DE GRUYTER
OPEN

Arch. Min. Sci., Vol. 59 (2014), No 3, p. 781–792

Electronic version (in color) of this paper is available: http://mining.archives.pl

DOI 10.2478/amsc-2014-0054

PETR HORYL*, RICHARD ŠŇUPÁREK**, PAVEL MARŠÁLEK*

# BEHAVIOUR OF FRICTIONAL JOINTS IN STEEL ARCH YIELDING SUPPORTS

# ZACHOWANIE POŁĄCZEŃ CIERNYCH W PODATNYCH ŁUKOWYCH OBUDOWACH STALOWYCH

The loading capacity and ability of steel arch supports to accept deformations from the surrounding rock mass is influenced significantly by the function of the connections and in particular, the tightening of the bolts. This contribution deals with computer modelling of the yielding bolt connections for different torques to determine the load-bearing capacity of the connections. Another parameter that affects the loading capacity significantly is the value of the friction coefficient of the contacts between the elements of the joints. The authors investigated both the behaviour and conditions of the individual parts for three values of tightening moment and the relation between the value of screw tightening and load-bearing capacity of the connections for different friction coefficients. ANSYS software and the finite element method were used for the computer modelling. The solution is nonlinear because of the bi-linear material properties of steel and the large deformations. The geometry of the computer model was created from designs of all four parts of the structure. The calculation also defines the weakest part of the joint's structure based on stress analysis. The load was divided into two loading steps: the pre-tensioning of connecting bolts and the deformation loading corresponding to 50-mm slip of one support. The full Newton-Raphson method was chosen for the solution. The calculations were carried out on a computer at the Supercomputing Centre VSB-Technical University of Ostrava.

**Keywords:** steel arch yielding support, frictional joints, bolt connection, slip support, fem

Nośność stalowych podpór łukowych i ich zdolność do przenoszenia odkształceń spowodowanych przez sąsiadujące warstwy skalne w dużej mierze uwarunkowana jest przez działanie połączeń, w szczególności przez siłę dokręcenia śrub. Praca niniejsza zajmuje się modelowaniem komputerowym podatnych połączeń śrubowych dla różnych momentów skręcających w celu określenia wielkości obciążeń przenoszonych przez połączenia. Innym parametrem w znacznym stopniu warunkującym nośność jest wartość współczynnika tarcia na połączeniach pomiędzy komponentami złączy. Autorzy zbadali zachowanie i warunki pracy poszczególnych elementów dla trzech wartości momentu dokręcającego, a także zbadali związek pomiędzy stopniem dokręcenia śruby a nośnością całego połączenia dla różnych wartości współczynnika tarcia. W modelowaniu komputerowym wykorzystano oprogramowanie ANSYS oraz metodę elementów skończonych. Rozwiązanie problemu jest nieliniowe ze względu na bi-liniowe

---

* VSB-TECHNICAL UNIVERSITY OF OSTRAVA, DEPARTMENT OF MECHANICS, 17. LISTOPADU 15, 70833 OSTRAVA, CZECH REPUBLIC, CENTRE OF EXCELLENCE IT4INNOVATIONS
** INSTITUTE OF GEONICS ASCR, STUDENTSKÁ 1768, 70800 OSTRAVA, CZECH REPUBLIC

właściwości materiałowe stali i z uwagi na wielkość odkształceń. Geometrię modelu komputerowego stworzono na podstawie projektów wszystkich czterech elementów konstrukcji. Obliczenia pozwalają także na zidentyfikowanie najsłabszego elementu w połączeniu w oparciu o analizę wytrzymałościową. Obciążenie przykładane podzielono na dwa etapy: wstępne naprężenie śrub i obciążenie odkształcające odpowiadające 50-mm przesunięciu jednej z podpór. W rozwiązaniu wykorzystano pełną metodę Newtona-Raphsona. Obliczenia przeprowadzono na komputerze w centrum obliczeniowym Supercomputing Centre na Uniwersytecie Technicznym w Ostravie.

**Słowa kluczowe:** podatna łukowa obudowa stalowa, połączenia cierne, połączenia śrubowe, przesunięcie podpory, metoda elementów skończonych FEM

## 1. Introduction

Steel arch yielding supports consisting of several segments joined by friction bolt connections are used widely in coal and ore mining. The construction of frictional joints from the viewpoint of the number and strength of different parts and the values of tightening of the screw bolts are important technological parameters for the optimal loading capacity of arch supports (Brodny, 2011).

The loading capacity of a friction connection (maximal value of normal forces capable of being withstood by the connection without slip of the segments) plays an important role in the dynamic and static design of arch supports (Stacey & Ortlepp, 2000). Constructions of yielding connections have to fulfil two requirements. The clamping force has to be sufficiently high to provide a safe load-bearing capacity of the arch but not so high as to eliminate yielding (Janas, 1990). The construction of the connection introduces meaningful technical aspects regarding the function of yielding supports (Fig. 1).

There is no consensus regarding the optimal values of frictional joints (the number of tightening bolts, loading capacity of frictional joint, tightening moment) (Podjadtke et al., 2009; Šňupárek & Konečný, 2010). Our knowledge of the behaviour of different types of frictional joints during loading can contribute to the optimal design of supports. In this paper, the constructions and operation of the yielding connections are discussed based on mathematic modelling (Horyl et al., 2013).

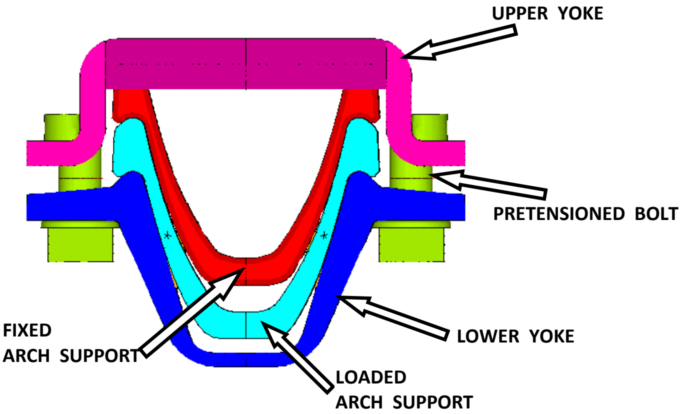

Fig. 1. Yielding connection, front view

## 2. Methodology

Computer modelling of the clamp connection was performed using the ANSYS finite element software (ANSYS Release 14.0, 2011). Large displacements and strains, nonlinear steel properties and many points of contact led to the solution of the task of finding a clamp static loading capacity as a complex nonlinear structural problem (Horyl & Šňupárek, 2012). Large displacements mean that the stiffness matrix of the entire structure depends on unknown deformation parameters. To model the nonlinear material behaviour, bi-linear material properties were used with three values: $E$, Young's modulus of elasticity; $\sigma_y$, yielding stress; and $E_T$, tangent modulus of plasticity. Our structure has three kinds of material, as shown in Table 1.

TABLE 1

Material property of steel parts

| **Structure Part** | **Material Properties** | | |
|---|---|---|---|
| | **Young's modulus of elasticity $E$ [MPa]** | **Yielding stress $\sigma_y$ [MPa]** | **Tangent modulus of plasticity $E_T$ [MPa]** |
| Steel support | 200,000 | 350 | 1,680 |
| Upper yoke and lower yoke | | 295 | 1,783 |
| High strength connecting screw | | 640 | 2,170 |

The geometry of the computer model was created from designs of all four parts of the structure. It was created in Workbench ANSYS 14.0. Because all boundary conditions were symmetrical, we created only half of the structure (Fig. 2). Discretisation was done with solid, contact and pre-tensioned bolt elements (Table 2).

TABLE 2

Finite elements used

| **Type of Elements** | **ANSYS Finite Elements** | **Number of Elements** |
|---|---|---|
| Solid elements | SOLID186, SOLID187 | 75,941 |
| Contact elements | CONTA174, Targe170 | 26,311 |
| Pre-tensioned bolts | PRETS179 | 3 |

The total number of structural elements was 75,941; there were 308,643 nodes and the middle size of the elements of the mesh was 6 mm with finer re-meshing in the contact areas. The number of equations was 920,035. The number of equations is the number of unknown deformation parameters of the system. The load was divided into two loading steps: the pretension of connecting bolts and the deformation loading corresponding to 50-mm slip of one support. The second support was fixed (see Fig. 3). The three torque values that were applied to the screws were: 350, 400 and 450 Nm. These values of torque correspond to the values of the preload forces: 100,966, 115,390 and 129,814 N. External torque values affect mainly the value of the loading capacity coefficient of friction in the contact pairs. This is why the calculations were performed with a coefficient of friction ranging from 0.12 to 0.32 in steps of 0.04. The full Newton-Raphson method was chosen for the solution.

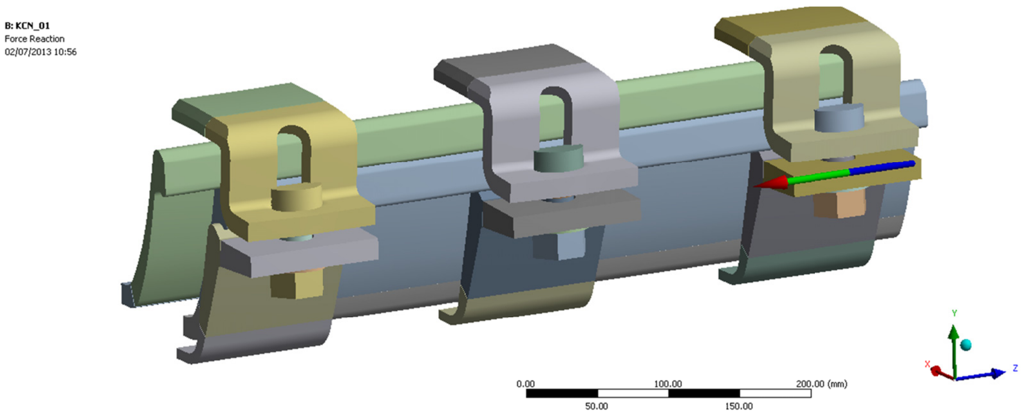

Fig. 2. Model of connection with three clamps

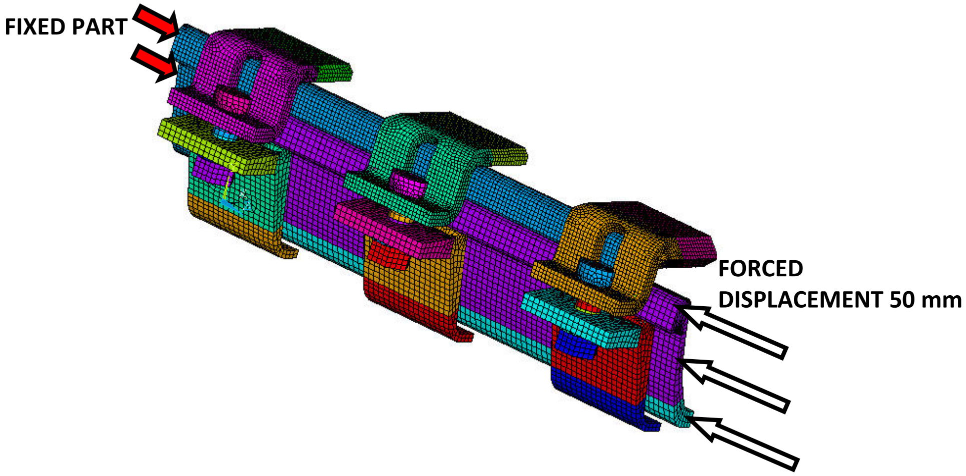

Fig. 3. Arrangement of model tasks

The calculations were carried out on a computer at the Supercomputing Centre VSB-Technical University of Ostrava; the number of cores used was nine and one calculation took 11-15 hours.

The models contain straight parts of support profile TH 29 with standard two or three clamp SD-type friction connections (width of yokes 100 mm, bolt M24) (Junker, 2009).

The quality of the mesh was checked by element metrics (see Figure 4). The element metrics option provides a composite quality metric that ranges between 0 and 1. This metric is based on the ratio of the volume to the edge length for a given element. A value of 1 indicates a perfect cube or square, whereas a value of 0 indicates that the element has a zero or negative volume. The average of the mesh metrics is 0.704, which means a good quality of mesh.

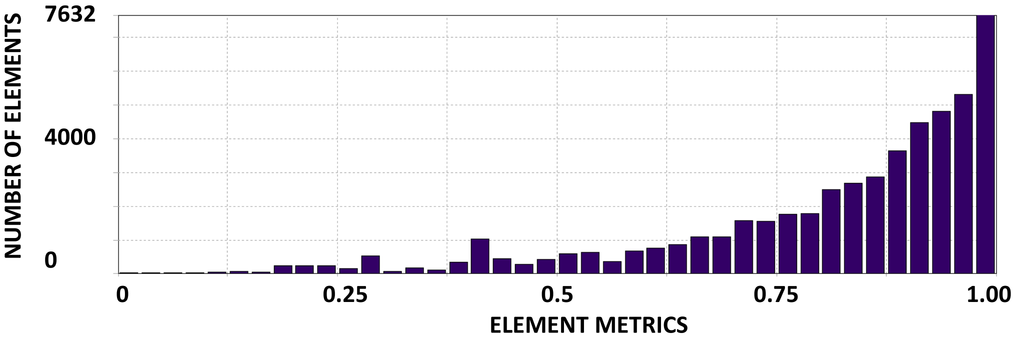

Fig. 4. Mesh quality of finite elements

The model performance contains two steps:

- stage one – implementation of bolt preload,
- stage two – implementation of forced displacement.

The trends of the nonlinear calculations are illustrated in the following figure. The convergence calculation, depending on the gradual loading, is displayed in Figure 5.

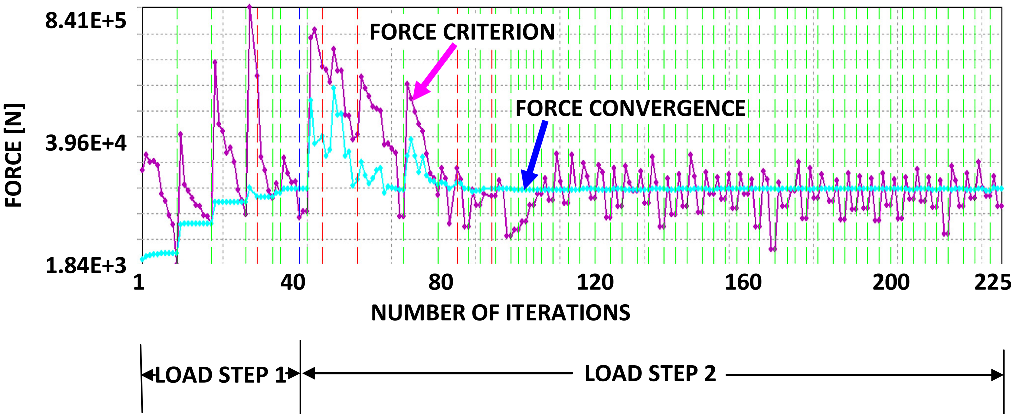

Fig. 5. Typical trend of force convergence

Convergence in each substep of the Newton-Raphson method is satisfied when, for all nodes of the model, the force convergence condition is fulfilled. Another criterion is the increment value of equivalent plastic deformation; the maximum could be less than 0.15. Load step one was calculated in the range of four to seven substeps, whereas the second load step was calculated in the range of 26 to 36 substeps. In each, the substeps had to be calculated with a few iterations to achieve convergence. The total number of iterations was around 230.

## 3. Results

### Stage one – implementation of bolt preload

In the first step, we investigate the strain and deformations after tightening the screw bolts. The deformed structure, after tightening the screws with torque of 450 Nm, is shown in Figure 6.

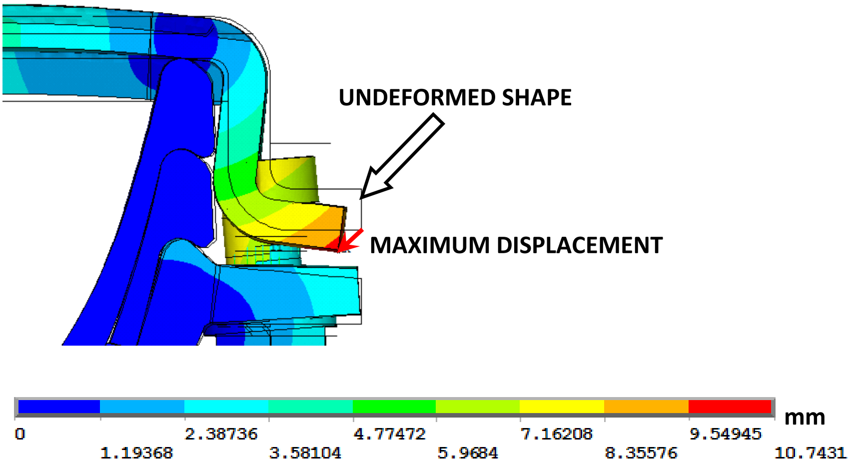

Fig. 6. Deformed structure; place of maximum deformation

The largest displacement was found at the end of the upper yoke and amounted to 10.7 mm. Although this value is significant, it does not affect the behaviour of the joint and it's yielding parameters. The results for the first preload step are presented in Table 3.

TABLE 3

Results from bolt preload

| **Description of the Variables** | | **Values** | | |
|---|---|---|---|---|
| Torque [Nm] | | 350 | 400 | 450 |
| Maximum displacement [mm] | | 8.1 | 9.2 | 10.7 |
| Support | $\sigma_e$ [MPa] | 409 | 414 | 402 |
| | $\varepsilon_{pl}$ [1] | 0.005 | 0.01 | 0.03 |
| Upper yoke | $\sigma_e$ [MPa] | 572 | 623 | 710 |
| | $\varepsilon_{pl}$ [1] | 0.16 | 0.183 | 0.24 |
| Lower yoke | $\sigma_e$ [MPa] | 326 | 344 | 363 |
| | $\varepsilon_{pl}$ [1] | 0.02 | 0.03 | 0.04 |
| Bolts | $\sigma_e$ [MPa] | 1064 | 1125 | 1254 |
| | $\varepsilon_{pl}$ [1] | 0.197 | 0.22 | 0.28 |

It should be noted that all parts of the joint in some areas exceeded the yield point during standard preloading, which means that, even after unloading, permanent deformation remains in the structure. As will be discussed below, usually, the deformation affects only a very small area, which should not influence the functionality of the connection. The locations of the small areas of yielding in the steel support are shown in Figure 7. Yielding in the upper yoke occurs in small areas in contact with the head bolt (Fig. 8). Although the value of equivalent plastic strain is high, only small plastic dimples arise in these areas. A few intensive areas of yielding occur also on the lower yoke. A high degree of yielding occurs on the bolt but it is only a small area that is in contact with the screw head (Fig. 9).

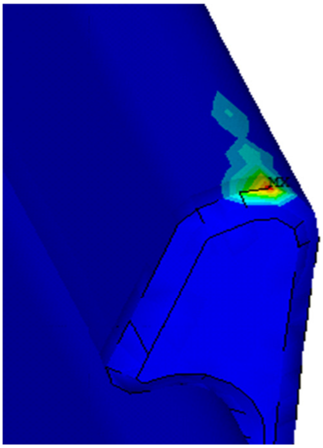

Fig. 7. Plastic areas on steel support, $\varepsilon_{pl} = 0.026$

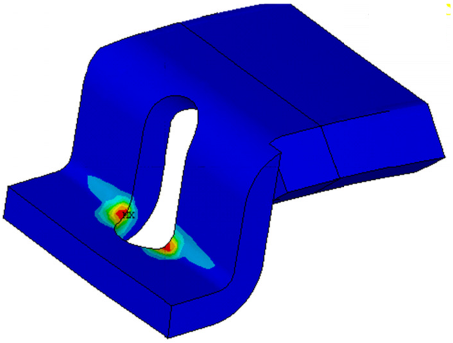

Fig. 8. Plastic areas on upper yoke, $\varepsilon_{pl} = 0.24$

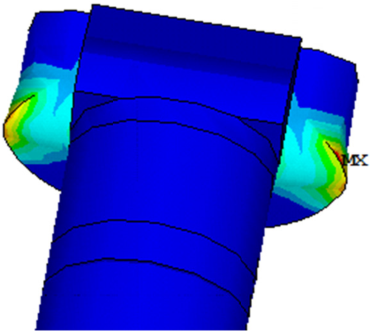

Fig. 9. Plastic areas on bolts, $\varepsilon_{pl} = 0.28$

## Stage two – implementation of forced displacement

Based on the described methodology, we created several models focused on the loading capacity (resistance) of the frictional joints:

- with different values of friction coefficient of segments in the range 0.12-0.32
- with different values of torque in the range 350-450 Nm
- using friction joints consisting of two or three yokes (Figs. 2, 10)
- with and without carrying projections (“noses” on upper and lower yoke for stable position of yokes at the ends of the segments)

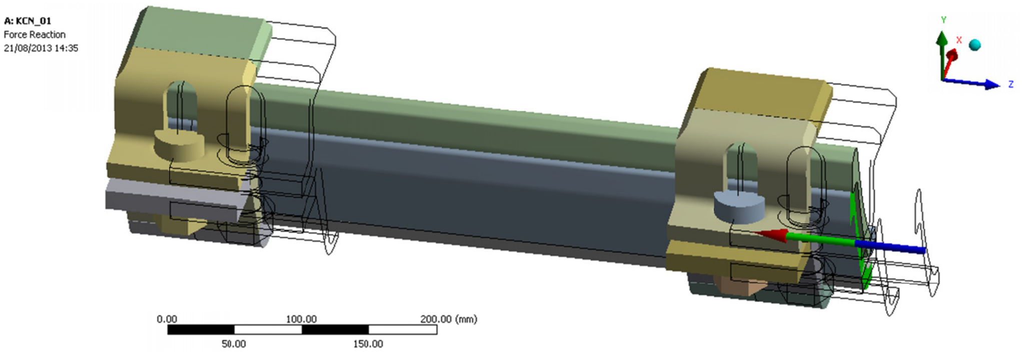

Fig. 10. Frictional joint with two clamps (Contours represent starting position before slip)

Loading capacity of a frictional joint means the value of the force at the slip of segments. The main results are shown in Figure 11.

It is obvious that the friction coefficient has decisive influence on the resistance of the frictional joint and that it can also eliminate enhanced torque of the bolts. Friction coefficient is connected with a corrosion of segments (Dorion & Lassonde, 2013) and generally, it increases

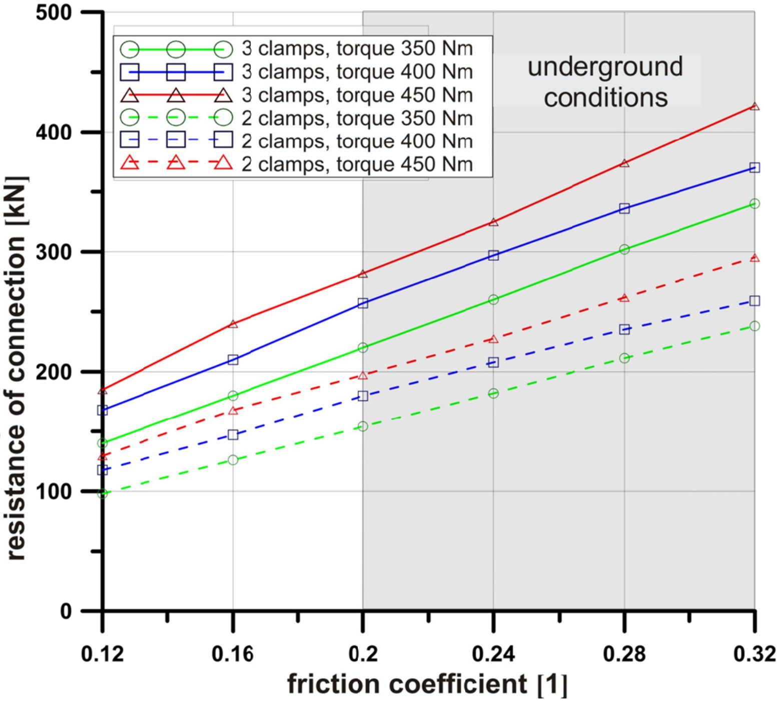

Fig. 11. Loading capacity of frictional joints

with the degree of corrosion. We can expect that the friction coefficient increases over time in underground conditions. Probably, a real value of the frictional coefficient of support segments in mines is 0.2, which corresponds to the results of laboratory tests (Brodny, 2012).

The loading capacity (resistance) of frictional joints in the range of the used torque moment presents a linear dependence on the torque moment of the bolts.

The results of the models with two and three clamps confirmed a theoretical presumption that the addition of the third clamp increases the resistance of the joint by 50%. Our numerical simulations show values of between 45.1% and 45.9% loading capacity of the joints under the researched values of torque moment of the bolts.

We also researched the influence of carrying projections (indents), which ensure the positions of the clamps at the ends of the segments. The comparison of the three clamp models (torque 400 Nm) with and without carrying projections is shown in Figure 12.

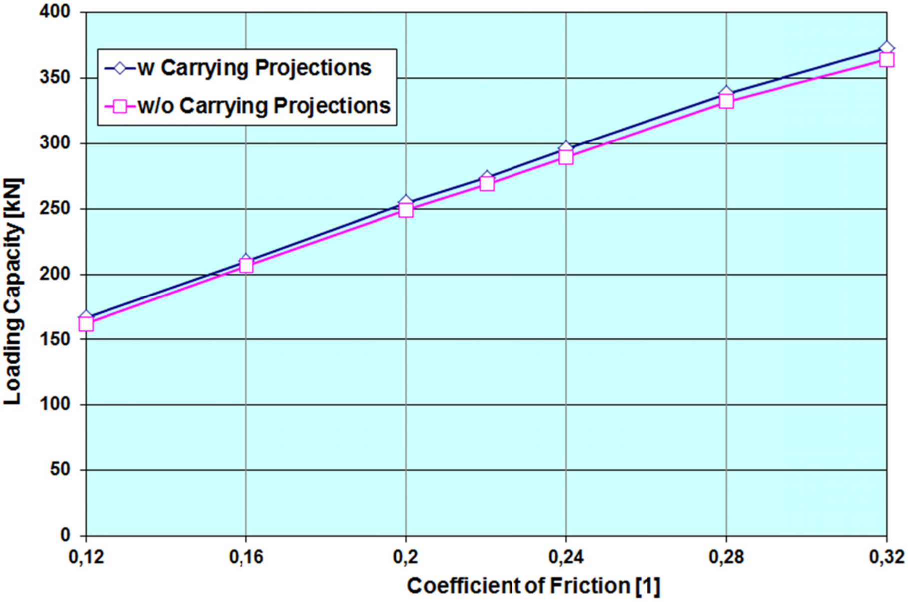

Fig. 12. Resistance of frictional joints with and without carrying projections

The resistance of the friction joints with indents rises by about 2% only, in range of the researched friction coefficients.

For the credibility of the models, it is important to observe values of the deformation energy of the structure and stabilisation energy was introduced into the models for better convergence of the contact elements. Generally, stabilisation energy would not exceed 1% of the deformation energy of the finite element. Figures 13 and 14 show that the maximum deformation energy is 2189 mJ, whereas the value of stabilisation energy reaches 0.45 mJ, which is only 0.02%.

Figure 13 demonstrates that in the researched straight joints, the decisive increase of deformation energy is connected with the tightening of the bolts (part 0 to 1 on the x-axis) and it changes hardly at all during the slip of the segments.

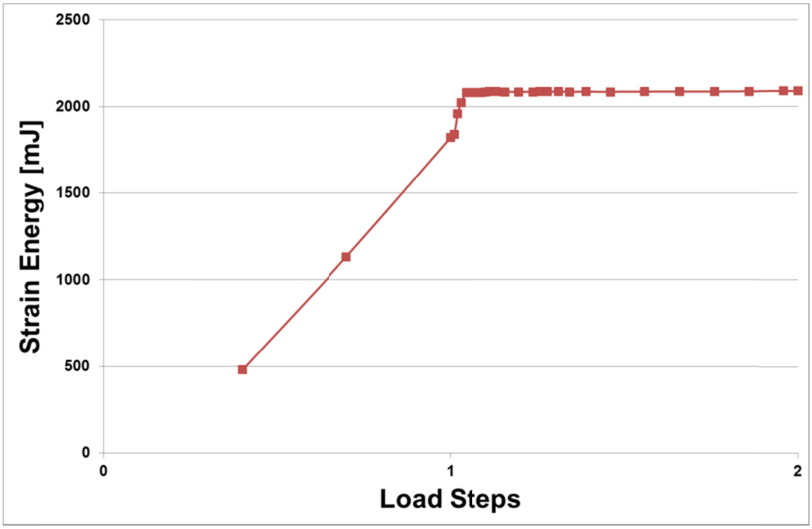

Fig. 13. Course of deformation energy

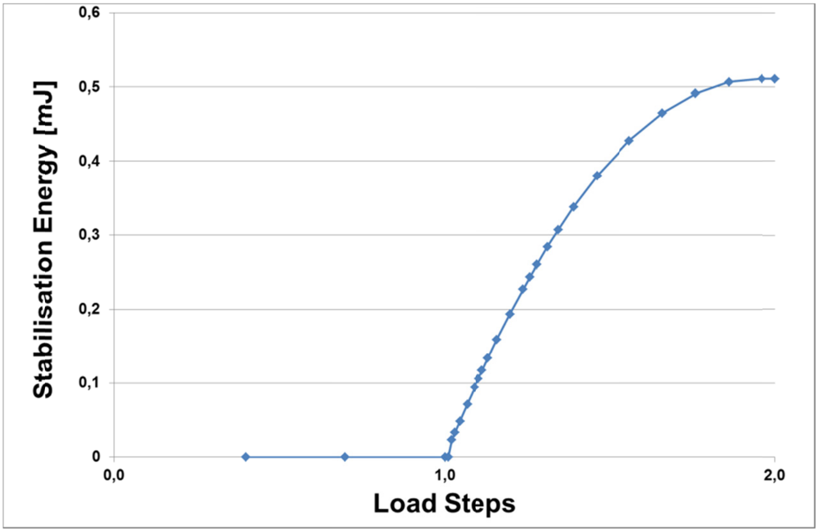

Fig. 14. Increase of stabilisation energy

# 5. Conclusions

The results of the models evidence that certain plasticised areas occur in the areas of contact for all joint elements, including the segments of support under standard tightening torque of 350–450 Nm. However, the yielding deformation affects only a very small area, which should not influence the functionality of the connection.

Expressive elastic deformation of the upper yoke comes during the tightening of the bolts. From this perspective, the upper yoke appears a little under-dimensioned.

The models confirm a linear dependence of friction joint resistance on the torque of the bolts in the researched range of torsional moments. The increase of friction joint resistance of 25-30 kN corresponds to the increase of the torque of bolts of 50 Nm.

The model results prove the expressive dependence of loading capacity of the connection on the friction coefficient of the steel segments. For instance, with the same value of tightening torque (400 Nm), it is possible to reach joint resistance of 370 kN with a friction coefficient of 0.32 but only 169 kN is achievable with a friction coefficient of 0.12. The friction coefficient at the connected segments is influenced mainly by corrosion of the surfaces of the segments.

The construction of a friction joint with three clamps, in comparison with that using two clamps, exhibits an increase of loading capacity of the joint by 45%.

The construction of a friction joint with indents, which ensure the positions of the clamps at the ends of segments, increases the resistance of the joint by only 2%.

We must point out that all models simulated friction connections of straight support segments. Models of friction joints that are more realistic with round segments will be the subject of the next stage of research.

## Acknowledgements

The paper has been undertaken in conjunction with the Institute of Clean Technologies for Mining and Utilisation of Raw Materials for Energy Use, Reg. No. CZ.1.05/2.1.00/03.0082, IT4 Innovations Centre of Excellence project, Reg. No. CZ.1.05/1.1.00/02.0070 supported by the Operational Programme "Research and Development for Innovations" funded by Structural Funds of the European Union and state budget of the Czech Republic and research project of the Ministry of Education, Youth and Sports of the Czech Republic No. MSM6198910027.

# References

ANSYS® Release 14.0, 2011. *ANSYS® Mechanical*, Help System, ANSYS, Inc.

Brodny J., 2011. *Tests of friction joints in mining yielding supports under dynamic loading*. Arch. Min. Sci., Vol. 56, No 3, p. 237-266.

Brodny J., 2012. *Analysis of operation of new construction of the frictional joint with the resistance wedge*. Arch. Min. Sci., Vol. 57, p. 209-227.

Dorion J.F., Lassonde H., 2013. *Corrosion considerations in the design and operation of rock support systems*. Proc. of the Seventh International Symposium on Ground Support in Mining and Underground Construction Perth, p. 227-233.

Horyl P., Šňupárek R., Hlaváčková M., 2013. *Loading capacity of yielding connections used in steel arch roadway supports*. Proc. of the Seventh International Symposium on Ground Support in Mining and Underground Construction Perth, p. 211-216.

Horyl P., Šňupárek R., 2012. *Reinforcing Measures of Steel Roadway Support in Rockburst Prone Areas*. Arch. Min. Sci., Vol. 57, No. 1, p. 193-208.

Janas P., 1990. *Dimensioning of roadway supports in conditions of Ostrava-Karvina Coalfield, Strata control in deep mines*. Proc. of the 11th Plenary Scientific Session of the International Bureau of Strata Mechanics/World Mining Congress, Novosibirsk, 5-9 June 1989 / edited by A. Kidybinski & J. Dubinski, p. 124-129.

Junker M., 2009. *Strata control in in-seam roadways*. VGE Verlag GmbH, Essen.

Podjadtke R., Witthaus H., Breedlove J., 2009. *Development in steel roadway support* - a track record. The 27th International Conference on Ground Control in Mining, Morgantown, West Virginia 2009 Strata Products (USA) Inc., p. 358-365.

Šňupárek R., Konečný P., 2010. *Stability of roadways in coalmines alias rock mechanics in practice.* Journal of Rock Mechanics and Geotechnical Engineering, 2010, Vol. 2(3), p. 281-288.

Stacey T.R., Ortlepp W.D., 2000. *Support appropriate for dynamics loading and large static loading in block cave mining openings*. Proc. Mass. Min. 2000 Brisbane, p. 783-789.

*Received: 29 October 2013*