DYNAMIC LOAD EFFECT ON CHARACTERISTIC OF FRICTION JOINTS

DYNAMICKÝ ZÁTĚŽOVÝ EFEKT PŮSOBÍCÍ NA CHARAKTERISTIKU TŘECÍCH SPOJEK

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Abstract

A mining yielding support is used for securing roadways against the static and dynamic impact of the rock mass. Steel frames and friction props are used to produce the support. Their essential part decisive for load-bearing capacity and yield capacity are friction joints. The article presents the results of theoretical studies and stand tests concerning the work of friction joints at their dynamic load. During the stand tests, a joint was loaded axially onto which a cross-bar was rested with a mass freely falling from a specific height. The forces occurring within the stirrups and the displacement of the yielding shaped section were recorded for the first time during the tests with a high-speed camera. The physical and mathematical models of the joint had been developed based on the stand tests, which were then used for a simulation analysis of joint work under impulse loading.

Abstrakt

Báňská pružná ochrana se používá pro zabezpečení vozovek proti statickým a dynamickým účinkům hornin. K vytváření této ochrany se používají ocelové rámy a třecí stojky. Jejich nejdůležitější částí, která rozhoduje o nosné a ochranné kapacitě, jsou třecí spojky. Článek předkládá výsledky teoretických studií a tlakových testů, které se týkají činnosti třecích spojek a jejich dynamické zátěže. Během tlakových testů spojka byla zatížena ve směru osy, na kterou působila příčná rozpěra s hmotou padající ze stanovené výšky. Síly, které se objevily ve třmenech a v posunutí stíněné části byly zaznamenány poprvé během testů vysokorychlostní kamerou. Fyzikální a matematické modely vznikly podle tlakových testů; použily se pak pro simulační analýzu práce spojky, která podléhá impulsové zátěži.

Keywords

yielding support, dynamic load, friction joint, mining support

1 Introduction

The hundreds of kilometres of roadways secured with a yielding support (also called ŁP type support) are used in the Polish hard coal mines. The support consists of steel frames made of V-shaped sections connected with friction joints. The frames are mounted along the heading and are distributed along that heading differently. Friction joints are also used in friction props (that are classified as yielding supports).

The characteristic feature of a yielding support and its crucial advantage is that it is capable of changing its dimensions by itself during work. The interworking shaped sections in a friction joint may displace (yield) due to a rock mass deformation load and after such operation a yielding support transits into a new state of equilibrium and may further ensure that the heading is protected.

A frame yielding support used commonly in dog headings is exposed to a static and dynamic load. A dynamic load acting on the support is particularly dangerous considering the continued functionality of headings and staff's working safety. The sources of such load are rock bursts and bumps occurring in the rock mass.

As dynamic phenomena have been seen more and more often during mining, it becomes necessary to carry out studies and analyses to identify their impact on the work of a mining yielding support.

If we assume that a friction joint is part of a yielding support having a decisive effect on the working characteristic of the support, it is substantiated to undertake friction joints studies under a dynamic load.

To date, the friction joints of a yielding support have been investigated mostly under a static load. The stand tests of friction props (Stoiński, 1988), support frames (Stoiński, 1988, Prusek and Rotkegel, 2008) and friction joints (Pacześniowski and Pytlik, 2008) were carried out under a dynamic load. The tests were focussed on determining yield resistance according to time and impact energy and were mainly of comparative nature.

In order to investigate and describe more fully the phenomena occurring in a friction joint during its dynamic loading, the author of the paper has performed stand tests and theoretical analyses, the results of which are presented in this work.

In the stand tests, a friction joint was subjected to impact loading with an impact mass dropped from a specific height. The measuring system established allowed to record variations in the values of the force transferred by the friction joint and the values of axial forces in the stirrups bolts. This has permitted to analyse the impact of the actual axial force values in the stirrups bolts used in friction the joints on the value of the force transferred by the joint and on the yield value. The effect of impact energy on the value of the force transferred by the friction joint was also identified.

Physical and mathematical friction joint models were established based on the system used in the stand tests. The friction forces between the interworking shaped sections were taken into consideration in such models and this allowed modeling the friction joint frictional susceptibility. The external load was assumed as a dynamic impulse described with a complex exponential function.

The mathematical model was subjected to a numerical analysis with the results being presented in the paper.

2 Stand tests of friction joints subject to a dynamic load

The stand tests of friction joints work under a dynamic load were carried out at a special test stand. The stand diagrams are shown in Fig. 1. A friction joint in such tests is subjected to an axial load with m_1 mass falling from a specific h height. The size of the m_1 mass during the tests was constant. The tests were carried out for four different heights from which the impact mass was dropped. The heights were so selected so that the characteristics of the determined parameters included the broadest possible range of variations in the impact energy. The impact of the falling mass on the joint was exerted through a cross-beam with constant m_2 mass that rested upon the friction joint.

A new measuring system was established for the purpose of the tests. The system permitted to register variations in the values of forces under the cross-beam and under the friction joint, the values of forces in the stirrups bolts and the displacement, speed and acceleration of the yielding shaped section. Sampling frequency during the tests equalled 9600 Hz.

The measuring system established consisted of six sensors with the sensor (1) used for registering the value of the force directly underneath the cross beam, the sensor (2) under the friction joint and four tunnel sensors (3) were registering variations in axial forces values in the stirrup bolts. All the data was transmitted to a recording and measuring system (4) (Fig. 1).

The force values variations under the friction joint recorded by the sensor (2) according to time determines the friction joint dynamic characteristic. This determines a variation in the value of the force transmitted by friction joints loaded with the impact mass. The value of this force characterises the impact exerted by a friction joint on the substrate which corresponds to its reaction *R*. This relationship allows to determine the maximum value of the force (R_{max}), transferred by a friction joint.

Axial forces in the stirrups bolts were measured continuously during the tests using tunnel sensors and ball washers (Fig. 2). It is very important to monitor variations in the values of such forces when mounting a friction joint and during its work as it is decisive for the joint load-bearing capacity and yield capacity.

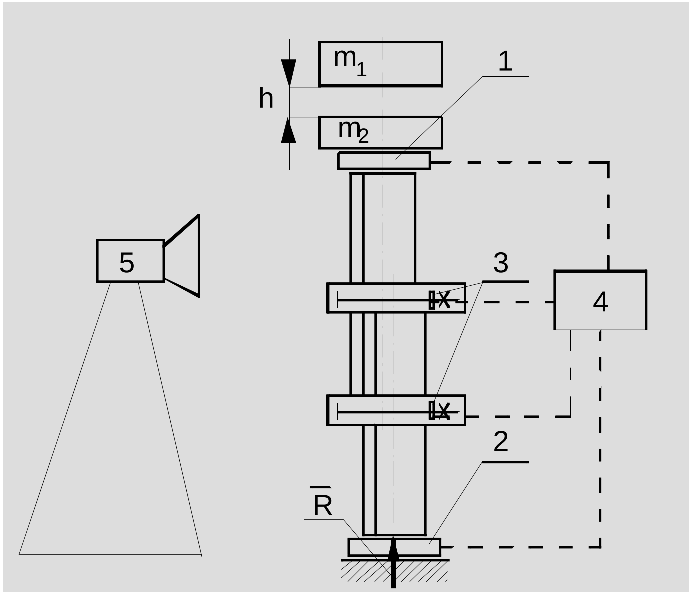

Fig. 1 Diagram of stand and measuring system for dynamic tests of friction joints

Fig. 2 Installation method of sensor for measuring axial force in a SDO29 stirrup bolt

The results of the tests and analyses performed (Brodny, 2010) prove that different axial force values can be obtained for the same value of the torque moment at which bolt nuts are tightened in such bolts. Their actual value can be obtained only if axial forces in the bolts are measured directly. The force at which the interworking shaped sections are pressed in a friction joint equals the sum of the axial forces in each of the stirrups bolts used in such a joint.

The yield degree in a friction joint was also measured during the tests. A high-speed camera (5) was applied for this purpose (fig. 1). The camera enabled to register the subsequent positions of the friction joint elements during yield under a dynamic load (Fig. 3).

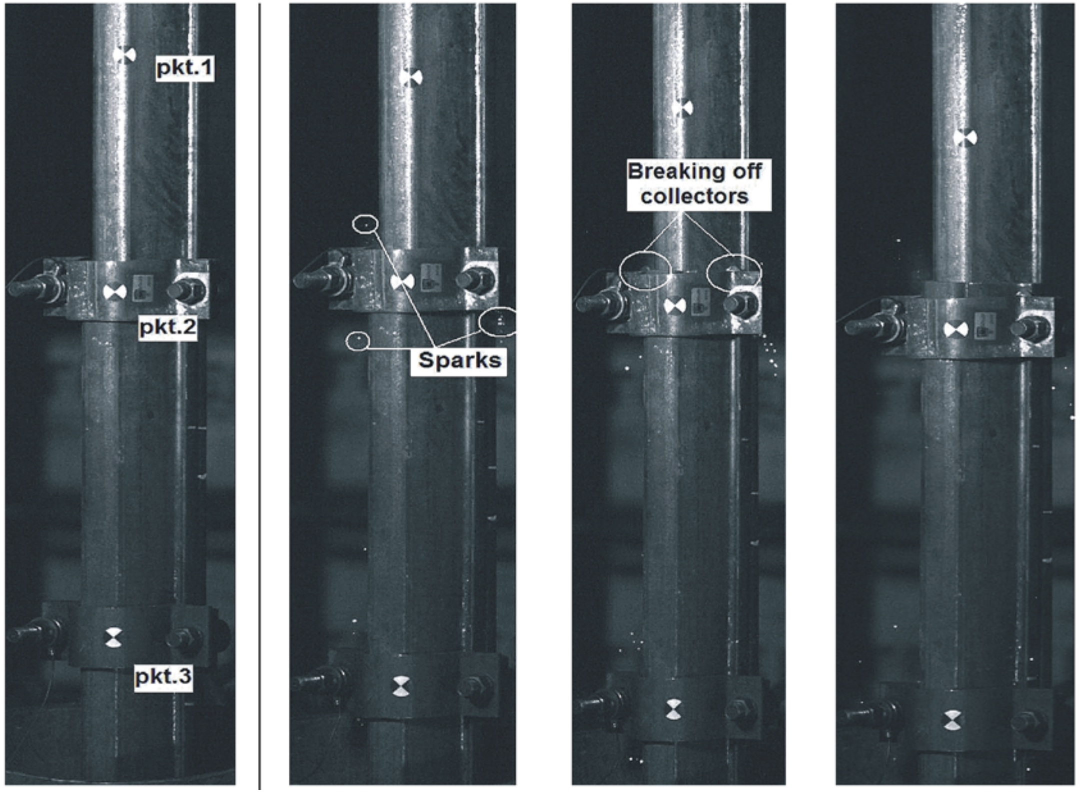

Fig. 3 Subsequent phases of friction joint yield

The displacements of the marked measuring points according to time were recorded during the tests. This enabled to determine their speeds and accelerations. Sparking in the friction joint was also observed during yield which confirms the results of underground observations (phase two and three in Fig. 3). The collectors breaking process was also recorded during yield (phase three and four in Fig. 3).

3 Measurements results

The dynamic characteristics of friction joints were established as a consequence of the stand tests. The friction joint dynamic characteristics are shown in Fig. 4. The joint is made of V29 shaped sections with two SDO 29 stirrups. The characteristic was established for the impact mass of 4000 kg falling from a height of 0.5 m onto a cross-beam weighing 1600 kg. The initial force value (N) at which the interworking shaped sections were pressed was equal to the sum of the initial axial forces (Q_i) in the bolts of the both stirrups and was: N=320 kN.

It can be concluded when analysing variations in the values of the force (R) transmitted by the friction joint that the force reaches the maximum value at the time just before starting the yield. The force value decreases substantially together with the yield until the system transits into the steady state.

As regards the known values of the impact mass, cross-beam mass and the friction joint elements mass and a height at which the impact mass was dropped, relationships were determined between the energy of the impact (E) and the maximum values of the forces transferred by a friction joint (R_{max}) for the different initial values of axial forces in the stirrups bolts (Fig. 5).

The energy of the impact was calculated as follows:

$$E = m \times h \times g \,, \tag{1}$$

where: h - impact height in [m],
m - impact mass in [kg].

Analysis of the obtained results unequivocally shows, that with the increase of the impact energy (height h, from which the impact mass drops), the maximum value of the force transmitted through the frictional joint, increases.

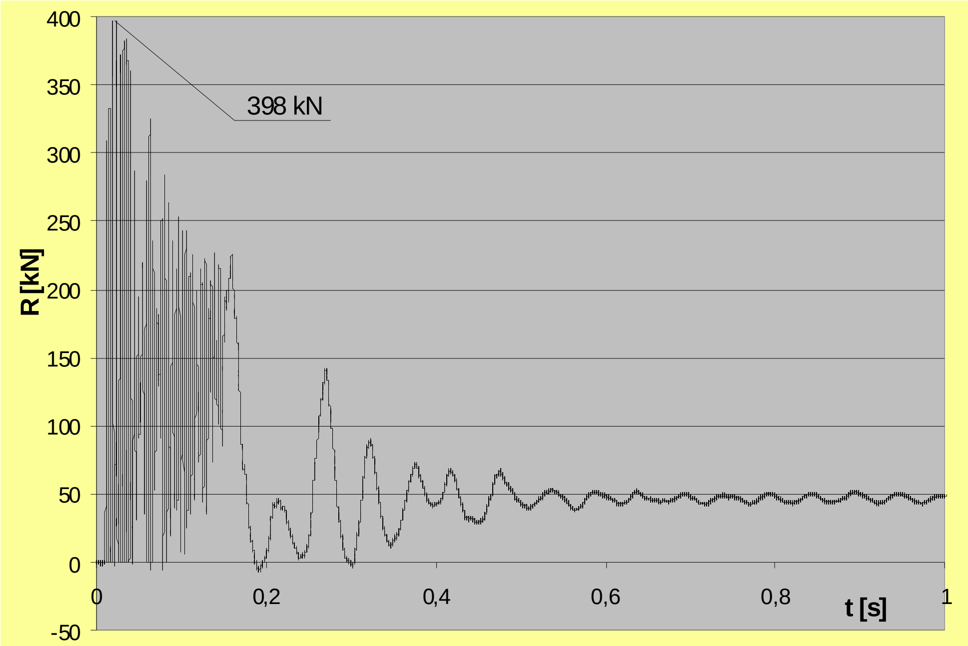

Fig. 4 Friction joint dynamic characteristic

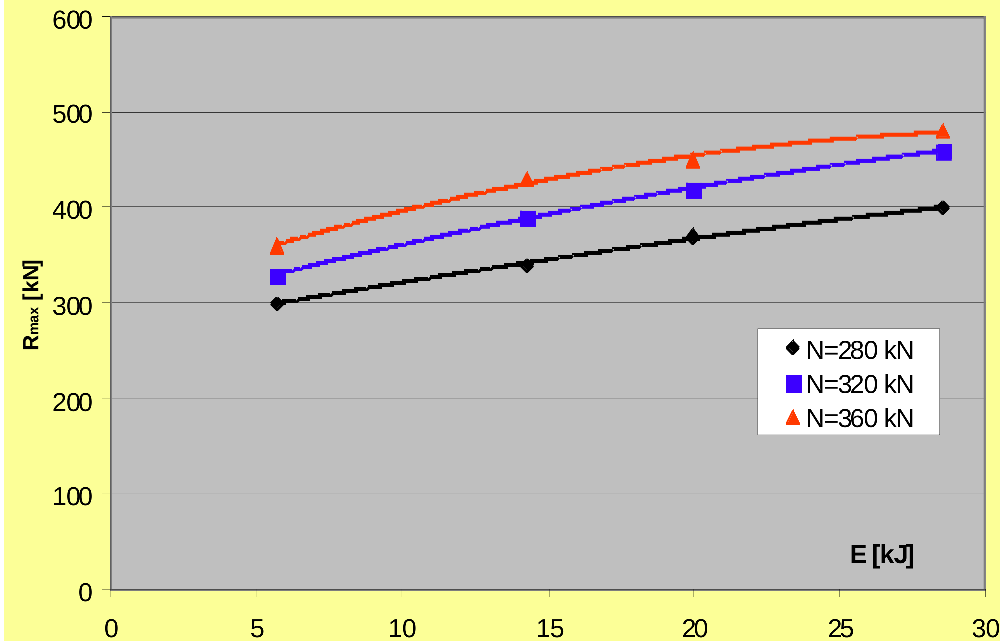

Fig. 5 Relationships between the maximum value of the force transferred by a friction joint according to impact energy for the different initial values of axial forces in stirrups bolts

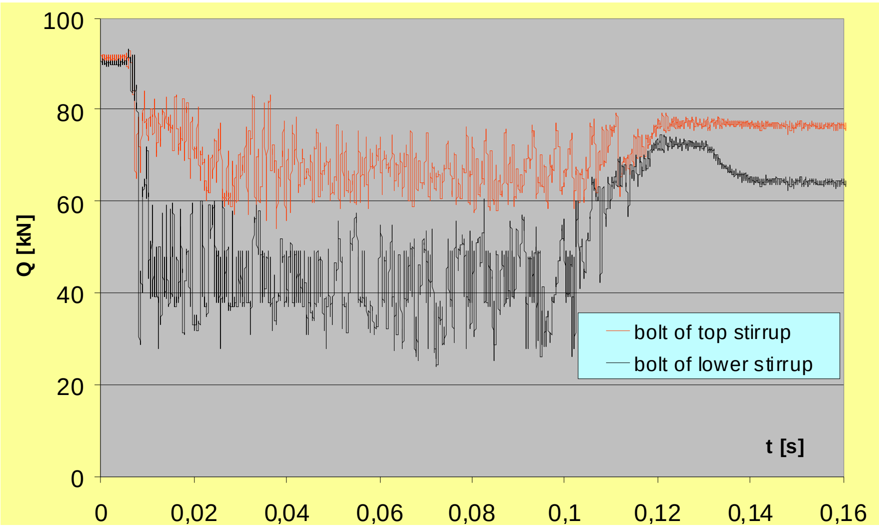

Fig. 6 Variations in axial forces values for stirrups bolt under friction joint dynamic load

The growing axial forces values in the stirrups bolts result in the higher maximum value of such force.

The tunnel sensors used for measuring the values of axial forces in stirrups bolts enabled to determine the characteristics of variations of such forces values during impact.

Fig. 6 shows variations in axial forces values (Q) in stirrups bolts for a joint loaded with a mass falling from 0.5 m. In this case the values of initial forces in the stirrups bolts were approx. 90 kN. As a result of the dynamic load on the friction joint, the values of such forces during the test were reduced. Their values after approx. 0.14 s were stabilised on the level lower as compared to the initial value. The values of axial forces in the top stirrup bolts declined by approx. 17 %, and in the bottom stirrup bolts by approx. 28 %.

A high-speed camera enabled to record yield in a friction joint. The displacement characteristics of the three points localised on the top shaped section and on the friction joint stirrups in a vertical axis were determined on such basis (Fig. 7). The characteristics were determined for an impact mass falling from the height of 0. 2 m (N=280 kN). The total yield in the joint was 0.123 m.

Point 1 is displacing together with the top section, just like point 3 that is situated in the bottom stirrup yoke. The bottom stirrup, during yield through collectors, is practically fixed to the top section; therefore their displacement characteristics are almost identical. Point 2 is located on the top stirrup yoke that is connected through collectors with the bottom section that does not move. As collectors were broken in the analysed case, the displacement of point 2 by 0.025 m towards the vertical axis was recorded.

The tests also enabled to establish the characteristics determining the overall top section displacement (yield in a friction joint) according to impact energy for the different initial values of axial forces in the friction joint stirrups bolts (Fig. 8).

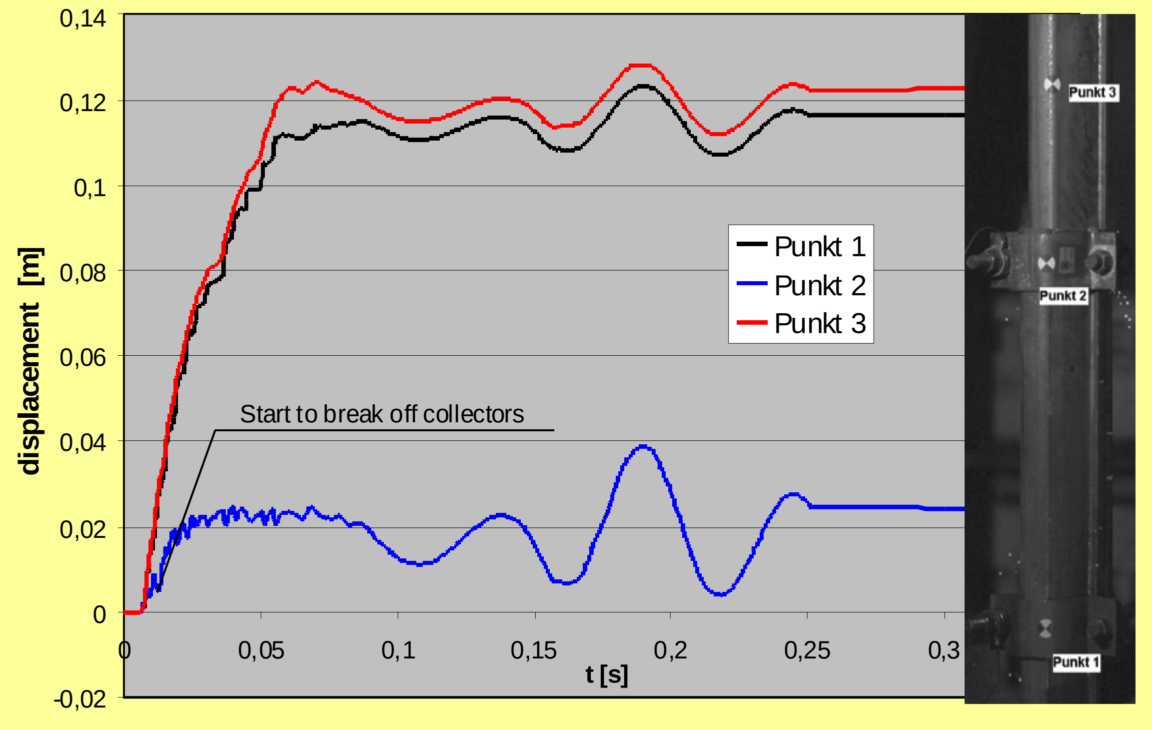

Fig. 7 Displacement of friction joint points during yield

Obtained results show, that with the increase of impact energy, the yield in the frictional joint increases. While increase of the initial values of axial forces in the bolts of stirrups, causes the decrease of the value of yield. At higher values of the forces, pressed to cooperating sections, the frictional joint becomes more rigid.

4 Model tests of friction joint

The configuration for stand tests shown in Fig. 1 was used for developing a physical model of a friction joint made of V29 shaped section and two SDO 29 stirrups (Fig. 9).

In this configuration, the friction joint was modelled as two concentrated masses of interworking shaped sections (m_1 and m_2). The mass of each shaped section is increased by the mass of one stirrup. It was assumed that each of the stirrups is connected through collectors with one of the sections. The sections are pressed with N force the value of which equals the sum of axial forces values in stirrups bolts.

The mathematical model describing the movement of m_1 and m_2 masses and the mass-free element around their equilibrium position forced by load P (t) assumes the following equations:

$$\begin{aligned} & m_1 \times \ddot{y}_1 + k_1 \times (y_1 - y_3) + c_1 \times (\dot{y}_1 - \dot{y}_3) = P(t) \\ & m_2 \times \ddot{y}_2 + k_2 \times y_2 + c_2 \times \dot{y}_2 - T = 0 \\ & k_1 \times (y_1 - y_3) + c_1 \times (\dot{y}_1 - \dot{y}_3) - T = 0 \end{aligned} \quad (2)$$

where: $k_1 = k_2 -$ sections plasticity coefficients, [N/m]

$c_1 = c_2 -$ sections damping coefficients, [kg/s].

A Coulomb model (Den Hartog, 1931) was used to describe the friction force. The value of T friction force depends on the N pressing force and the static (μ_{st}) and kinetic (μ_k) friction coefficient between the contacting surfaces of the shaped sections.

A friction force value varies according to the relationship:

$$T = \begin{cases} T_{st} \times \mathrm{sgn}(W) \text{ for } \dot{y}_3 - \dot{y}_2 = 0 \text{ and } |W| \geq T_{st} \\ W \times \mathrm{sgn}(W) \text{ for } \dot{y}_3 - \dot{y}_2 = 0 \text{ and } W \langle T_{st} \\ T_k \times \mathrm{sgn}(\dot{y}_3 - \dot{y}_2), \text{ for } \dot{y}_3 - \dot{y}_2 \neq 0 \end{cases} \quad (3)$$

where:

$$W = k_1 \times (y_1 - y_3) + c_1 \times (\dot{y}_1 - \dot{y}_3),\ T_{st} = N \times \mu_{st}, T_k = N \times \mu_k \quad (4)$$

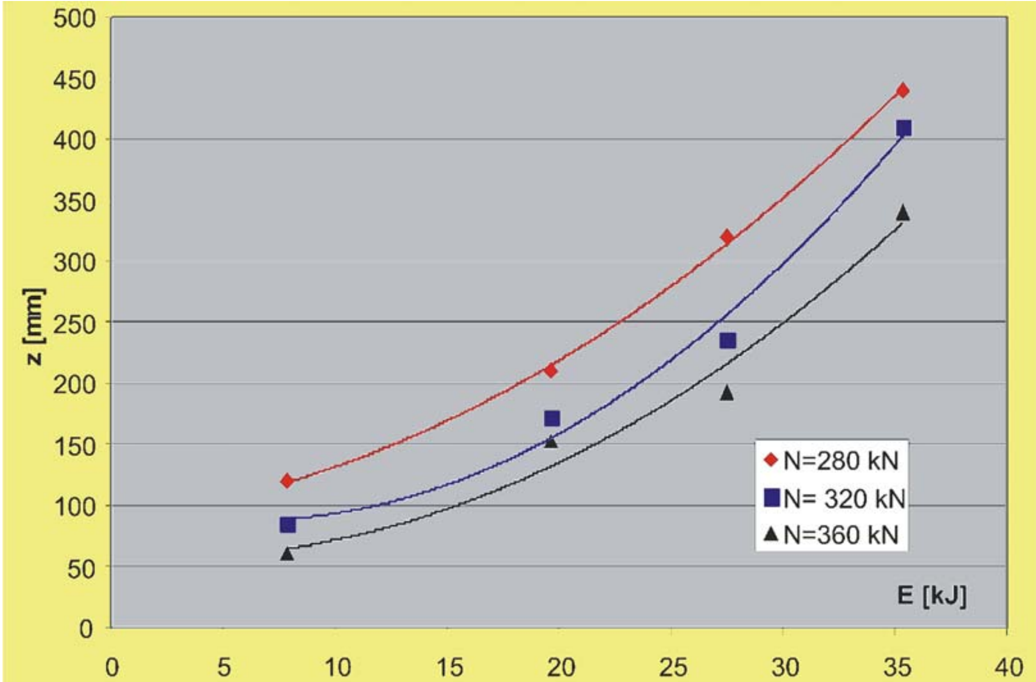

Fig. 8 Relationships of total z yield in a friction joint according to impact energy for the different initial values of axial forces in stirrups bolts

The external active force *P(t)* acting on the friction is a result of the rock mass activity on the mining support for the real system.

Considering the measurements results of variations in the value of the exciting force acting on the friction joint under an impact load, a characteristic was adopted similar to the real distribution of the force. The characteristic is shown in Fig. 10. It is a result of assembling the characteristics of two exponential functions and is described with the following equation (5).

$$P(t) = (P_y - P_{st}) \times e^{-\frac{t}{T_d}} + P_{st} \times (1 - e^{-\frac{t}{T}}) \quad (5)$$

for $T_d >> T$,

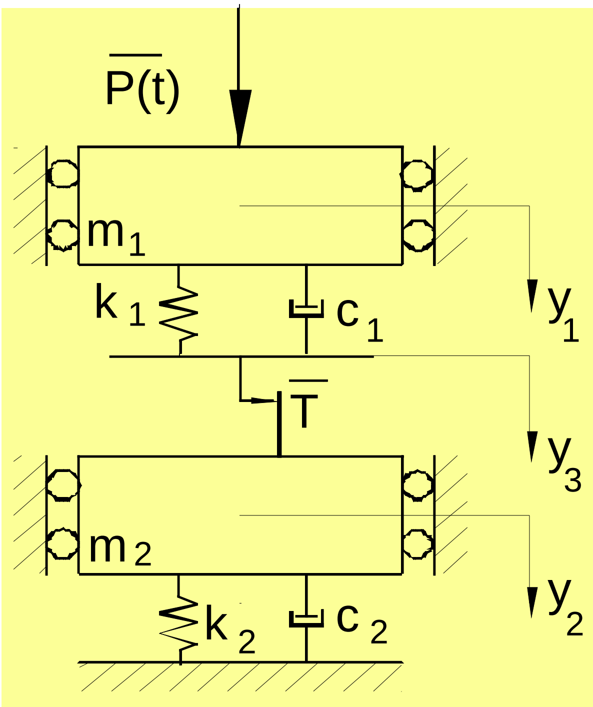

Fig. 9 Physical model of friction joint

where:

P_y - maximum dynamic impulse value in [kN],

P_{st} - agreed static load value in [kN],

T_d - time constant of dynamic impulse fading in [s],

T - time constant of the component impulse fading in [s].

The value of the time constant of the dynamic impulse fading T_d is decisive for the time after which *P (t)* force reaches the steady state. A friction joint in the steady state is loaded with static force resulting from the load of the impact mass and cross-beam mass.

The mathematical model established was subjected to a numerical analysis the purpose of which was to determine the friction joint dynamic characteristic.

Fig. 11 shows the dynamic characteristic of a friction joint for its dynamic loading resulting from the impact of 4000 kg mass (m_3) falling from a height of 0.5 m for the total value of the initial axial forces (N) in the stirrups bolts of 320 kN.

By comparing the dynamic characteristics of a friction joint achieved in stand tests (Fig. 4) and numerical analysis (Fig. 11) one can notice that they are similar with respect to their curve and values achieved. The maximum value of the force (R_{max}) transferred by a friction joint determined in a numerical analysis is 390 kN, and 398 kN from stand tests. The subsequent phases of friction joint work determined according to such characteristics are also similar. Assumingly, therefore, the model established is reflecting correctly the real system as regards determining the value of the maximum force transferred by a friction joint and the damping time of such force.

Differences between the courses of time characteristics, obtained on the basis of the numerical studies and stand tests, result from the larger damping of numerical system. Dynamic characteristics of construction for the real time can be determined using the finite elements method (Horyl and Šňupárek, 2007).

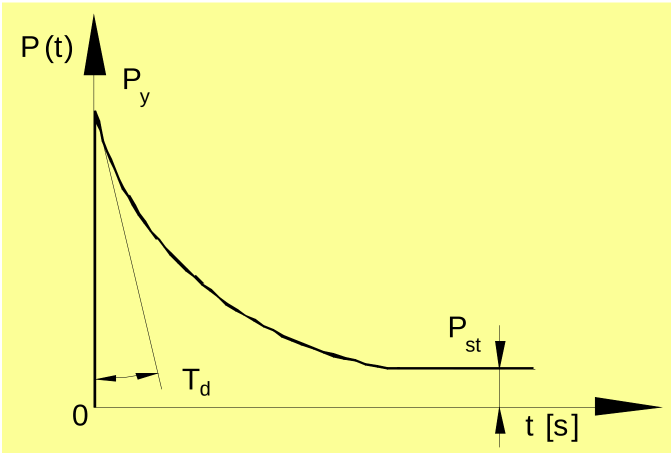

Fig. 10 Characteristic dynamic loads of friction joint

5 Conclusions

The stand tests of friction joints subject to a dynamic load with an impact mass enabled to determine their dynamic characteristics. The curves were determined of variations for the values of the forces transferred by a friction joint depending on the value of the forces pressing the interworking shaped sections and the impact energy value. The characteristics determined allow tracing the individual phases of friction joint work under a dynamic load, to determine the values of maximum forces transferred by a joint and to set time after the lapse of which the system transits into the steady condition.

The results obtained clearly show that as the height of the mass impact increases (a greater impact energy value), the value of the maximum force transferred by a friction joint is growing.

When analysing the axial forces values in the stirrups bolts recorded for the first time during the impact, it is clear that - as a result the values of such forces decline. It is an adverse phenomenon and in practise, after each yield, the stirrups bolts should be tightened or constructional solutions should be applied constraining this phenomenon, e.g. friction wedges (Brodny, 2010).

It should be emphasised that a highly specialised test stand and measuring and recording equipment is required to undertake such stand tests, which involves high costs.

It is reasonable to conduct theoretical analyses, regardless the stand tests, aimed at developing models representing the tested object and offering extensive simulation opportunities to analyse their work. The friction joint model presented in this paper satisfies such a claim.

The results obtained when analysing the theoretical model signify that it is strongly consistent with the real object. The results obtained, in particular in relation to the determination of the maximum values of the forces transferred by a friction joint and the determination of displacements during yield, do not vary by more than approx. 10 % from the values obtained in the stand tests. This signifies that the model established is sufficiently accurate.

The presented friction joint modelling method offers great opportunities for simulating joint work as regards changing the method and character of the load and the selection of joint physical parameters.

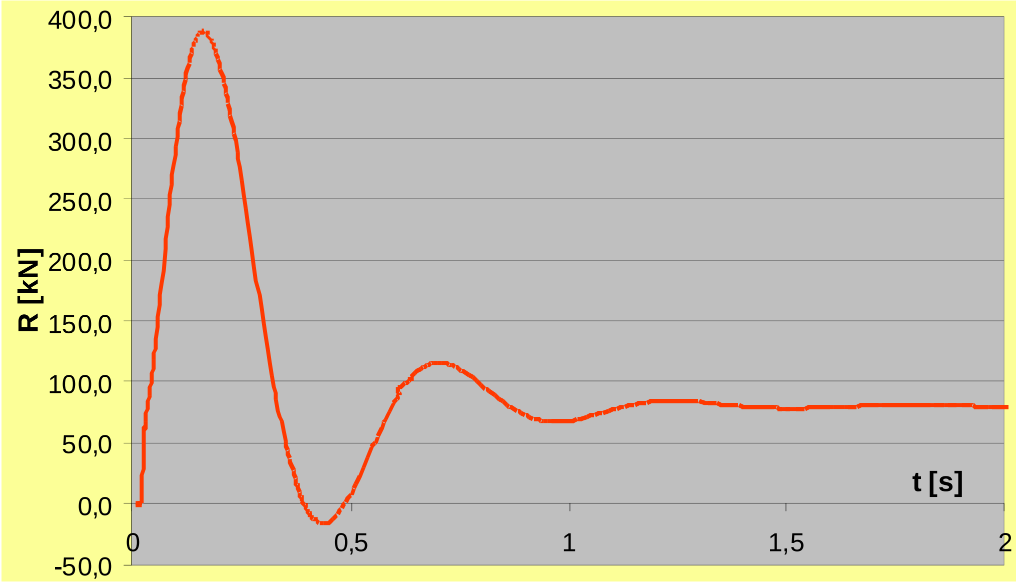

Fig. 11 Characteristic of friction joint reaction value variation R(t)

The case of loading a friction joint with mass impact was considered in the tests. This reflects the actual case of loading a support with a dynamic impulse that is widespread in practise in case of rock bumps, stress reliefs and tremors.

The friction joints testing method presented and the results obtained should, in the author's opinion, broaden awareness on the work of a yielding support and be utilised when designing new solutions for mining and tunnel supports used in the conditions of exposure to a dynamic load.

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