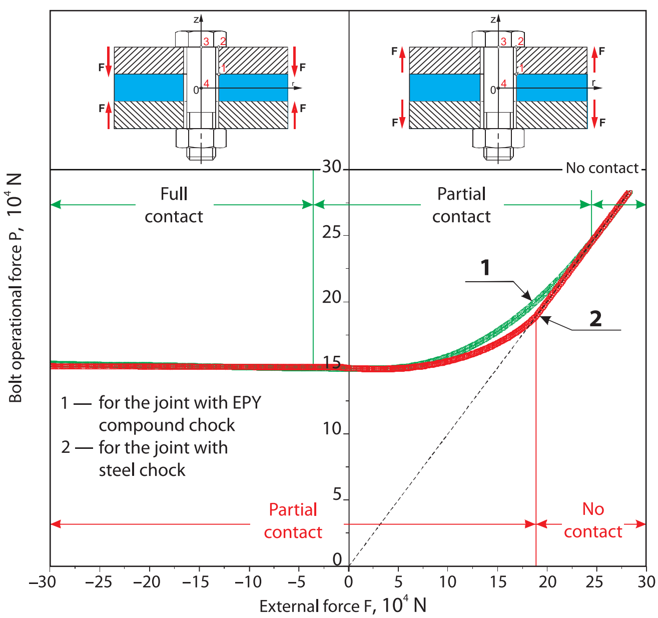


Fig. 8.100. Relation between the bolt operational force P resulting from the external force F applied circumferentially to the joined elements (at P_0 = 150 kN)

For the values of external force F ranging from about –4 kN to about +25 kN, the chock, bed-plate and foundation get into contact only on a part of the nominal contact surface area. The higher external tension force the smaller actual contact surface area. When the external force F is higher than +25 kN, the bed-plate does not touch the chock at all (Fig. 8.99).

In case of a bolt joint with steel chock, the bedplate and the foundation chock can never get into contact over the whole nominal contact surface area (Fig. 8.100, Curve 2).

Such contact is possible to occur only on a part of this area, or none, which happens under sufficiently large values of external tension force, higher than about +17.5 kN. Under compressive force, the gap between the joined elements does not disappear completely. It means that the chock transfers the compressive force only through a part of its surface.

Fig. 8.101 presents, for comparative purposes, the relation of the force P in the bolt and the external force F acting along the axis of the bolt joint. This way of applying the external force is the most typical solution which can be found in the books on the principles of mechanical engineering [82].

When comparing the diagrams in Fig. 8.100 and 8.101, considerable differences can be noticed. The diagrams in Fig. 8.101 refer to the joint elements treated as rigid

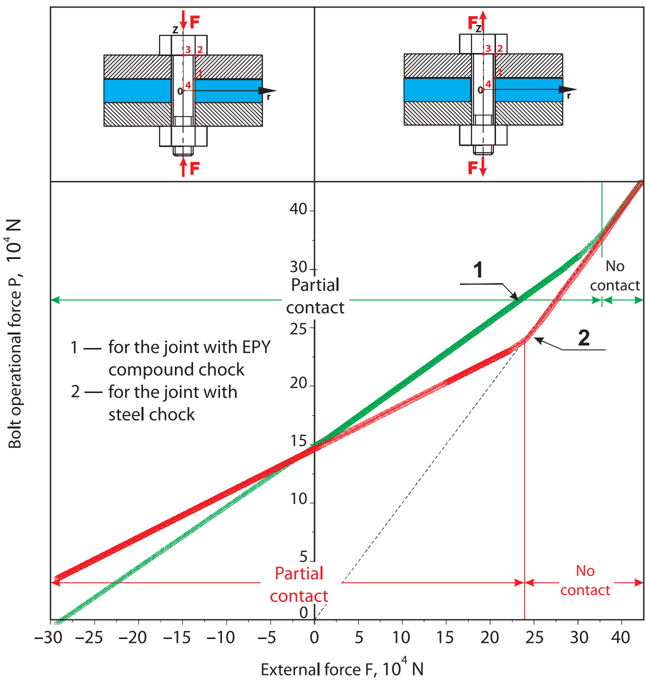


Fig. 8.101. Relation between the bolt operational force P and the external force F applied in line to the bolt joint axis (at $P_0 = 150$ kN)

bodies. In reality, they are elastically deformable. Therefore, the diagrams in Fig. 8.100 are closer to reality than those in Fig. 8.101. They show (Fig. 8.100) that the external tension forces up to about +10 kN and the compressive forces up to about –30 kN applied to the elements of the joint do not significantly change the initial tension in the bolt. In particular, the tension does not decrease under compressive force as it can be seen in Fig. 8.101 (for rigid bodies).Owing to non-dilatational strains in the elements of the joint, the external force is transferred to the chock without unloading the bolt, which is especially advantageous for a bolt under dynamic load.

8.11.5. Influence of temperature changes on pre-tension stress and strain in bolt joints with compound chocks

EPY compound chocks have different thermal expansion coefficients than the steel elements, and they together constitute a bolt joint as in Fig. 8.89. The values of thermal expansion coefficient and modulus of elasticity of the compound considerably depend on temperature (within the range from –20 to +80°C). Therefore, if the assembly of a foundation bolt joint is assumed to be performed at a temperature of +20°C, the change of ambient temperature will affect the initial stress and strain values in the joint.

The aim of the presented research was to determine the resulting change of pre-tension stress and strain in bolt joints with resin compound chocks of the type shown in Fig. 8.89, with the use of FEM ADINA computing system. It was assumed that the external diameter of the joint was 240 mm, the assembly was conducted at +20°C temperature, and the pre-tension force in the bolt was P_o = 222,500 N. The joint was cooled down by 40 K (to –20°C), and then heated up from the initial temperature of 20°C by 60 K (to +80°C). Pre-tension of the bolt was reached with stress σ_z = 315 MPa applied to the cross-section of the bolt shank at Z = 0, causing the relative displacement of the section (Fig. 8.102a). Next, freedom of displacements of the cross-section along Z-axis was locked and thermal stresses were determined. The following values were taken for numerical computations:

a) for the resin compound (on the basis of these authors' own research):
— at temperature of +20°C E_{tw} = 6369 MPa, ν_{tw} = 0.375, $\alpha_{tw} = 30.0 \cdot 10^{-6}$ 1/K,
— at temperature of –20°C E_{tw} = 8000 MPa, ν_{tw} = 0.375, $\alpha_{tw} = 24.7 \cdot 10^{-6}$ 1/K,
— at temperature of +80°C E_{tw} = 5000 MPa, ν_{tw} = 0.375, $\alpha_{tw} = 40.4 \cdot 10^{-6}$ 1/K,

b) for steel (constant values): $E_s = 2.1 \cdot 10^5$ MPa, ν_{st} = 0.28, $\alpha_{st} = 12.5 \cdot 10^{-6}$ 1/K.

The results of computations are presented in Fig. 8.102. Fig. 8.102a presents the distribution of contact force and the field of reduced stresses in a foundation bolt joint after its assembly at a temperature of +20°C. Fig. 8.102b and 8.102c present the same values after cooling the joint down by 40K (to –20°C) and heating it up by 60 K (to +80°C), respectively.

The computation results show that the changes of temperature in the joint within the assumed range result in a change of value of contact forces. The temperature

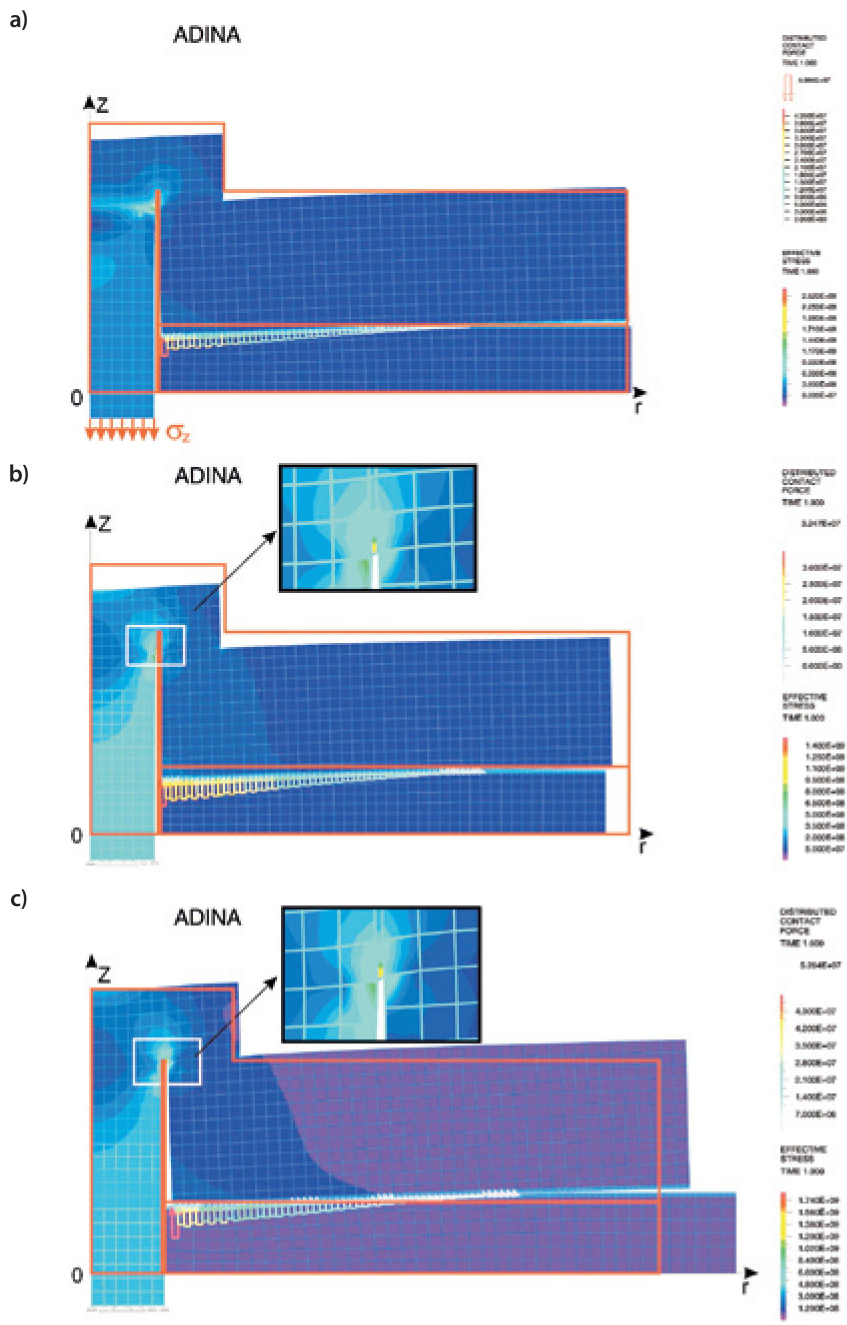


Fig. 8.102. Deformed FE grids, reduced (effective) stress fields and contact force distributions over foundation chock in the pre-tension state (a), after cooling down the joint (b) and heating it up (c)

drop slightly decreases the contact forces, and the rise in temperature increases the forces. The respective pre-tension stresses in the bolt are as follows:

— at a temperature of +20°C, P_o = 222,500 N (initial state),
— at a temperature of –20°C, P_o = 217,712 N (decrease by 2.15%),
— at a temperature of +80°C, P_o = 267,193 N (increase by 20.0%).

The increase of bolt stress and contact pressure applied to the chock, under increasing ambient temperature due to running the engine or other machinery, is advantageous for foundation bolt joints. In reality such high changes of temperature as the above mentioned seldom ever appear, in particular the cooling down to –20°C. Therefore, the fluctuations of initial bolt tension occur within much narrower limits than those given above.

8.11.6. Summary and conclusions

Foundation bolt joint fitted with compound chock is a complex non-linear system of non-homogeneous bodies, difficult to model and calculate, and the same applies to bolt joints with steel chocks as well. The modelling of joints requires taking into account many complex geometrical and material factors as well as complicated contact effects. Such systems cannot be solved by means of the known analytical methods based on theory of elasticity, but it has been made possible nowadays by introducing numerical methods and advanced FEM programs (for example FEM ADINA software).

The simplified model of a foundation bolt joint with a chock, such as assumed for the purposes of this work, made it possible:

— to determine the pre-tension and service states of stress and strain in the joint,

— to carry out the analysis of the impact of the assumed pre-tension conditions, the applied external forces, and the changes of temperature in the system onto size of contact surface areas, distribution and values of contact pressure, displacement fields in joint elements and the actual force in the bolt.

Comparative analysis of the obtained computation results shows that the application of resin compound instead of steel for the machinery foundation chocks provides a greater zone of actual contact between the chock and bedplate, as well as more uniform distribution of surface forces, which is true both in case of pre-tension state and operation conditions. As a result, such foundation bolt joints can be more reliable and durable.

The temperature increase in the bolt joint with resin compound chock, due to running the machine or other environmental factors, results in a slight (up to 20%) increase of tension in foundation bolt joints, which is beneficial for the machinery. A slight drop of tension in the bolt occurs in lowered temperatures, which may happen when the machinery is not operated or is stored in the open space, for example on the ship's deck.

Foundation bolt joints of real-life machinery are as a rule geometrically and physically more complex than the models examined in this work. The analysis of their static and dynamic states is presently possible, but it can be performed only with the use of more sophisticated models, more advanced computational programs, and computers with high processing power, and all these measures are connected with significant costs.

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The chronological list of research reports and papers concerning polish plastic compounds used for foundation chocks, and their practical application for the seating of machinery

1. *Gluing technology in shipbuilding* (*„Klejenie w konstrukcjach okrętowych"*). Scientific research report, Technical University of Szczecin, Institute of Mechanical Engineering, Technical Mechanics Section, Szczecin 1971 (unpublished)
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