Parametric Studies of Total Load-Bearing Capacity of Steel Arch Supports

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The supports in roadways are dimensioned to the amount of the load applied during the roadway's life. Roadways are exposed to the effect of rock pressure associated with the roadway drivage and with subsequent operations that extract coal, which significantly affect the original stability of rock mass. This induced secondary stress leads to the disturbance of sedimentary rocks, which are mostly of slight and medium strength, and to the significant deformations in roadways. The gate-roads are mainly supported with yielding steel arch support (TH profiles). The load-bearing capacity of the steel arch supports is a key parameter in the design of roadways support. Determination of this parameter can be done using large testing frames in experimental laboratories. Another essentially cheaper way is to create a computer model which exhibits a good correlation with respect to the existing data from equivalent laboratory conditions. In this paper, we present the validated computer model of the steel arch supports through which the influences of important factors, namely different materials, number of the clamps in the yielding friction joints, and different values of tightening torque on the total load-bearing capacity, were determined. This parametrical study was created based on the practical requirements from industry, and the obtained results will be reflected in the design of new types of steel arch supports.

Keywords: *steel arch support, yielding, friction, bolted connection, clamp, joint, mining, FEM*

Introduction

The predominant amount of Europian coal deposits exploited underground are extracted by the longwall method with controlled caving. Experience shows that roadways, which ensure all transport and ventilation in coalfaces, restrict both output and safety as well as the economy in coal production (Becker, 1984). Roadways are exposed to the effect of rock pressure associated with the drivage of roadways and with subsequent operations that extract coal, which significantly affect the original stability of rock mass (Hood and Brown, 1999). This induced secondary stress leads to the disturbance of sedimentary rocks, which are mostly of slight and medium strength, and to the significant deformations in roadways. With the occurrence of very firm rock layers, the dynamic phenomena of rock pressure-rock bursts are induced, which again primarily affect roadways (Brauner, 1981). Therefore, the research of the most efficient methods for supporting and ensuring the roadways in coal mines presents a fundamental problem for mining as well as geomechanical engineers (Šňupárek and Konečný, 2010). From the geomechanical point of view, the shape and size of the underground workings are essential. The gateways are driven in the seam, often with some stripping in the floor or in the roof, and their full-size cross-section is 15–20 m^2 in average, with the mean advance of machine-driven openings about 8 to 10 m per day. The gate-roads are mainly supported with yielding steel arch support (TH profiles). For these roadways, it is necessary to design an optimal support system respecting the loads to which the roadway will be exposed during its life (Hoek and Brown, 2002).

The plan of monitoring in roadways and determination of stabilization measures are usually part of monitoring procedures in order to avoid exceeding critical values of loading. The supports in roadways are dimensioned to the amount of the load applied during the roadway's life. In the first period of drivage of a mine working, the minimum bearing capacity of the supports must correspond to the load of the loosened rock in its vicinity or, as the case may be, to a portion of this load. Moreover, the supports must comply with the yield function with respect to a certain coherence of the loosened rock (Brady and Brown, 2004). According to the arch theory, a natural arch is formed above the roadway, and along this natural arch, the rocks separate from the rock mass. The rocks inside the arch are disturbed, and, therefore, these rocks have to be supported with the supports in the roadway. The necessary spacing of arches of the conventional support can be determined on the basis of comparison of the calculated standard load with the load-bearing capacity of supporting (Jacobi, 1961).

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The total load-bearing capacity F_E of arch frames plays an important role in the design of steel arch supports. Under the laboratory conditions, this capacity F_E is defined as the scalar sum of the external forces actively produced by hydraulic cylinders No. 4-6 (red arrows in Figures 1 and 2). This value of capacity of the steel arch supports is affected not only by their structure and material but also by the method of load application (Brodny, 2010). It is necessary to obtain the values of the total load-bearing capacity for different constructions under the agreed scheme of loading corresponding to the real mining conditions. The total load-bearing capacity of arch frames in mining practice is currently being approximately assessed. The exact values can be verified in laboratories with large frames (in Europe, for instance, in DMT Essen or GIG Katowice).

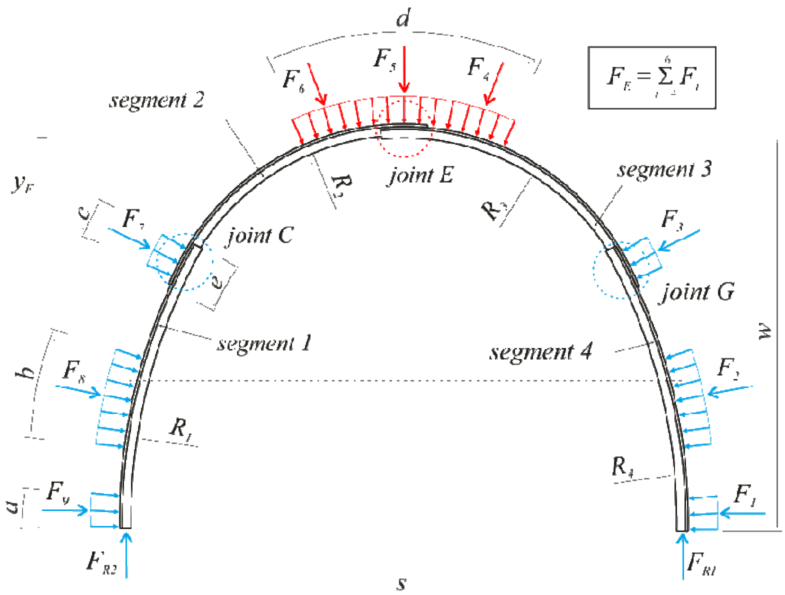

Fig. 1. Testing scheme, front view

The experimental research for verification of the computer modelling method was realized in the Laboratory of Mechanical Devices Testing GIG Katowice (Poland). The tests of the steel arch supports comply with the requests of the standard (Standard PN-G-15000-05, 1992). The external loading is excited by movable hydraulic force elements $F_4 – F_6$, see Figure 1. Other hydraulic force elements $F_1 – F_3$ and $F_7 – F_9$ are immobile, and they serve as supports. The subject of laboratory testing is the SP16 steel arch supports used in Ostrava Karvina mines with basic dimensions, width s = 5 920 mm and height w = 4 240 mm. This support frame consists of four segments (the TH29 profile) connected by the clamps realized by the bolted connections. The overlap length of segments is e = 500 mm. All geometrical properties are shown in Table 1. Testing of the steel arch supports was performed in the two following modes: as the rigid (welded) support - unyielding segments are fixed by welding of double segments - and as the yielding support with standard clamps - friction joints.

Table 1. Geometry of steel arch support

Parameter	[mm]	**Parameter**	[mm]
s	5 920	a	170
w	4 240	b	1 000
e	500	c	220
$R_1 = R_4$	5 950	d	3 000
$R_2 = R_3$	2 620		

Material and Methods

The history of computer modelling of steel arch mining supports, presented first in the crucial paper by authors Horyl and Šňupárek (Horyl and Šňupárek, 1992), began even before 1992. The calculations were performed using their own Finite element method-based software, and supports (segments) were modelled by a planar beam element. The joints between the segments were simplified – they were modelled without a yielding function. The results in that paper indicated that steel arch supports combined with rock-bolts are most resistant against the instantaneous dynamic loading. The computer models were further refined using a shell finite element. The bolted connections with the pre-loading effect were firstly included in this model of friction joints (Horyl et al., 1997). It caused intense numerical modelling of the support response on the rock bursts (Horyl and Šňupárek 2005). Later on, the bolting fixation impact on that response was modelled (Horyl, Šňupárek, 2007, 2009 and Horyl, Vicherek, 2007). On a global scale, these calculations were unique. Only later, computer models were consistently created by spatial finite element – solid type (Horyl et al., 2012, 2013, and 2014). The aim of the calculations was to determine how much energy of external load causes plastic deformation of the supports. Energy values, which have a damaging effect on the bolt body and cause loose stability of the whole support frame after that situation, were observed.

The methodology of Computer Modelling. On the basis of this long-term experience with modelling and analysis of main parts of the support, a complete spatial finite element (FE) model of SP16 steel arch support was designed. The problem was solved as a static structural analysis with neglecting of inertia effects. All parts of this support (segments, clamps) were created and assembled according to drawings without any shape simplification. The scheme of the FE model is depicted in Figure 2.

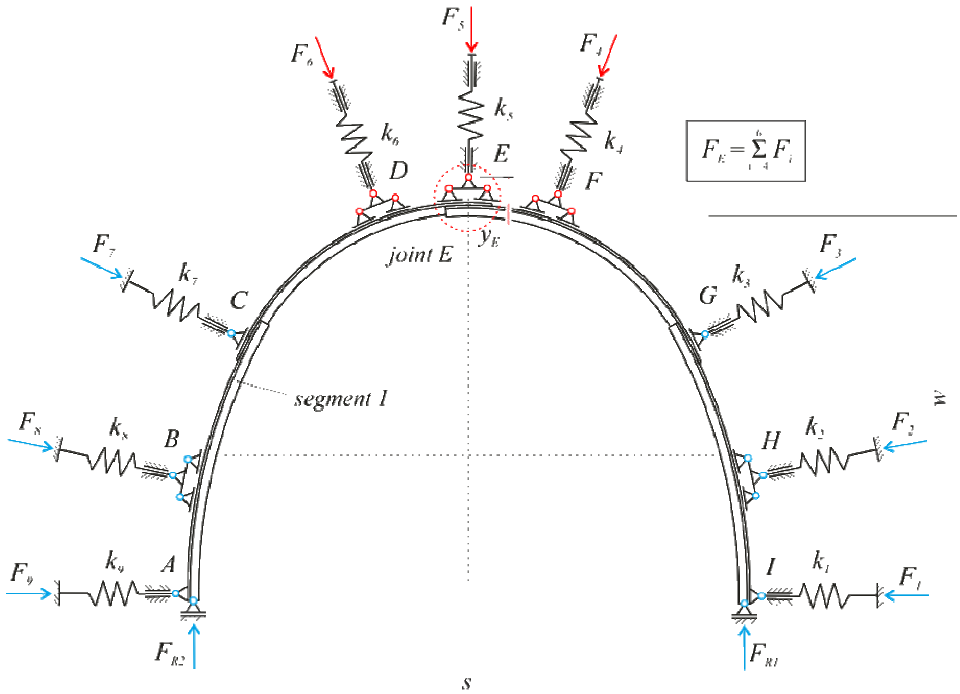

Fig. 2. Boundary condition of the FE model, front view

The boundary conditions correspond to those described above in the standard (Standard PN-G-15000-05, 1992). Hydraulic cylinders were replaced by spring elements with equivalent stiffness k_1 – k_9 = 9 kN/mm (without considering these flexible members, the values of vertical deformations y_E will be significantly distorted in comparison with the testing data). The supporting mechanism of the hydraulic cylinders pushing on the segments was realised by the multi-point constraints (MPC) elements connecting one layer of solid elements with a joint mechanism (detail in Figure 5). The bolted connections used for clamp preloading were modelled by a specific method. The bolt body represents two beam elements which are attached using the MPC elements to the upper and lower yokes, see Figure 5. The whole task of the total load-bearing capacity of the steel arch support containing 1.1 mil degrees of freedom (DOF) was solved using MSC MARC 2013 solver. The time for solving one task on the computer station with 16 central processing units (CPU) corresponded to 15 hours. The summary of used finite elements is shown in Table 2.

Table 2. Finite elements used for welded / yielding support model

Type of element	MARC description	Number of elements
Solid elements	Hex8 (SOLID7), Penta6 (SOLID136)	242,000 / 260,000
Spring elements	-	9 / 9
Bolt body d_b = 22.05 mm	Line2, (Beam98)	12 / 18
Multi-point constraints	RBE2	33 / 39

The FE models of both support types (welded and yielding) were compared with the experimental results from the tests (Horyl et al., 2016). The evaluated results show considerable correlation with the existing experimental testing data from laboratory, see Figure 3, 4 (Horyl et al., 2017). This validated FE model of the steel arch supports was used for the following parametric studies.

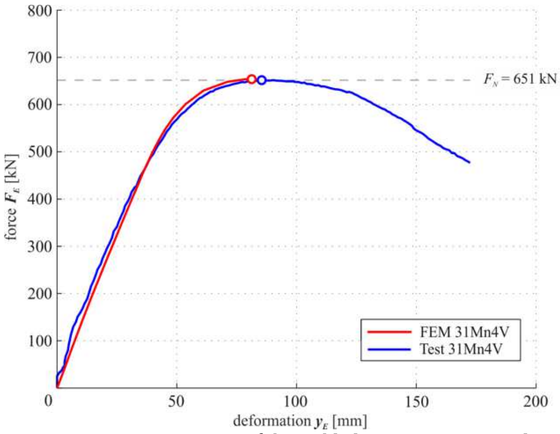

Fig. 3. Comparison of the welded support testing and FE simulation (Horyl et al., 2017)

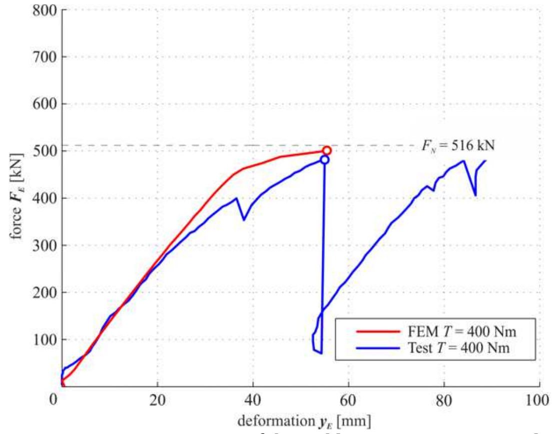

Fig. 4. Comparison of the yielding support testing and FE simulation, tightening torque T = 400 Nm (Horyl et al., 2017)

Material Variations (welded support). The scheme of the welded support was used for investigation of the material variations, i.e. three common steel types for segments (Table 3) – because in this scheme the friction between segments does not affect the total load-bearing capacity in this test. The way of welding of the unyielding joint E (see Figure 2) and discretization of the FE model is described in Figure 5. The supporting mechanism E represents the pressure plates of hydraulic segment E, which carries a part of external loading on the arch support.

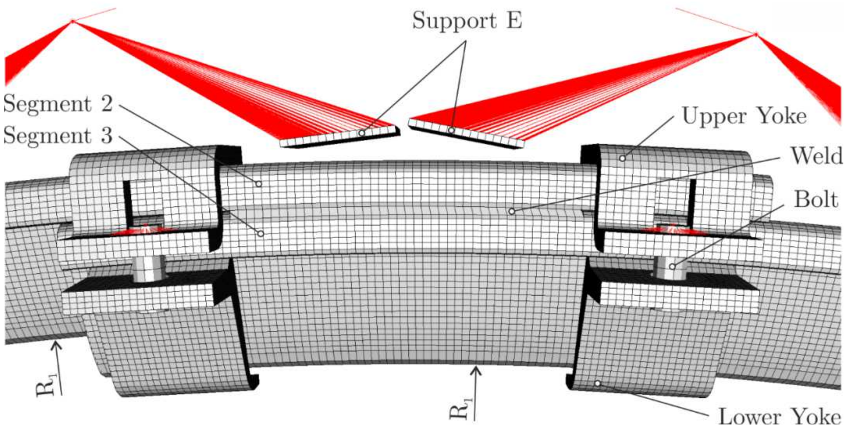

Fig. 5. FE model of welded support – detail of the joint E

The material properties of all FE model parts are listed in Table 3. Young's modulus of elasticity E, yielding stress σ_y, ultimate stress σ_u, and elongation A were determined from the manufacturer data sheets (Steel Qualities, 2015). For describing the plasticity effects, the bilinear material model with isotropic hardening was used.

Table 3. Material properties of structure parts

Structure part	**Material properties**			
	Young's Modulus of Elasticity E [MPa]	Yielding Stress σ_y [MPa]	Ultimate Stress σ_u [MPa]	Elongation A [%]
Steel support 31Mn4U	200 000	350	520	18
Steel support 31Mn4V		520	650	19
Steel support H500M		480	650	18
Weld 31Mn4U		245	364	18
Weld 31Mn4V		364	455	19
Weld H500M		336	455	18
Upper / lower yoke (S295)		295	470	20
High strength screw M24 (class 8.8)		640	800	12
Stiffness of hydraulic cylinders		$k_1 - k_9 = 9$ [kN/mm]		

The total load-bearing capacity F_E is determined at the end of the simulation due to excessive displacement. This excessive displacement is caused by a small increase in loading forces. The calculation did not converge at this time, producing extremely large deflection in the form of the rigid body motion. The relationships between the load-bearing capacity F_E and vertical deformation y_E for different steel types (31Mn4U/V and H500M) used for the welded support are shown in Figure 6 and Table 4.

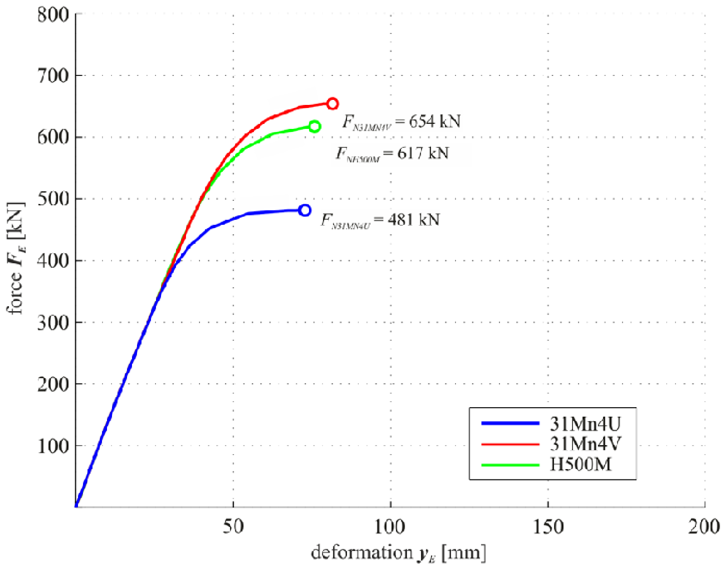

Fig. 6. Relationship between the total load-bearing capacity F_E [kN] and vertical deflection y_E [mm] for different steel types used for welded support

Table 4. Total load-bearing capacity of the welded supports

Steel type used for the welded support	Maximal deflection y_E [mm]	Total load-bearing capacity F_E [kN]
31Mn4U	73	481
H500M	76	617
31Mn4V	82	654

Variations of Friction (yielding support). The total load-bearing capacity of the friction joints (maximal value of normal forces being capable of bearing the connection without a slip of the segments) plays an important role in the static design of the steel arch supports (Hoek and Brown, 2002). Construction of the friction joint with respect to the strength of its different parts and the tightening torque applied to the bolted connection represent meaningful technical aspects regarding the function of the yielding supports. The constructions of the yielding joints have to meet two requirements. The clamping force has to be strong enough to provide a safe total load-bearing capacity of the steel arch support but not too strong to eliminate the yielding effect (Brodny, 2014). While the current design of the friction joints is unified, there is no general consensus regarding the values of the applied tightening torque T on the bolted connections with two or three clamps per friction joint.

The 31Mn4V standard steel type was chosen as the preferred material. The support frame consists of four segments connected by friction joints. The Coulomb friction was prescribed for the friction between parts in the model. The coefficients of friction were taken from (Horyl et al., 2014). The coefficients of friction used for all structure parts are presented in Table 5. The computer modelling was focused on the comparison of supports with two or three clamps per joint and different values of the tightening torque applied to the bolted connection *T* = 300-450 Nm used in practice (Maršálek and Horyl, 2016). However, especially the higher values of the tightening torque cause the creation of plastic hinges in parts of the connection and the very segments.

Tab. 5. Coefficient of friction and preloading of the bolted connection

Structure part	Coefficient of friction f [-]	**Tightening torque** T [Nm]	Axial force in the bolt body F_0 [kN]
Bolt thread	0.13	300	63.3
Under nut	0.17	350	73.9
Between segments/yokes	0.27	400	84.4
		450	95.0

Three clamps per connection (yielding support). The yielding joint was realised by a uniform distribution of three clamps per connection, as is shown in Figure 7.

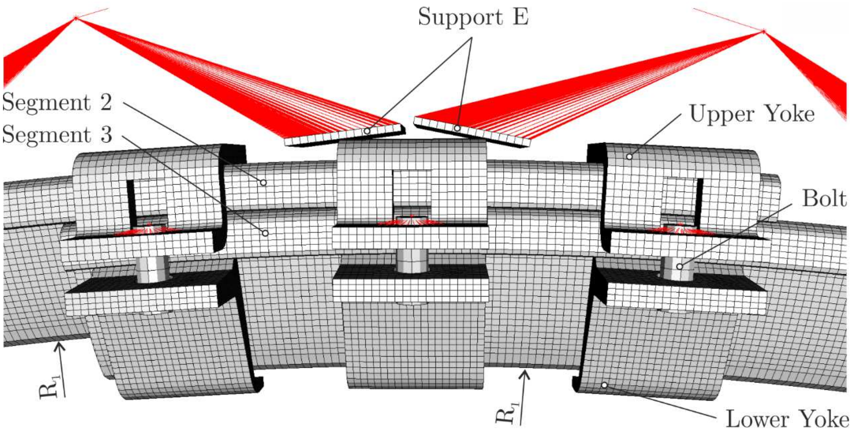

Fig. 7. FE model of yielding support with three clamps per connection – detail of friction joint E

The results of computer simulations show the lowest total load-bearing capacity F_E = 408 kN for the tightening torque T = 300 Nm and highest total load-bearing capacity F_E = 552 kN for the tightening torque of T = 450 Nm, see Figure 8 and Table 6. These values cause a significant uncontrolled slip of the upper friction joints E and the end of the calculation.

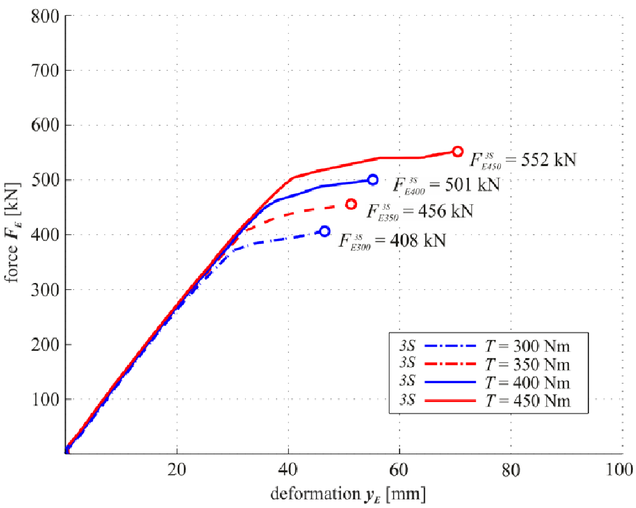

Fig. 8. Relationship between total load-bearing capacity F_E [kN] and vertical deformation y_E [mm] for different torque T at the yielding support with three clamps per connection obtained by the FE model

Table 6. Total load-bearing capacity of the yielding support with three clamps per connection obtained by the FE model

Tightening torque	Deflection at the first slip y_1 [mm]	Total load-bearing capacity F_E [kN]
T = 300 Nm	47	408
T = 350 Nm	52	456
T = 400 Nm	56	501
T = 450 Nm	71	552

The field of equivalent stress (von Misses hypothesis) in the most important part of the structure is depicted in Figure 9. It is the ultimate condition identified for minimum tightening torque T = 300 Nm. As is apparent from Figure 9, in the location of the contact of two different radii of the segments significant increase of plastic hinges are formed.

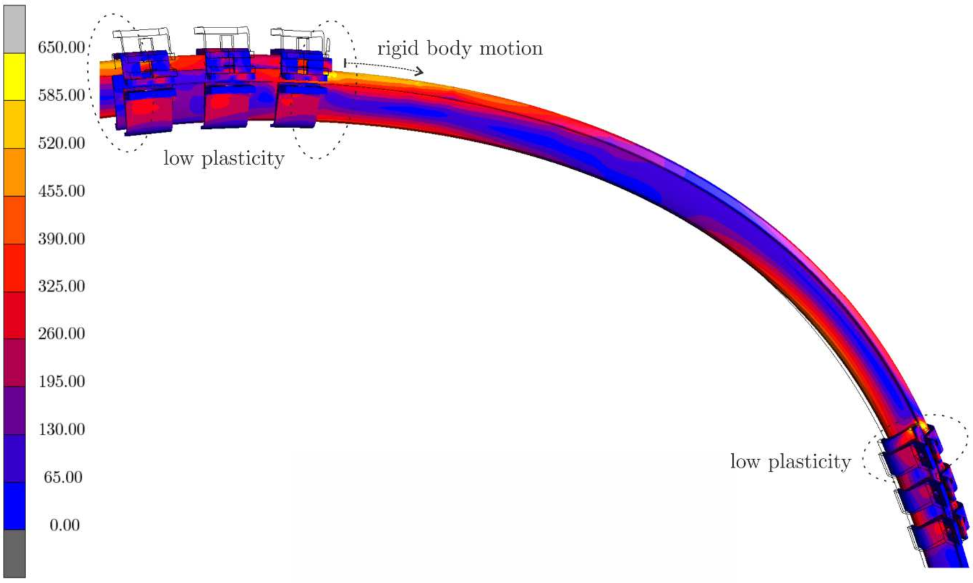

Fig. 9. Field of equivalent stress σ [MPa] – von Mises – in the yielding support with 3 clamps per connection, tightening torque T = 300 Nm, state before the rigid body motion (load F_E = 408 kN)

Two clamps per connection (yielding support). This modification of the yielding joint is performed by removing the middle clamp in each joint (Figure 10).

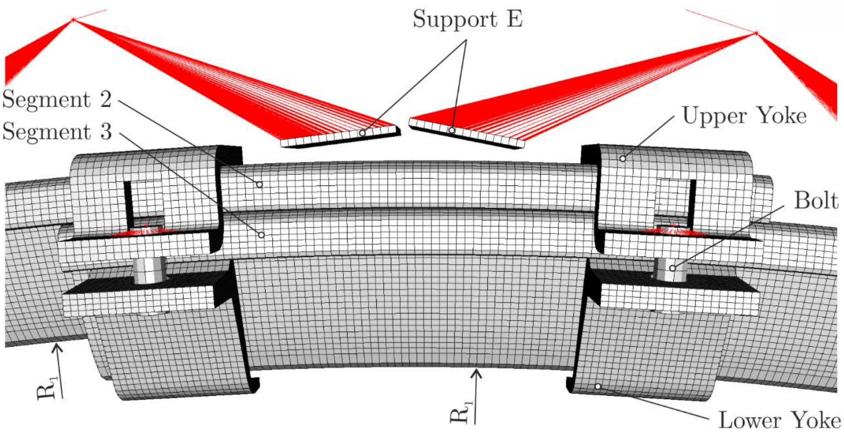

Fig. 10. FE model of the yielding support with two clamps per connection - detail of friction joint E

The results of computer simulations show the lowest total load-bearing capacity F_E = 268 kN for tightening torque T = 300 Nm and the highest total load-bearing capacity F_E = 399 kN for tightening torque T = 450 Nm, see Figure 11 and Table 7.

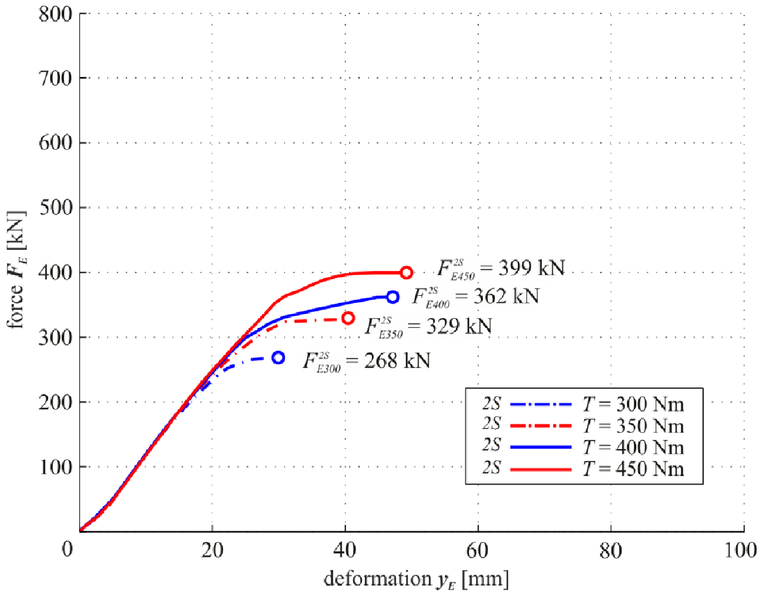

Fig. 11. Relationship between total load-bearing capacity F_E [kN] and vertical deflection y_E [mm] for different torque of bolts at the yielding support with two clamps per connection obtained by the FE model

Table 7. Load-bearing capacity of the yielding support with two clamps per connection obtained by the FE model

Tightening torque	Deformation at the first slip y_1 [mm]	Total load-bearing capacity F_E [kN]
T = 300 Nm	30	268
T = 350 Nm	40	329
T = 400 Nm	47	362
T = 450 Nm	49	399

Figure 12 presents the field of equivalent stress (von Misses hypothesis) for maximum tightening torque T = 450 Nm in the last state before the uncontrolled slip. It is apparent that each clamp transfers a higher load, but the value of the load-bearing capacity is similar to the yielding joint realized by tree clamps tightened by torque T = 300 Nm.

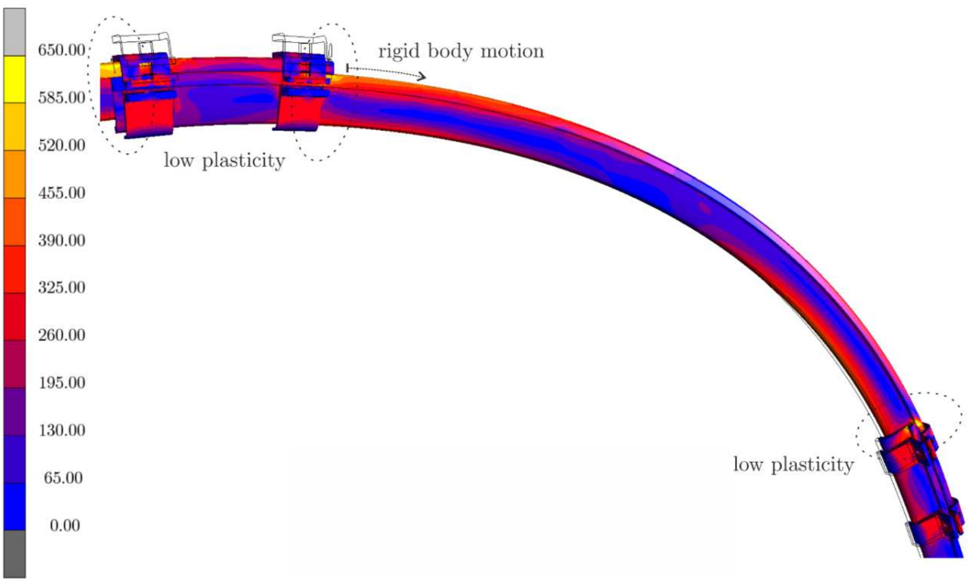

Fig. 12. Field of equivalent stress σ [MPa] – von Mises – in yielding support with two clamps per connection, tightening torque T = 450 Nm, state before the rigid body motion (load F_E = 399 kN)

Results

Material variations were performed on the model of the welded support. The total load-bearing capacity of the supports is more or less directly proportional to yielding stress values of used steel type (Figure 6). The comparison of the computer modelling results of the total load-bearing capacity of the yielding steel arch supports is described in Figure 13.

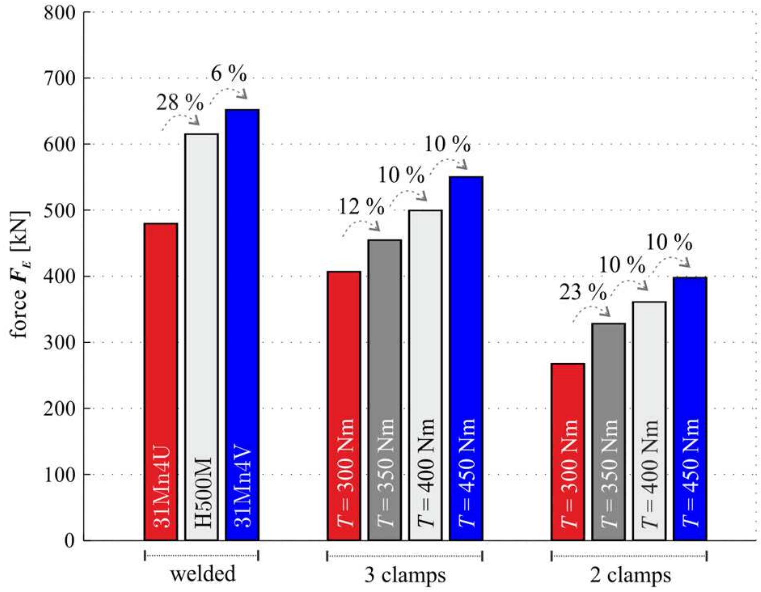

Fig. 13. Comparison of the total load-bearing capacity of the steel arch supports

The effects of the friction joints on the total load-bearing capacity of the yielding steel arch supports were investigated on different types of connections (two or three clamps per friction joint) and different values of the tightening torque on the bolted connection. Using three clamps per connection brings approx. 40 % increase in the value of the total load-bearing capacity of the support in comparison with two clamps. Increase in the tightening torque applied on the bolted connection in the range of 300-450 Nm brings 35-40 % increase in the value of the total load-bearing capacity of the yielding support (with steps approx. 10-12 % per tightening torque T = 50 Nm). The load-bearing capacity of the yielding support with two clamps tightened by maximum torque T = 450 Nm is almost the same as the total load-bearing capacity of the support with three clamps tightened by minimal torque T = 300 Nm (Figure 8 and Figure 11). Increasing resistance against the slipping effect in frictional connections due to a number of clamps and due to torque of bolts also causes the higher total load-bearing capacity of the whole steel arch.

Discussion

The total load-bearing capacity of steel arch support presents an important parameter for support design. This value is affected not only by their construction and material but also by the scheme of load application. In some cases (point loads, high lateral loading) even yielding arch support behaves like rigid welded construction. In our paper, we deal with the scheme of loading with major vertical weight corresponding with loading in the experimental laboratory (Figure 1). A serious problem of computer modelling of yielding arch supports consists in the course of deformation in yielding joints. The slips occur in jumps, and after every slip, the geometry of the whole arch is changed. Moreover, the jumps causing successive slips are caused by the slow velocity of the displacement of the hydraulic cylinders and by the non-linear behaviour of the frictional forces between the contact pairs. The coefficient of friction is dependent not only on the degree of corrosion between the arches but also on their relative velocities. For a detailed description of this behaviour, it would be necessary to consider the inertia of the system and to solve the task as a dynamic with a nonlinear description of the friction effect.

However, by the study of data from laboratory tests of yielding arches, we found that the load-bearing capacity at the first slip in yielding joint represents with sufficient accuracy the total load-bearing capacity of steel arch support (Horyl et al., 2017) (Figure 4). To determine the total load-bearing capacity, the presented static model described in this work is sufficiently accurate and can be used to predict laboratory tests.

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