JOURNAL OF THEORETICAL
AND APPLIED MECHANICS
44, 1, pp. 51-73, Warsaw 2006

THE CLAMPED JOINTS – A SURVEY AND ANALYSIS OF SHAPES AND MATERIALS

Janusz Juraszek

Department of Mechanical Engineering Fundamentals, University of Bielsko-Biała
e-mail: jjuraszek@ath.bielsko.pl

The paper presents a survey of available joints of the clamped type (CJ), which are of crucial importance in view of the design safety level. A numerical analysis has been carried out to estimate the efficiency of a given shape of the CJ. A digital database of material parameters most often employed in CJs has been presented as well.

Key words: clamped joint; jaw shapes, FEM, stress-strain state

1. Applicability and analysis of clamped joints used in practice

Clamped joints, which can be classified as permanent joints, are often used for connecting and fixing steel wire ropes, electric cables or hydraulic conduits. For example, in the power engineering, joints of that type are used for fixing and connecting different items; e.g., conductors, cables, elements of overhead transmission lines, etc. In aviation, they are used as an alternative way for making a control cable tip. Other examples can be found in cranes (lifting rope tip) and in hydraulic piping (joining of conduits). Another type of permanent joints connecting steel wire ropes consists in filling a joint with a low melting alloy, which is, however, a very laborious, expensive and toxic (lead and zinc vapours) process. Moreover, it cannot be used in all the aforementioned cases.

On the other hand, it should be mentioned that temporary joints reveal also some substantial disadvantages, e.g., complex design, large dimensions and mass, which considerably rises costs of making such joints. The method of clamping is relatively inexpensive, requires little work, and its broad applicability covers also outdoor cases. The main advantage of clamped joints consists in its small size. A hexagonal clamped joint can be considered as a typical example of such a joint [5]. The main idea of fastening consists here in changing the initial circular shape of a sleeve into a hexagon inscribed in that circle (Fig. 1). The process of clamping is performed using two clamping jaws. The surface of the jaw contact determines the joint parting plane, which is its plane of symmetry as well. In power engineering applications (Fig. 2), the Al-Fe (aluminium and steel) conductor tip after being inserted into a sleeve is clamped due to transversal plastic deformation of the sleeve. The joint operation is two-fold, i.e. besides doing a mechanical work (i.e. carrying a load) it operates also as a conductor so that the electric circle is not broken. The material of the clamping sleeve should reveal good conducting properties, usually the sleeve is made of aluminium A0.

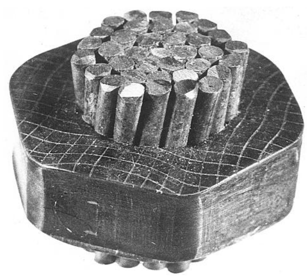

Fig. 1. Rope clamped "into a hexagon"

Fig. 2. Exemplary joints used in power engineering systems

There are also other forms of clamping jaws available, e.g., octagon, dodecagon, ellipsis, modified ellipsis, circle (one parting plane), modified circle, axi-symmetric forms, etc. Some papers devoted to that problem can be found in the literature as well. The most interesting publicationa are presented below.

The distribution of pressure in the course of a clamping process in not a uniform one. The way of axi-symmetric clamping proposed in Juraszek (1995, 1997, 1999, 2000, 2004) eliminated noticeably that non-uniformity revealed by the pressure distribution. That approach, however, requires application of a special hydraulic power press of a complex design, and the clamping process should be carried out at a laboratory or a suitable factory department.

Another research that should be mentioned here consists in inventing a new method for mounting wires for temperature measurement in an oily seed silo, based on mounting them into a self-clamping cone. The wires break off along the radius of the inner hole-to-cone segment. The application of the axi-symmetric way of clamping allowed for elimination of the wire breaking off which made both the design and mounting much simpler.

Basing on the aforementioned examples, one can arrive at the conclusion that clamped joints exert decisive influence upon a safety level and reliability of structures they are applied to (fixing of lifting ropes in cranes, overhead transmission line supports, electric cables, etc.). A proper qualitative strength analysis may result in improving the safety and allowing for a proper choice of joint parameters.

Each clamped joint comprises the following two elements:

1) rope, cable or a hydraulic conduit
2) clamping sleeve.

Steel wire ropes, electric cables and hydraulic hoses should meet requirements specified in relevant standards, while their properties are presented in Juraszek (1992). Molnar et al. (Maligda *et al.*, 2000; Molnar, 2004; Stanova and Molnar, 2003) presented a problem of 3D modelling of ropes. A clamping sleeve made of a plastic material is the second element of the joint. The sleeve material deforms plastically when subject to an external pressure, and after unloading the residual stresses remain on the sleeve-rope contact surface. When modelling the phenomena appearing in the clamped joint, values of material parameters introduced into the model after exceeding the yield point are of crucial importance. The values of parameters available from the literature differ substantially from those measured for a given material at its working point or within the expected loading range. To make the calculations more accurate, the Digital Database of Material Parameters has been proposed.

Most interesting research works on the contact problems between a wire rope and foundation was presented by Dorfmann *et al.* (1999). The authors carried out a numerical analysis and experimental investigations on the contact between a rope and a rubber-aluminium wheel. Numerical simulations were performed using the AbaQus code, with the phenomenon of wheel heating introduced into the model, which, however, presented only a simplified external contour instead of the real wires. Kliber (2000) carried out numerical analyses of large plastic deformations with the phenomenon of linear strain hardening included. Buczkowski and Kleiber (1992) examined models with friction introduced into elastic-plastic problems.

The model of contact should be specified before analysing the process of clamping of a wire rope. Altenbach (1991) presented an incremental method for contact description in 2D models, while Hrycaj *et al.* (1999) showed an elastic plastic model with the Coulomb friction introduced. Among the papers devoted to clamped joints, one should mention the analysis of clamping into a hexagon (Juraszek, 1994), research on multi-clip joints (Juraszek, 2004) and a study on the equivalent transversal stiffness of a steel wire rope and steel-aluminium cables (Juraszek, 1992, 1995).

Problems of large deformations in plastic forming were analysed by MacDonald and Hashmi (2002) using the ANSYS code. Landre *et al.* (2003) presented a discussion of FEM mesh changes during upset forging with the Cockroft-Latam criterion taken into consideration. Provatidis (2003) showed an interpolation of the Coon type applied to an axi-symmetrical problem, which allowed for making the calculation time much shorter for non-linear problems of large deformations.

Most often, joint designs result from the experience gained by different manufacturers (Juraszek, 1997). A survey of designs available reveals the lack of a consistent main idea laying behind the joint design. Moreover, one should mention the lack of data on strength calculations, designing and appropriate selections of rope fastenings (connections between elements that reveal substantially different stiffnesses). The investigations are being conducted by scientific centres associated with manufacturing companies and, consequently, market competition prevents publication of the results. A survey of materials used in clamped joints, having a systematic form of the Digital Database has been presented hereinafter, together with the discussion on shapes of clamping jaw, taking into consideration the twisting of jaes about rope wires.

2. Digital Database (DD) of material parameters used in calculations of clamped joints

2.1. Introduction

Materials used in clamped joints reveal a great variety of physical parameters. In the case of steel wire ropes, the sleeve is made of a high-plasticity steel, while electric cables should be clamped with sleeves made of the aluminium A0 or other aluminium alloys. The process of clamping involves large plastic deformations. Therefore, one of the crucial phases of the clamped joint modelling consists in a detailed analysis of characteristics of the materials to be joined, focusing on the material parameters beyond the yield point.

A new systematic approach has been proposed allowing for a consistent presentation of material parameters that can be applied to joints, providing at the same time a way of producing digital forms of material characteristics. Different models of a material can be constructed as well, by means of a special program the database is supplied with. The possibility has also been offered to find necessary parameters for analysis of a non-linear material.

Nowadays, some databases are available:

- created by the Centre of Excellence for Safety-Critical Pressure Systems (www.ippt.gov.pl/centrum-cdsc/baza); it contains only characteristics of materials used when constructing pressure vessels, providing however no discussion of material properties beyond the yield point;
- established by the Centre for Advanced Materials and Technologies – a catalogue of new materials;
- very large database www.matweb.com;
- database of parameters www.suppliersoline.com and
- database of material properties depending on temperature www.jam.software.inc.

Unfortunately, they do not provide any data allowing for precise determination of the properties of materials used in clamped joints, especially beyond the yield point. There are only standard material characteristics available; providing values of Re, Rm, $A5$, $A10$, E and hardening modulus, without any specification of the strain range for which they have been determined. There is a lack of accurate data on the strain-hardening coefficient at an arbitrary point of the characteristics. Typical material catalogues (e.g. Dobrzański, 2001) concentrate on a chemical constitution and the aforementioned standard parameters. Bures and Kohutek (2000) presented constructional possibilities of material databases using the Internet. A new solution to the problem has been proposed based on the enormous capabilities offered by modern, advanced experimental equipment that satisfies the needs for data necessary to carry out a non-linear numerical analysis using FEM. The research scope covered all materials used in clamped joints, which can be classified into several groups depending on their application:

- Low-carbon plastic steels, e.g. steel of 10 grade – clamping sleeve
- High-carbon steels, assisting sleeve in hydraulic joints
- Aluminium and its alloys, e.g. aluminium A0 – clamping sleeve working as conductor in electric joints
- Wires of ropes
- Wires of electric cables
- Hoses in hydraulic systems – elastomers and polymers
- Superplastic materials like NITINOL.

The values of characteristic parameters of materials used in joints of that type differ fundamentally, e.g., the value of Young's modulus varies within the range from 2 MPa (elastomers) to 210 000 MPa (steels).

A new database has been proposed for material parameters necessary in numerical investigations on clamped joints. To the best author's knowledge, the approach put forward has not been taken before. It allows for automatic data collecting from experiments performed using the general-purpose testing machine INSTRON as well as for data processing to arrive at the form required by the FEM approach. The numerical analysis is carried out basing on true values of the tangential modulus determined for a given load. Such an approach improves accuracy of numerical calculations, assuming at the same time the role of pre-processor of material parameters necessary for analysis of plastic deformation problems.

The database proposed allows for a proper material choice for new types of joints, improving that way their safety. Capabilities of modern computer techniques enable application of values of parameters stored in the database to the analysis carried out basing on non-linear physical relationships.

Therefore, one can now attempt at a numerical analysis based on true properties of a material determined within the whole expected loading range. It should be noted, however, that the values resulting from experiments differ substantially from those presented in the literature.

A special computer program has been developed, which:

- downloads results of strength testing from the INSTRON machine, which could have been interpreted only by the machine software;

- processes these results to arrive at the form allowing for data transfer to the FEM code;
- determines parameters necessary for the non-linear analysis.

2.2. Models of materials available in the DD base

The DD database offers a special computer program that allows for producing a series of models of materials that can be used in the non-linear FEM analysis. The applied simplifying approach most often consists in neglecting "the plasticity platform" and substituting a segment of constant inclination for an exponential hardening. The model obtained that way is called bilinear and comprises two segments of different angles of inclination. The tangent of the inclination angle the first segment makes with the axis ε represents Young's modulus (elastic range), while the second segment represents the plastic range determined by the hardening modulus E'. The common point of both segments represents the elastic limit Re.

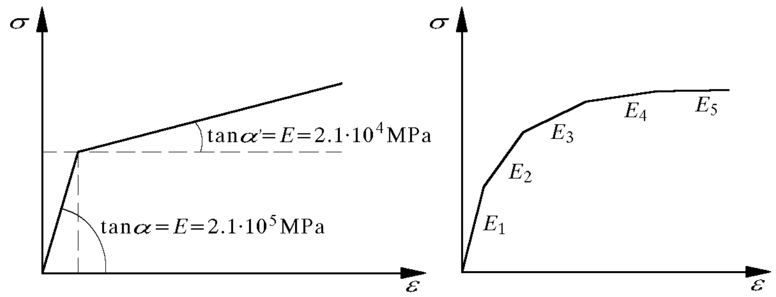

Fig. 3. Bilinear and multi-linear models of the considered material

To attain higher calculation accuracy in the elastic-plastic analysis, one can represent the true stress-strain curve using more segments, e.g. with a broken line comprising 5 segments. Such a model is called multi-linear. The provided computer program allows also for developing models having form of an exponential curve or a polynomial.

When designing clamped joints for hydraulic conduits, a hose made of an elastomer (often reinforced) fitted into a socket is the element to be clamped. In the case of steel-rubber ropes, the space among wires is filled with a special mixture of elastomers. Material properties of the elastomer are represented by the hyper-elastic Mooney-Rivlin model.

When modelling bodies made of rubber or other materials revealing non-linear elasticity and incompressibility, one should apply hyper-elastic models

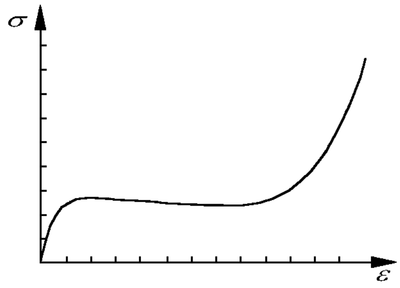

Fig. 4. Hyper-elastic Mooney-Rivlin model

to analysis carried out within the range of large deformations. Practically, the following two approaches to the problem are incorporated most commonly. The first one consists in the interpolation of stress components separately, while in the second one the apparent compressibility is introduced together with a relationship limiting the number of unknown degrees of freedom in the global stiffness matrix.

The Mooney-Rivlin equation has been employed for describing properties of elastomers

$$\sigma = 2C_1(\alpha - \alpha^{-2}) + 2C_2(1 - \alpha^{-})$$

where

σ	–	normal stress
C_1, C_2	–	Mooney's constants
α	–	l/l_0 deformation.

The constant C_1 assumes values within the range 0.05-0.2 MPa rising as the vulcanisation level rises, while the constant C_2 depends on the rubber hardness (0.05-0.1 MPa).

After calculating the derivative of the Mooney-Rivlin equation with respect to ε, one arrives at a formula for the equivalent modulus Ez

$$E_z = \frac{d\sigma}{d\alpha}\Big|_{\alpha=1} = 4C_1 + 6C_2$$

Values of C_1 and C_2 are automatically determined by importing the processed table of $\sigma - \varepsilon$ data (resulting from the compression curve) to the ANSYS code, and then using the Moon function.

Another group of materials used in clamped joints comprises shape memory alloys. Figure 5 shows exemplary characteristics of Nitinol.

Models of shape memory materials were presented by Tanaka *et al.* (1986), while Auricchio (2001), Brinson (1993), Jung *et al.* (2002) showed models with thermodynamic effects included.

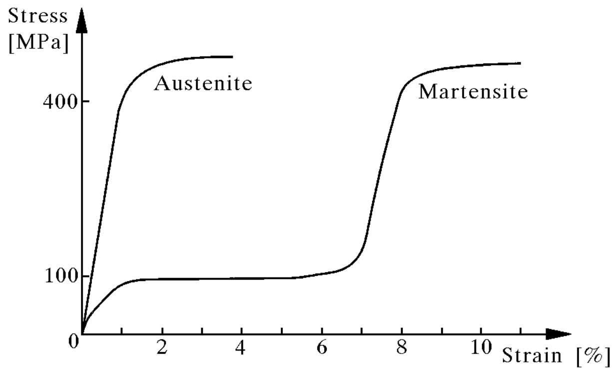

Fig. 5. Nitinol characteristics with phase transitions taken into consideration

The constitutive model (pseudoelastic, bilinear) bases on the directional strain components that have been determined. The model is based upon the double trigger line concept, according to which the gradient of the stress–strain curve depends on the sign of the deformation speed

$$C_Z = \begin{cases} E_1(\varepsilon_z, \dot{\varepsilon}_z, \tau_z) \in \Omega_A(T) \\ E_2(\varepsilon_z, \dot{\varepsilon}_z, \tau_z) \in \Omega_{AM}(T) \\ E_3\varepsilon_z, \dot{\varepsilon}_z, \tau_z) \in \Omega_M(T) \\ E_4(\varepsilon_z, \dot{\varepsilon}_z, \tau_z) \in \Omega_{MA}(T) \end{cases}$$

where ε_z denotes the strain and the dot above it – the strain speed.

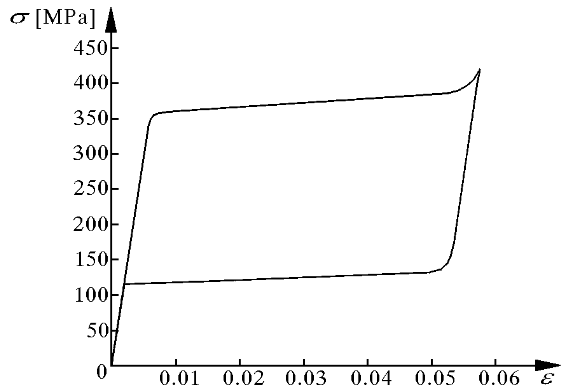

Fig. 6. Nitral characteristics – 7% deformations

Figure 6 presents characteristics found from experiments with a characteristic loop due to phase transitions involved by a temperature drop down to 183°C, when deformations reach 7%.

2.3. Description of the computer program

The program "Digital database of material parameters" has been developed to improve the accuracy of FEM numerical calculations. At the same time, it allows for:

- application of true material characteristics;
- determination of the Young modulus at an arbitrary point of the stress-strain curve in tension or compression;
- linear interpolation of the stress-strain curve in tension or compression in terms of a broken line passing through 5 points;
- using the exponential or polynomial model.

A sample window of the program is shown in Fig. 7. There is a stress-strain curve visible on the screen together with values of deformation (column X) and the corresponding force (column Y) basing on which the diagram was generated. The user can scale the display up or down, delete the picture or store it in a hard disc (see Fig. 7).

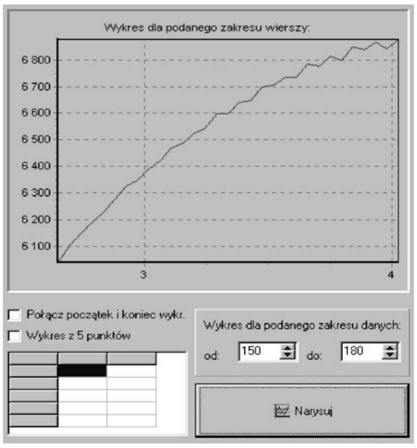

Fig. 7. A view of the computer screen after rolling in the data (in Polish)

The program proposed allows for determination of the Young modulus (i.e. the modulus represented by the tangent to a given point of the diagram, within the non-linear range of course) at every chosen point within the measurement range. Additionally, for a given range, one can determine the so-called secant modulus (i.e. represented by the secant to a given point of the diagram within the non-linear range). When indicating an arbitrary point on the diagram with a mouse cursor, the user can determine the Young modulus. For the purpose of storing diagrams in computer memory as well as disseminating the information via the Internet, a special module was developed for storing the items in the form of GIF image files with their quality being maintained.

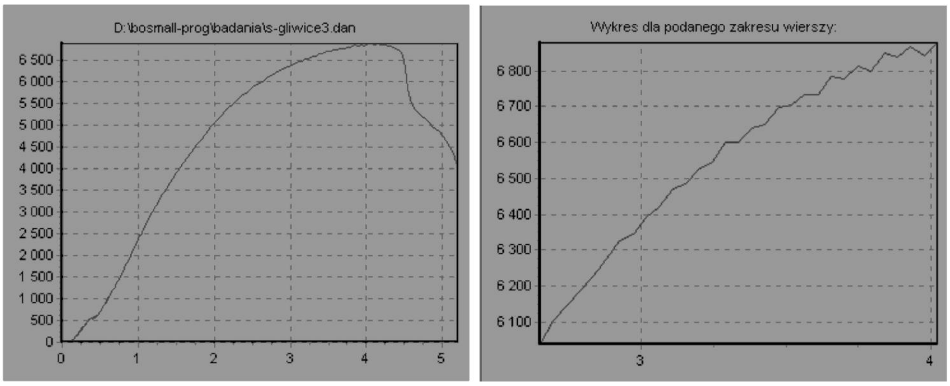

Fig. 8. Sample diagrams saved using the graphics module

When making measurements using the INSTRON machine, one obtains results in the form of a file, which, up till now, could have been interpreted only by that machine. Clicking on the "Converter" drop down list box one can roll in such a file, browse or convert it, i.e. store in the form of a common text file containing two data columns necessary for generation of the stress-strain curve.

The aforementioned database provides also a model allowing for rolling in the data registered by the specific software of the general-purpose testing machine INSTRON, and for processing files containing measurement results into the form required by the ANSYS code. Material parameters necessary for non-linear analysis are determined as well, depending on the adopted model of the considered material. It is obvious that the program is user-friendly. The database presented allows also for storing and comparing between the results of other experiments. The possibility of introducing true material characteristics and taking the expected loading range into account improves the accuracy of numerical calculations.

3. Theoretical background

The present research aims at the analysis of the stress-state in clamped joints with clamping sleeves of different shapes. The following assumptions have been accepted:

- the clamping process is quasi-static;
- the plane model is employed with the joint width neglected;
- twisted steel lines of the T1x7 type are considered which implies that that a relatively long length of lay twisting of the rope strands can be neglected;
- three-node Contac48 elements represent the contact zone between the sleeve and rope;
- kinematic hardening of the material is introduced into the model.

The theoretical background of the method is presented below. The changes in material parameters in the course of the deformation process are taken into account. The Amont-Coulomb fricton model is introduced into the sleeve-rope contact area. The clamping process is assumed as a quasi-static one. The FEM approach assists the analysis of plastic deformation problems.

The equation of equilibrium for a medium can be derived from the virtual work principle (Kleiber, 1984). In the case of a general Lagrange's formulation, we have

$$\int\limits_V S_{ij}\delta\varepsilon_{ij}\,dV = R \tag{3.1}$$

where

S_{ij} – component of the second Piola-Kirchoff stress tensor

ε_{ij} – component of the Green-Lagrange strain tensor.

The work done by the external forces R can be represented in terms of the surface and volume works, respectively

$$R = \int\limits_A p\delta U_k\;da + \int\limits_V f\delta U_k\;dV \tag{3.2}$$

The above equation has been derived on the assumption that the body configuration changes from one loading step to another.

In Eq. (3.2), the symbols A and V stand for the surface and volume, of the body, respectively, while p and f represent components of the vectors of surface and volume forces acting upon a unit surface and unit volume of the body corresponding to the initial configuration. δU_k represents the displacement variation while $\delta_t e_{ij}$ stand for the strain variations

$$\delta_k e_{ij} = \delta\frac{1}{2}({}_kU_{i,j} + {}_kU_{j,i}) \tag{3.3}$$

The above equation in the FEM approach can be rewritten in the following discrete matrix form

$$ {}^k\mathbf{K}\,{}^k\boldsymbol{U} = {}^{k+1}\boldsymbol{R} - {}^k\boldsymbol{F} \tag{3.4}$$

One can arrive at Eq. (3.4) after substituting the following matrix forms for the integrands

$$\begin{aligned}
&\int\limits_{V^0} {}^k\sigma_{ij}\delta e_{ij}\; dV^0 = \int\limits_{V}^{0} \mathbf{B}_L^\top {}^k\boldsymbol{\Sigma}\; dV^0 = {}^k\boldsymbol{F}\\
&\Big(\int\limits_{V}^{0} \mathbf{B}_L^\top \mathbf{D}\mathbf{B}_L\; dV^0\Big){}^k\boldsymbol{U} = {}^k\mathbf{K}{}^k\boldsymbol{U}
\end{aligned} \tag{3.5}$$

The following denotation is used in Eqs (3.4) and (3.5):

- ${}^k\mathbf{K}$ – tangential stiffness matrix at the loading step k
- ${}^k\boldsymbol{U}$ – vector of node displacement increments at the loading step k
- ${}^{k+1}\boldsymbol{R}$ – incremental vector of nodal loads at the loading step $k+1$
- ${}^k\boldsymbol{F}$ – vector of nodal correcting forces at the loading step k
- $\mathbf{B}_L$ – so-called "geometric" matrix relating strains to displacements
- $\mathbf{D}$ – matrix of material properties (tangential matrix)
- ${}^k\boldsymbol{\Sigma}$ – vector of current stresses (at the step k).

The term "step" throughout the considerations means subsequent incremental loading steps.

4. Modelling of the process of clamping and unloading with the shape of clamping jaws taken into consideration

As has been mentioned above, the choice of type of clamped joints is usually made basing on manufacturers' experience. The main issue to be considered here consists in the analysis of clamping and unloading processes, respectively, in the way allowing for proper assessment of states of displacements and deformations together with the stress state depending on the type of clamping jaws employed. A one-plane hinged jaw of a hexagonal shape inscribed in a circle is most commonly used. Such a jaw is very simple in use, and the clamping process can be performed with a small flash of the clamped material. On the opposite end of the application list, an axi-symmetrical jaw is located, being used hardly ever. First to propose it for clamping of a twisted steel lines was Juraszek (2000). For the axi-symmetrical clamping process to be performed, four parting planes should be introduced and turned about 45 degrees relative to each other, which highly complicates the clamping process. The used hydraulic systems prevent from simultaneous translation of the jaws. Therefore, a mechanical system driving the translations of all jaws in a controlled way combined with hydraulically driven motion were introduced which enabled proper realisation of the axi- symmetrical clamping process. This approach reveals very high complexity in view of the process technology. It should be noted, however, that besides the two aforementioned "extreme" types of jaws, there are several other shapes available:

- Octagonal
- Octagonal-twisted
- Dodecagonal
- Dodecagonal-twisted
- Elliptic
- Modified elliptic
- Circular (one parting plane)
- Modified circular
- Of a special shape.

In the last case, roughly speaking, clamping jaws have a shape of a polygon inscribed in a circle or ellipsis. The main advantage of this type of jaws consists in shaping its contours in the way ensuring additional displacements or proper metal forming of the sleeve internal surface.

All the aforementioned types of clamping jaws have been analysed.

The presented jaws comprise all types used in practice as well as several newly proposed. Some possibilities of their modifications are shown as well. The clamped element was the rope T1X7 – a very difficult one to be dealt with in such joints. A parametric model was produced allowing for introduction of the rope wire diameter with the corresponding external diameter. Table 1 lists exemplary geometrical parameters of the rope. Both the internal and external diameters are automatically chosen basing on the condition that the required tensile strength should be equal to the tensile strength of the considered rope.

Table 1. Exemplary normalised diameters of the rope (r) and wire (w) [mm]

r	w	r	w
0.63	0.2	3.6	1.2
0.7	0.22	4.0	1.3
0.8	0.26	4.5	1.5
0.9	0.3	5.0	1.6
1.0	0.33	5.5	1.8
1.1	0.36	6.3	2.0
1.2	0.4	7.0	2.2
1.4	0.45	8.0	2.6
1.6	0.52	9.0	3.0
1.8	0.6	10.0	3.2
2.0	0.65	12.0	4.0
2.2	0.7	15.0	4.7
2.5	0.8	18.0	6.0
2.8	0.9		
3.2	1.0		

Each of the presented jaws has at least two parting planes (Fig. 9a) that are, at the same time, two axes of symmetry. Basing on the symmetry of the system, one can take into consideration only 1/4 of the clamped joint model (Fig. 9b). To arrive at the results for the whole joint – those obtained for one quarter were mapped with respect to the corresponding axes. That allowed for shortening of the calculation time by 83% and reduction of the resulting file size by 68%.

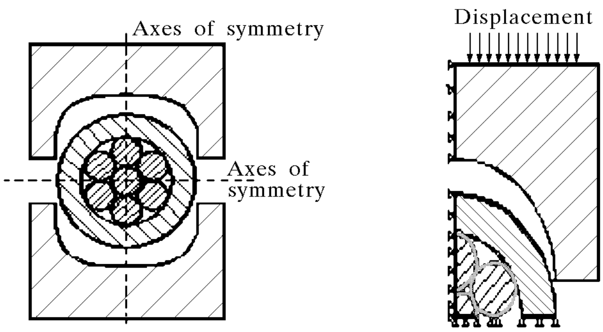

Fig. 9. (a) Symmetry axes of the model; (b) symmetry introduced into the model and boundary conditions

In the first part of calculations (analysis of clamping) the jaw comes closer to the element to be clamped at a very low speed, i.e. the process can be considered as a quasi-static one. In practice, the jaws are pressed against each other until they come into contact. In the presented scheme, this stage of the process is denoted as "translation". At this stage, the initial circular shape of the clamping sleeve changes into the shape determined by the clamping jaws. The boundary conditions, based on the assumption of symmetry with respect to the axes x and y are marked as well. The next stage of the process consists in unloading the joint through taking the jaws away down to their initial position. The process is performed according to the unloading curve and requires a high number of unloading steps. After completing the unloading process, some stresses still remain in the material. They are known in the literature as the residual stresses. These stresses, as it has been many times proved by the author basing on his investigation results, determine the joint carrying capacity. The carrying capacity means here the maximum force acting upon the joint that does not cause the rope or cable to slip out of the clamping sleeve. Magnitudes and distributions of residual stresses, a part from offering the possibility of monitoring the deformation process, provide also very important information about the process efficiency. Figures 10a,b show exemplary octagonal and dodecagonal jaws. The jaw is twisted about rope wires to achieve the most suitable jaw-sleeve-rope configuration that ensures larger magnitudes of residual stresses after unloading. The effect is most profitable in the case of the dodecagonal-twisted jaw.

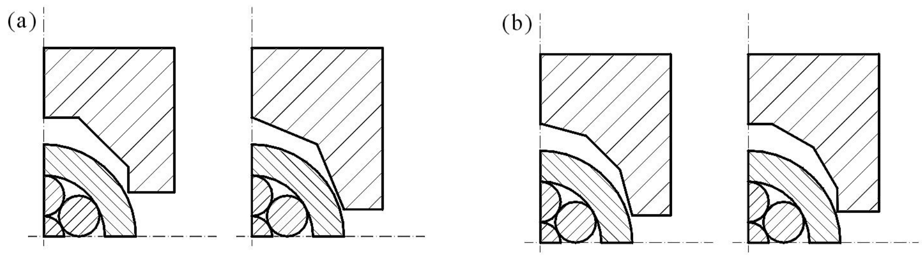

Fig. 10. (a) Octagonal jaw; (b) octagonal-twisted jaw

Some simulation results of the processes of clamping and unloading for a circular jaw within the residual stress range are shown in Fig. 11 and Fig. 12. During the clamping process, the material effort of the clamping sleeve reaches the magnitude of 300 MPa, while within the sleeve-rope contact zone it attains 500 MPa. The residual stresses remain after unloading due to different deformability of the joint elements and different material parameters.

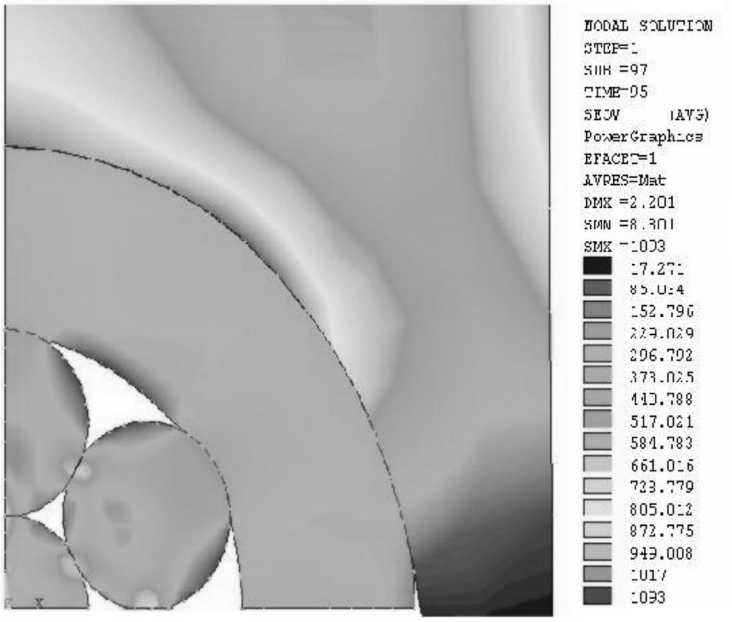

Fig. 11. Residual stresses – the process of clamping

Fig. 12. Residual stresses – the process of unloading

The magnitudes of residual stresses within the contact zone take values within the range from 150 to 250 MPa.

In view of the carrying capacity of the joint, distributions of stresses and deformations over the rope-sleeve contact zone play the most important role. To carry out the analysis within this area, mesh nodes were suitably selected. Results are presented in the form of circle diagrams. Figure 13 presents nodal displacements in the courses of clamping and unloading a dodecagonal jaw. The lateral planes of jaws together with their parting planes are clearly visible.

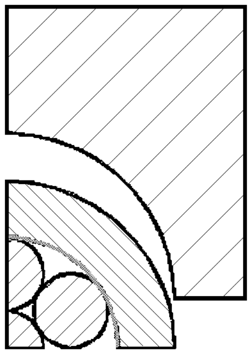

Fig. 13. Nodal displacements in the rope-sleeve contact zone during clamping (black) and unloading (grey)

The clamping efficiency of joints clamped by octagonal and dodecagonal jaws was compared in terms of the reduced residual stress (unloading) that determines the joint carrying capacity (see "- - -" lines in Fig. 14). The efficiency was determined by the area below the diagram or the mean value of the reduced residual stress. For the dodecagonal joint, the mean value was 157 MPa, while in the case of elliptic one – 57 MPa, therefore the difference between stress magnitudes reached 100 MPa. The dodecagonal jaw allowed for increasing magnitudes of the residual stresses within the contact zone almost three times.

Then, a comparison between the dodecagonal jaw twisted by 12.5 degrees about the axis and the elliptic jaw was made. Figure 16 presents a complete survey of the efficiency of the analysed jaws. The efficiency of joint forming means here the magnitude of reduced residual stress. From this figure, it can be clearly seen that higher values appeare for dodecagonal-twisted, elliptic and circular joints. It is obvious that most uniform stress distributions can be observed in axi-symmetrical joints. Due to technological aspects of the clamping process, hexagonal joints are employed most commonly. The efficiency is comparable with that revealed by octagonal joints.

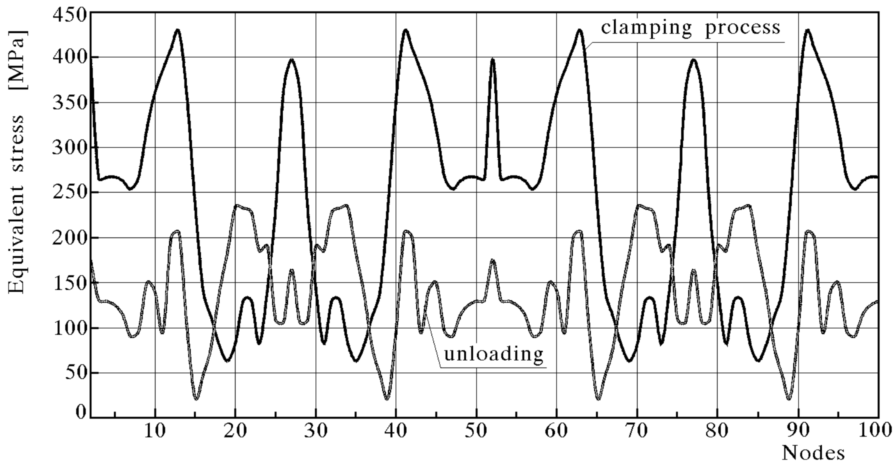

Fig. 14. Reduced residual stress in the dodecagonal clamped joint

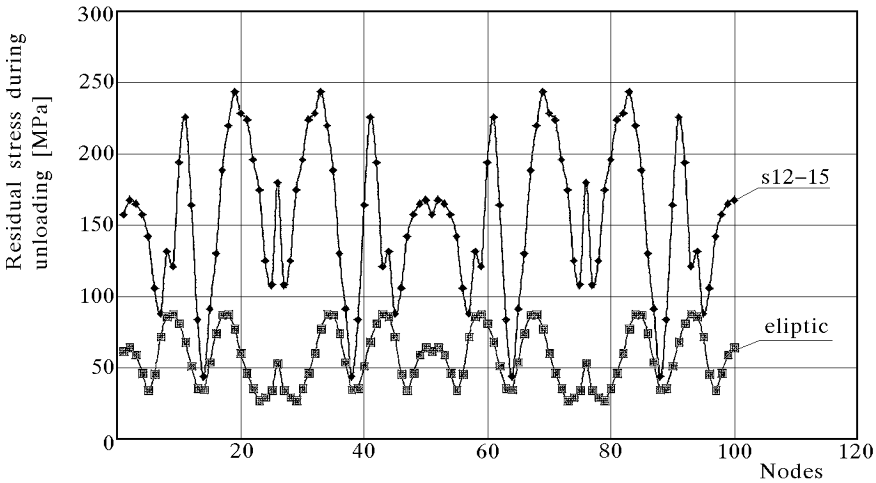

Fig. 15. Reduced residual stress in the dodecagonal and elliptic clamped joint during unloading

The obtained results have been experimentally verified using the diffraction-based "sin2(gamma)" method for stress state measurements at chosen points of the joint. The diffraction instrument D-8 Advance made by Broker was used for measuring the stress tensor components within the contact zone. For example, the radial stress component of 228 MPa was measured for the axi-symmetrical joint, which agreed perfectly with the simulation results. This new magnetic-memory method, invented by prof. A. Dubov, was veri-

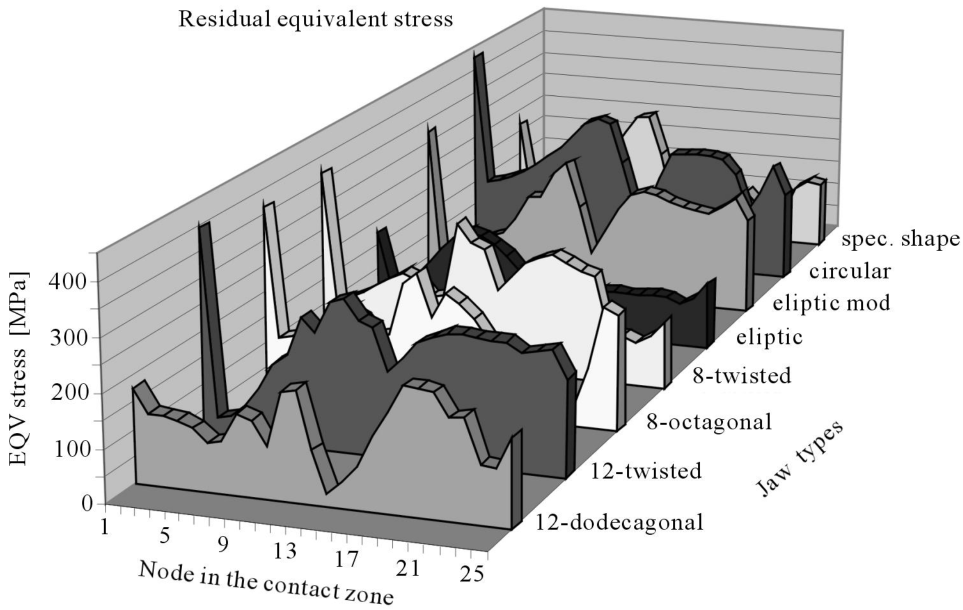

Fig. 16. Comparison of the clamping efficiency in the considered jaws

fied as well. The main advantage of this method consists in the possibility of making measurements both during the clamping and unloading process. The method is based on the fact that the diffraction of magnetic field depends on the stress distribution in the sleeve. The resulting cross-sectional distributions of the magnetic field agreed with the stress distributions.

5. Conclusions

- The presented analysis allows for comparison of clamped joints made by making use of clamping jaws of different shapes.

- Most of the uniform reduced residual stress distribution (according to the Huber-Mises-Huncky hypothesis) is achieved in the case of axi-symmetrical joints, the shape of which is closest to a dodecagon. In this respect, the octagonal jaw yields most disadvantageous results, which however can be improved by means of turning the jaw about the rope axis by 12.5 degrees.

- Higher stresses appear in the course of clamping – after release of the jaw the internal (residual) stresses take much lower values.
- The special-shape jaw brings about a relatively uniform stress distribution along the internal sleeve edge. The main advantage consists in the largest sleeve-rope contact zone when compared to other shapes of jaws. This influences strongly the maximum force carried by the joint. On the other hand, it reveals some disadvantages as well – very large deformation of the external surface and very complex shape difficult to follow in a manufacturing process.
- The proposed data base of material parameters allows for improving the accuracy of numerical calculations.
- The presented modelling methodology of clamped joints allows for new designs as well as for improving the existing ones.

References

1. Altenbach J., Buczkowski R., 1991, Inkrementelle Finite-Elemente Modellierung des 2D-Kontaktproblems, *Technische Mechanik*, **12**, 93-106
2. Auricchio F., 2001, Three-dimensional modeling of shape-memory materials, *J. Phys.*, **IV**, 11
3. Brinson L., 1993, One dimensional constitutive behavior of shape memory alloys, *J. Intel. Mater. Syst. Struct.*, **4**, 229-242
4. Buczkowski R., Kleiber M., 1992, Finite element analysis of elastic-plastic plane contact problem with nonlinear interface compliance, *Journal of Theoretical and Applied Mechanics*, **30**, 4
5. Bures R., Kohutek J., 2000, Intenetove Materialowe Data Bazy, *9th International Metallurgical Conference, METAL 2000*
6. Dobrzański L.A., 2001, *Zasady doboru materiałów inżynierskich z kartami charakterystyk*, Wyd. II, Wydawnictwo Politechniiki Śląskiej
7. Dorfmann A., Pabst O., Beh R., 1999, Combined numerical and experimental analysis of the mechanical and thermal stress distribution in rubber-aluminium roll, *The 8TH International Congress for Transport by Rope OITAF*, San Francisco
8. *Elektroenergetyczne linie napowietrzne*, Elbud Kraków 1980

9. HRYCAJ P., CESCOTTO S., OUDIN J., 1999, Elasto-plastic finite element analysis of unilateral contact with generalized Columb friction, *Engineering Computations*, **8**, 291-303

10. JUNG Y., PAPADOPOULOS P., RITCHIE R., 2002, Constitutive modelling and numerical simulation on multivariant phase transformation in superelastic alloys, *Int. J. Num. Meth. Engin.*

11. JURASZEK J., 1992, Zastępcza sztyność poprzeczna lin stalowych i przewodów aluminiowo-stalowych, *Zeszyty Naukowe Poliechniki Łódzkiej Filii w Bielsku-Białej*, **9**, 53-62

12. JURASZEK J., 1994, Analysis of the hexagonal clasp-joint – plastizitat, *GAMM*, **5.7**, p. 78 TU Braunschweig

13. JURASZEK J., 1995, Modeling of steel ropes and steel-aluminium wires with substitute crosswise stiffness, *International Congress on Industrial and Applied Mathematics ICIAM'95*, Hamburg

14. JURASZEK J., 1997, Elasto-plastic analysis of the wire, *GAMM*, **7**, *Computational Mechanics*, p. 48, TU Regensburg

15. JURASZEK J., 1999, Elasto-plastic analysis of the clasping process, *Gesellschaft für Angewandte Mathematik und Mechanik, GAMM'99*, Metz

16. JURASZEK J., 2000, Analysis of steel wire clamp by FEM, *XI International Wire Conference*

17. JURASZEK J., 2004, Method of analysis of wire clasp joint, *The International Journal of Transport and Logistics*, **6**

18. KLEIBER M., 1984, *Metoda elementów skończonych w nieliniowej mechanice kontinuum*, PWN, Warszawa

19. KLIBER J., 2000, Theoretical and technological aspects of rails rolling, *9th International Met. Conference Metal*, Ostrava

20. LANDRE J., PERTENCE A., CETLIN P.R., RODRIGUES J.M.C., MARTINS P.A.F., 2003, On the utilisation of ductile fracture criteria in cold forging, *Finite Elements in Analysis and Desing*, **39**, 3

21. MACDONALD B.J., HASHMI M.S.J., 2002, Shape desing sensitivity analysis and optimization of general plane arch structures, *Finite Element in Analysis and Desing*, **39**, 2, 137-1653

22. MALIGDA J., STANOVA E., DANCI M., 2000, Geometrical dresing of steel cable using optima strands of circular cross section, *Transactions of the Universites of Kosice*, **2**

23. MOLNAR V., 2004, Computer utilization for desing of the rope constructions and their strain modeling, *The International Journal of Transport and Logistics*, **6**

24. Provatidis C.G., 2003, Analysis of axisymmetric structures using Coon's interpolation, *Finite Element in Analysis and Desing*, **39**, 5/6, 535-558

25. Stanova E., Molnar V., 2003, The steel rope and the possibilities of its mathematical modeling, *Transactions of the Uniwersities of Kosice*, **3**

26. Tanaka K., Kobazashi S., Sato Z., 1986, Thermomechanics of transformation pseudoelasticity and shape memory effect In alloys, *Int. J. of Plasticity*, **2**, 59-72

Złącza zaciskowe – przegląd i analiza ich kształtów oraz stosowanych materiałów

Streszczenie

W pracy dokonano przeglądu stosowanych złącz zaciskowych. Złącza mają istotny wpływ na poziom bezpieczeństwa całej konstrukcji. Przeprowadzono analizę numeryczną oceniającą efektywność stosowanych kształtów połączeń zaciskanych. Zaprezentowano cyfrową bazę danych parametrów materiałowych stosowanych do budowy złącz zaciskanych.

Manuscript received March 29, 2005; accepted for print April 19, 2005