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ANALYSIS OF OPERATION OF NEW CONSTRUCTION OF THE FRICTIONAL JOINT WITH THE RESISTANCE WEDGE

ANALIZA PRACY NOWEJ KONSTRUKCJI ZŁĄCZA CIERNEGO Z KLINEM OPOROWYM

Frictional joint is the basic part of the friction props and yielding steel frames of dog headings. It constitutes a constructional connection and have decisive influence on the basic operational parameters of the steel frames and props, *i.e.* their loading capacity and yielding capacity. Currently applied constructions of frictional joints characterize with low loading capacity and unstable operation. In order to improve their operational parameters a new constructional solution of frictional joint, consisting on the application of resistance wedge assembled between the cooperating sections, was developed. Application of the resistance wedge caused an increase of resistances to motion in the frictional joint, what influenced on the increase of its loading capacity and on the increase of values of axial forces in the bolts of stirrups. In the paper results of stand tests of frictional joints with the resistance wedge, subjected to the static axial compression and impact of freely falling mass, were presented. In order to determine the influence of the resistance wedge on the operational parameters of the frictional joint, obtained results were compared with the results of studies of the frictional joints without the resistance wedge. On the basis of stand tests a physical and mathematical models of the frictional joint with the resistance wedge, were developed, and utilized to simulation analysis of its operation at impulse loading. On the basis of conducted tests and analysis one can state, that application of the resistance wedge influences on the enhancement of loading capacity, improves the state of loading the bolts in stirrups, and creates possibility of regulation of operational characteristics of the frictional joints

Keywords: mining yielding support, friction joint, resistance wedge

Złącze cierne jest podstawową częścią stojaków ciernych oraz odrzwi obudowy podatnej wyrobisk korytarzowych. Stanowi ono połączenie konstrukcyjne i ma decydujący wpływ na podstawowe parametry pracy odrzwi i stojaków, czyli na ich nośność i podatność. Obecnie stosowane konstrukcje złączy ciernych charakteryzują się niską nośnością oraz niestabilną pracą. W celu poprawy parametrów ich pracy opracowano nowe rozwiązanie konstrukcyjne złącza ciernego polegające na zastosowaniu klina oporowego montowanego między współpracującymi kształtownikami. Zastosowanie klina oporowego spowodowało wzrost oporów ruchu w złączu ciernym, co wpłynęło na wzrost jego nośności oraz na wzrost wartości sił

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osiowych w śrubach strzemion. W artykule przedstawiono wyniki badań stanowiskowych złączy ciernych z klinem oporowym poddanych statycznemu osiowemu ściskaniu oraz udarowemu obciążeniu swobodnie spadającą masą. W celu określenia wpływu klina oporowego na parametry pracy złącza ciernego uzyskane wyniki porównano z wynikami badań złączy ciernych bez klina oporowego. W oparciu o badania stanowiskowe opracowano modele fizyczny i matematyczny złącza ciernego z klinem oporowym, które wykorzystano do analizy symulacyjnej jego pracy przy impulsowym obciążeniu. Na podstawie przeprowadzonych badań i analiz można stwierdzić, że zastosowanie klina oporowego wpływa na podwyższenie nośności złącza ciernego, poprawia stan obciążenia śrub strzemion oraz stwarza możliwości regulacji charakterystyk pracy złączy ciernych.

Słowa kluczowe: górnicza obudowa podatna, złącze cierne, klin oporowy

1. Introduction

Yielding support of dog headings consists of supporting arch constructions (called steel frames) and rectilinear supporting constructions (called friction props), and also of elements cooperating with them (lining, anchor props etc.).

The basic part of the steel frames and props are frictional joints, providing the constructional connection of particular elements of steel frames and friction props, and deciding about their basic parameters, which are load capacity and yielding capacity.

Thanks to the operation of the frictional joint the yielding support of dog headings has got an ability to self-acting change of its dimensions under the influence of the external loadings. Operation of the frictional joint is based on the utilization of the friction forces between the co-operating sections. Value of the friction forces depends on the pressing force, and on the static and kinetic friction coefficients between the sections. Pressing force of sections is the result of stirrup's operation and depend on the value of axial forces acting in their bolts and on the friction force in the thread connection.

Current applied constructional solutions of the frictional joints are the source of unstable operation of yielding steel frames and friction props loaded statically and dynamically. Yields occur at relatively low loadings and loading potential of sections, of which steel frames and friction props are made, is insufficiently used. Steels with enhanced mechanical properties (Kowalski et al., 2004; Skrzyński & Prusek, 2006) more and more widely used in production of sections, much more decrease the degree of utilization of strength parameters of a support.

Series of studies was carried out up to now, in order to enhance the load capacity and improvement of operational characteristics of the frictional joints. In majority of presented works to achieve this goal, there are proposed an increase of value of torque moment with which the nuts of bolts in stirrups are tighten up, an increase of number of stirrups in the frictional joint or application of more and more heavier sections of which the friction props and steel frames are made. Only in works (Ciałkowski, 1996; Michałek, 1997) new constructional solutions of frictional joint are presented, which enable obtaining more stable operational characteristics and increase of their load capacity, with simultaneous preservation of yielding capacity. Due to complicated constructions and consequential high costs connected with the manufacture and implementation, these solutions did not find practical use. However, they marked out a direction of further works and studies related to search of new solutions of frictional joints.

Considering above remarks, it becomes necessary to carry out the studies in order to develop new constructional solutions of the frictional joint. Such solution should increase the resistances

to motion during the yield in the frictional joint and through that influence on the increase of loading capacity of the joint, and subsequently the whole yielding support.

Purposefulness of conduction of such works is justified by the fact, that in the nearest years yielding support will still constitutes the basic protection of mining dog headings. Also expectations of its users regarding the directions of improvement of the construction and the way of operation of this support, concentrate mostly on the need of search of new solutions in order to increase its load capacity, ease of assembly and operation, as well as limitation of damages (Brodny, 2011a).

Having regard to all mentioned aspects of operation of yielding support and the frictional joint, both in a case of static and dynamic loading, author of this paper proposed the new constructional solution of the frictional joint. This solution depends on the application of additional constructional element in a form of the resistance wedge assembled between the cooperating sections of the frictional joint.

The main aim of application of the resistance wedge is an increase of value of forces transmitted through the frictional joint (increase of the load capacity of the frictional joint) through the rise of resistances to motion during a yield. It was assumed that in consequence of displacement of sliding down section in the frictional joint, there will occur a deformation of the resistance wedge and the cooperating sections. It will cause an increase of resistances to motion during a yield, what will influence on the rise of load capacity of the joint.

Application of the resistance wedge should also limit sudden and often of great value uncontrolled yields in the joint, and influence on the increase of value of axial forces in the bolts of stirrups, what additionally will improve a load capacity of the frictional joint.

In the paper construction and principle of operation of the frictional joint with the resistance wedge are discussed, and results of stand tests of frictional joints with the resistance wedge loaded statically and dynamically are presented.

In order to determine the influence of the resistance wedge on the operation of the frictional joint, obtained results were compared with the results of studies of the frictional joints without the resistance wedge. Comparison included the operational characteristics of the frictional joints and the changes in values of axial forces in the bolts of stirrups of the joints with and without the resistance wedge.

Due to that the stand tests of the frictional joints are expensive investigations, requiring the specialized stands and proper apparatus, it become purposeful to conduct analysis for development and utilization of less expensive methods of studies, which in correct way would represent the real character of the investigated phenomenon. Analytical methods create such possibilities.

Therefore on the basis of system used in stand tests, physical and mathematical models of the frictional joint with the resistance wedge were developed. In these models friction forces between the cooperating sections was taken into account, what allowed to model the yield capacity of the frictional joint. External loading was assumed in a form of complex exponential function. Mathematical model was subjected to numerical analysis, whose results was also presented in the work.

2. Characteristics of the frictional joint with the resistance wedge

The aim of application of the resistance wedge in the frictional joint is to increase the resistances related to the displacement of cooperating sections. These resistances are connected with the process of deformation of sections, stirrups, and wedge, which can undergo also the cutting process.

In a Figure 1 scheme of the frictional joint with the resistance wedge is presented. In this joint the wedge is assembled between the cooperating sections, so as to fill the empty space between their bottoms.

Geometrical parameters describing shape of the wedge and having significant influence on the operational characteristics of frictional joint with the wedge are: angle inclination of wedge's generatrix α, height of the wedge in its initial part h and length L (Fig. 1). It was assumed that the width of the resistance wedge will be equal to the width of internal section's bottom.

Principle of operation of the frictional joint with the resistance wedge depends on the increase of the resistances to motion of upper section displacing during the yield, which is pressed against to the lower section in a result of stirrups' action (Fig. 1). Beginning of the increase of these resistances occurs at the moment of beginning of contact of upper section with the resistance wedge. In this case, to yield could occur, an increase of value of external force acting on the upper section is necessary. It results in an increase of the value of force transmitted through the frictional joint, *i.e.* load capacity of the frictional joint.
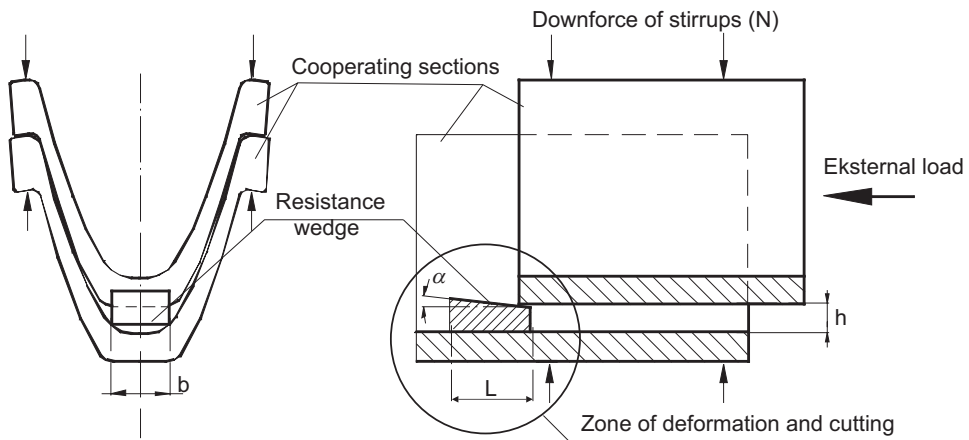

Fig. 1. Scheme of frictional joint with the resistance wedge

Therefore application of the resistance wedge in the frictional joint causes that the resistances in the joint at which the yield can occur and resistances during the yield increase.

In such case, assumption of condition that the beginning of a yield in the joint is connected with the exceeding of maximum value of static friction force ($T_{st\,max}$) by value of external force, do not full represents the real state (Fig. 2).
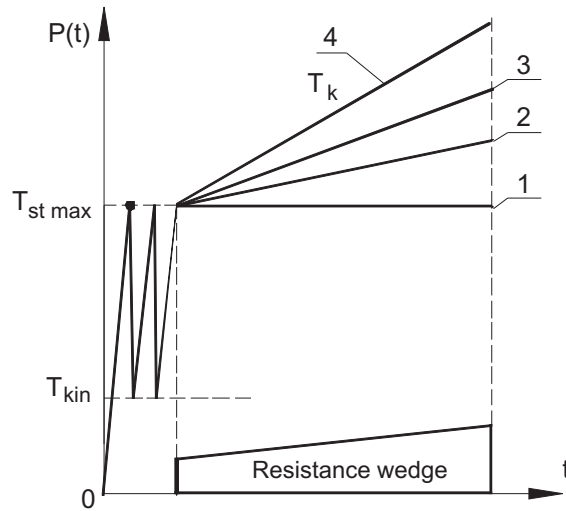
Fig. 2. Change of value of forces in the frictional joint with the resistance wedge

Application of resistance wedge causes that for the beginning of mutual displacement of cooperating sections the value of external force has to be greater than maximum value of static friction force increased by the resistances connected with the deformation and cutting of resistance wedge. An increase of resistances to motion connected with the deformation of yokes of stirrups, bolts, and cooperating sections has to be also taken into account.

It is similarly during the yield itself. In the joint occur then not only resistances resulting from the action of the kinetic friction force (T_{kin}), but also resistances connected with the deformation process of joint's elements and with cutting of the resistance wedge (Fig. 2).

Influence of the resistance wedge on the operation of the frictional joint is explained by the Figure 2, in which operational characteristics of the frictional joints with the resistance wedges of different geometrical parameters, assembled in some distance from the edge of upper section, are presented.

Such arrangement of the resistance wedge causes, that at the initial phase the frictional joint operates classically, *i.e.* it is in rest until the value of external force do not exceed the maximum value of static friction force. At the moment of exceeding this value a yield in joint occurs, which lasts until the value of external force will drop below the value of kinetic friction force. Then the system turns to standstill and the whole cycle is repeated. Such a motion of sections in the frictional joint is discontinuous motion of *stick-slip* type (Leine et al., 1998; Nakano & Maegawa, 2009).

At the moment of contact of external section's edge with the resistance wedge the frictional joint's operational characteristics changes. It is connected with the increase of resistances to motion resulting from operation of resistance wedge. Then the total resistances occurs in the joint, resulting from the friction and deformation (T_k).

Operational characteristics of frictional joints with the resistance wedges presented in Figure 2 and designed with digits 1 to 4 are determined for different geometrical parameters of the resistance wedge. Increase of inclination angle of wedge's generatrices α or its height h, causes an increase of resistances to motion, and in turn load capacity of the frictional joint.

In presented case application of resistance wedge causes an increase of load capacity of the frictional joint with the increase of yield's magnitude. Simultaneously the drop of this load capacity does not occur during the yield, what is a large problem during the operation of yielding support with the classical frictional joints.

On this basis one can state, that application of resistance wedge should significantly improve the operational characteristics of the frictional joint.

Application of resistance wedge as an element causing that operational characteristics of the frictional joint, and subsequently the yielding support will change its character, is compatible with expectations of support's users (Brodny, 2011a) and was also postulated in many works (Ciałkowski, 1996; Michałek, 1997; Stoiński, 1988; Stoiński & Matwiejszyn, 1997).

3. Analysis of operation of the frictional joint with the resistance wedge subjected to the static compression

Tests of frictional joints at static compression consist in their axial loading with the force, which is a result of displacement of piston of testing machine with the constant velocity of 10 mm per minute.

Tests of frictional joint with the resistance wedge were performed on the testing machine equipped in the control system which enables continuous regulation of piston's displacement speed or the speed of increment of loading in the unit of time.

For the necessity of the studies a measuring system was developed, which enables the continuous registration of values of force transmitted through the joint with the resistance wedge, values of axial forces in the bolts of stirrups, and displacements, accelerations of sliding down section.

Tests were conducted for 21 frictional joints made of V29 section with two SDO 29 stirrups, and resistance wedges of different geometrical parameters and of different initial values of axial forces in the bolts of stirrups.

To determine the influence of the resistance wedge on the operational characteristics of the frictional joint, operational characteristics of the frictional joints with and without the resistance wedge are presented in a Figure 3. In both joints values of initial axial forces in the bolts of stirrups were the same and amounted to 82,5±2,5 kN in each bolt. Resistance wedge was made of the steel S235JR of inclination angle of generatrix (α) amounting to 6°, initial height (h) equal to the height of slit between the cooperating sections and length (L) equal to 0.2 m (Fig. 1).

Analyzing obtained characteristics one can state, that for the frictional joint with the resistance wedge, the loading transmitted through it, increases with the displacement of section sliding down. Also drops of load capacity during the yield in joint, characteristic for the frictional joints without the resistance wedge, do not occur. The consequence of these drops are the great values of displacements (yields) in the frictional joint.

Presence of the resistance wedge limits the possibility of occurrence of large drops of value of force transmitted through the frictional joint (its load capacity) during the occurrence of a yield, what causes that sudden yields in the frictional joint do not occur. Process of displacement of the section sliding down goes much more fluently, than in a case of the joint without the resistance wedge. The value of yield is lower than for the joint without the resistance wedge, hence yield capacity of the frictional joint decreases.

Using the operational characteristics of the frictional joint a series of parameters describing its operation can be determined. The most important of them are the maximum value of force
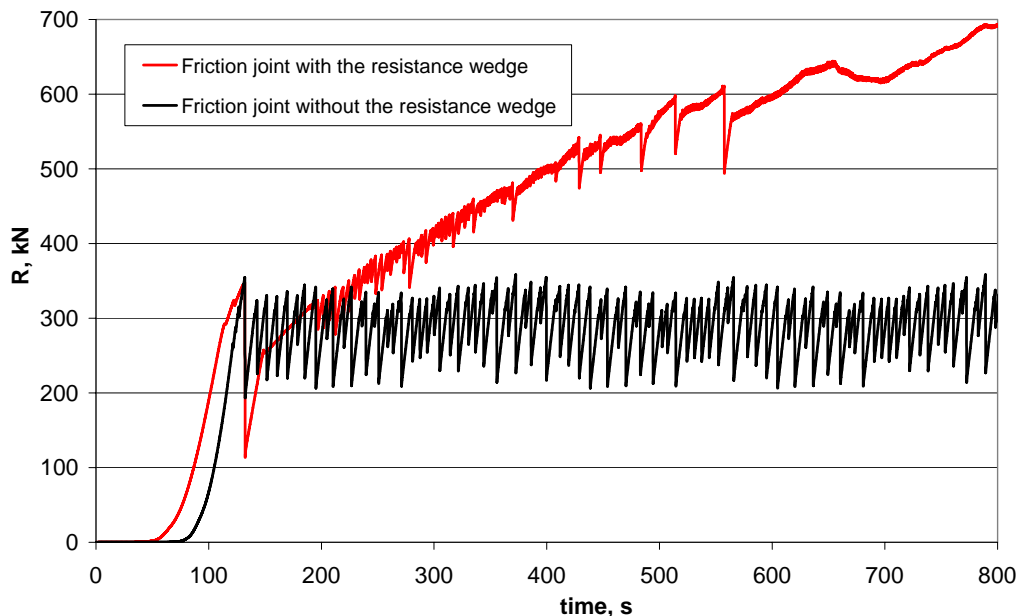
Fig. 3. Performance characteristics of the frictional joint with and without the resistance wedge

transmitted through the frictional joint (maximum bearing-sliding capacity) and the value of force, at which the first yield in the frictional joint occurs (bearing-sliding capacity at the moment of occurrence of the first yield) called also the force breaking the frictional joint.

Very significant influence on the operational characteristics of the frictional joint with the resistance wedge beside the geometrical parameters of the wedge, has also the place of its assembly.

In Figure 4 operational characteristics of the frictional joint with the resistance wedge of inclination angle of generatrices amounting to 12°, assembled in a distance of 0.1 m from the initial edge of displacing section is presented.

Analyzing obtained dependence one can state, that in the initial phase we deal with operational characteristics as for the joint without the resistance wedge. After the yield of ca. 0.1 m change in character of joint's operation occurs, and it starts to operate as a joint with the resistance wedge. One can assume that at such assembled resistance wedge obtained characteristics is late-bearing.

During the tests of frictional joints with the resistance wedge, the changes in values of axial forces in bolts of stirrups were also registered with the use of specialized sleeve sensors.

It has to be emphasized that in reality axial forces in the bolts of stirrups have very significant influence on the operational characteristics of the frictional joint. They decide on the value of force with which the sections cooperating in the joint are pressed against, what directly influences in the load capacity and yield capacity of the frictional joint (Brodny, 2010; Brodny 2011b).

In a Figure 5 the course of axial forces (Q) in the bolts of stirrups of frictional joints with and without the resistance wedge is presented.
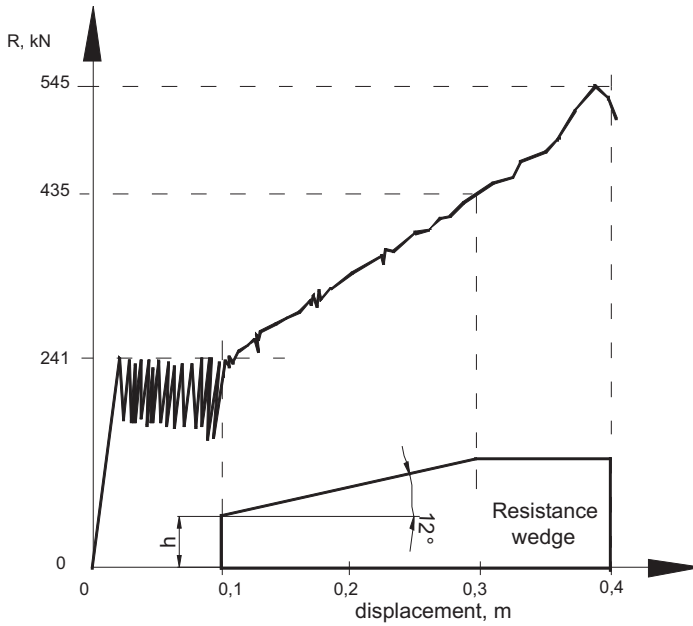
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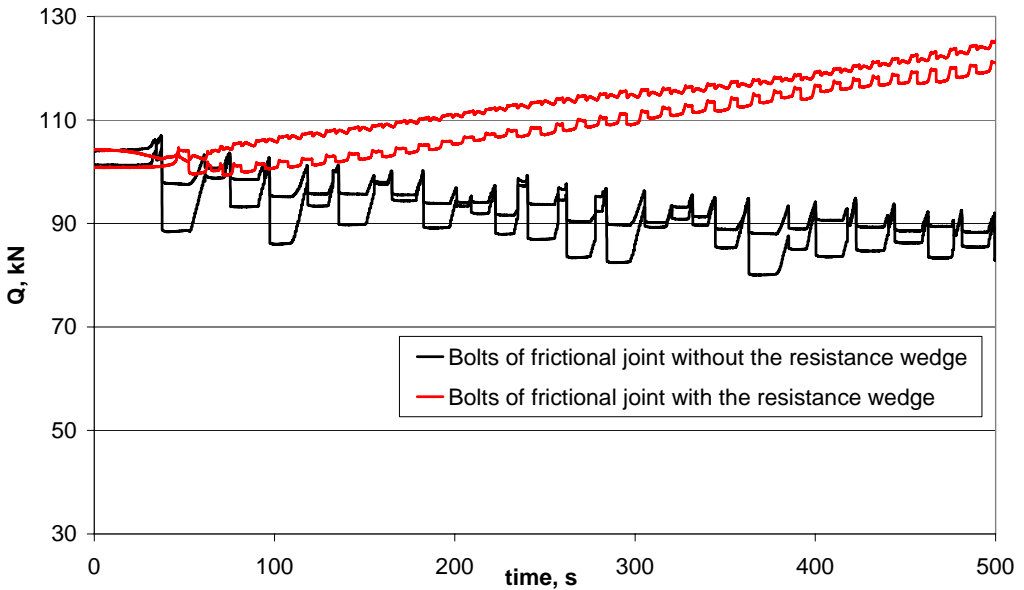Fig. 4. Performance characteristic of frictional joint with the resistance wedge ($\alpha = 12°$)

Fig. 5. Change of values of axial forces in the bolts of stirrups of frictional jointwith
and without the resistance wedge

Obtained charts illustrate clear difference between the characteristics of changes in values of axial forces in the bolts of stirrups for the frictional joints with and without the resistance wedge. In a case of frictional joint without the resistance wedge values of axial forces in the bolts of stirrups decrease with the yield. This drop reaches ca. 30% towards the initial value. It has very significant meaning for the further operation of the joint, because it decreases the value of force with which the cooperating sections are pressed against. It causes a decrease of load capacity of the joint and increase of its yield capacity. In a case of yielding support it can be very dangerous phenomenon, because it causes a considerable decrease of its loading parameters.

In a case of frictional joint with the resistance wedge together with the increase of value of a yield, an increase of values of axial forces in the bolts of stirrups occurs, what has to be recognized as advantageous process. Phenomenon of self-tightening of bolts of stirrups occurs, causing that value of force with which the cooperating sections are pressed against increases, what influences on the increase of load capacity of the joint.

4. Analysis of operation of the frictional joint with the resistance wedge loaded to the impact mass

Determination of operational characteristics of the frictional joints with the resistance wedge loaded with an impact of the mass was conducted on the specialized research stand, whose scheme and description is presented in work (Brodny, 2011b). The tests consisted in axial loading of the frictional joint with the constant impact mass amounting to 4000 kg freely falling from the defined height on the traverse of mass 1600 kg. Tests were performed for different heights from which the drop of impact mass occurred, at different values of axial forces in the bolts of stirrups, and for different geometrical parameters of the resistance wedge.

Using the measuring system used in the tests of frictional joints loaded statically, changes in values of axial forces in the bolts of stirrups, displacements, velocities, and accelerations in the elements of frictional joint were registered.

In a result of tests carried out dynamic characteristics of the frictional joints with the resistance wedge were determined. They define change in value of force (R) transmitted through the frictional joint during its loading with an impact of the mass.

To determine the influence of the resistance wedge on the operation of the frictional joint, dynamic characteristics of the frictional joints with and without the resistance wedge are presented in a Figure 6. Both joints were loaded with the mass falling from the height of 0.7 m, and values of axial forces in each bolts of their stirrups amounted to 102,5±2,5 kN. Value of inclination angle of generatrices of the resistance wedge amounted to 12° and its height in the initial part was equal to the height of the slit between the cooperating sections.

Comparing determined characteristics one can state that the application of the resistance wedge causes a significant increase of value of forces transmitted through the frictional joint. Since the value of this force corresponds to maximum load capacity of the frictional joint one can admit that thanks to the resistance wedge the maximum load capacity of the joint increases. Differences in the course of both characteristics has be also noted. In a case of the frictional joint with the resistance wedge we observe greater damping and faster transition of the system into the steady state.

Reason of that is the operation of the resistance wedge causing the increased dissipation of impact energy connected with the deformation of the resistance wedge and its cutting by the displacing section, and increased state of deformations of frictional joint's elements.

Deformation state of the resistance wedge in the frictional joint after loading it with an impact of the mass, presented in a Figure 7, confirms previous assumptions according to its cutting.

In a result of performed tests dependence between the maximum force (R_{max}), which is transmitted through the frictional joint with and without the resistance wedge, and the height from
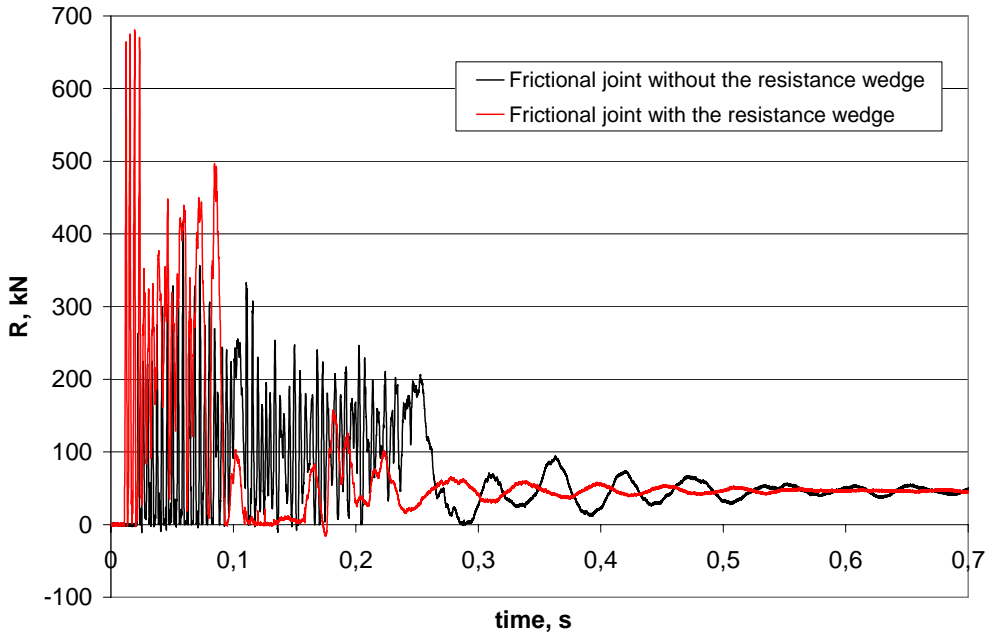

Fig. 6. Dynamic characteristics of the frictional joint with and without the resistance wedge

Fig. 7. Deformation state of the resistance wedge in the frictional joint

which the drop of impact mass occurs, was determined (Fig. 8). Values of forces with which the sections were pressed against before the impact corresponded to the total value of initial axial forces in the bolts of stirrups, and varied in range of 360–400 kN, what corresponds to the values of forces mostly occurring in reality.

On the basis of obtained values one can state, that application of resistance wedge in the frictional joint causes an increase of its load capacity towards the joint without the wedge.

Analogically as in a case of studies of joints loaded statically, also at their loading with an impact of the mass, an influence of the position of assembly of the resistance wedge towards the edge of displacing section on the operational characteristics of the joint was determined.
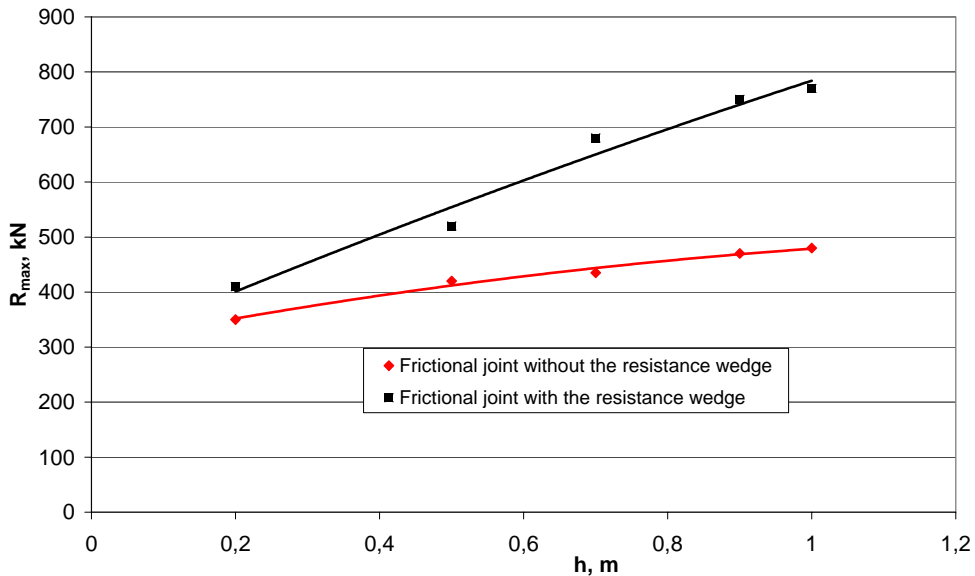

Fig. 8. Maximum values of forces transmitted through the frictional joint with
and without the resistance wedge

In Figure 9 operational characteristics of the frictional joint with the resistance wedge of inclination angle of generatrices amounting to 12°, assembled in a distance of 0.1 m from the initial edge of displacing section, is presented. Section was loaded with an impact mass falling from the height of 0.7 m.

Presented characteristics shows that application of the resistance wedge influences on the increase of value of force transmitted through the frictional joint (its load capacity). At the moment of contact of displacing section with the resistance wedge the value of this force significantly increases. In spite of the loss of impact energy for a yield in the part of the joint without the wedge, a large increase of value of force transmitted through the frictional joint was registered. Maximum value of this force for the part with the resistance wedge amounted to 615 kN.

Similarly as in a case of test of the frictional joints loaded statically, also at the dynamic loading very significant influence on the operational characteristics of the frictional joint have values of axial forces in the bolts of stirrups.
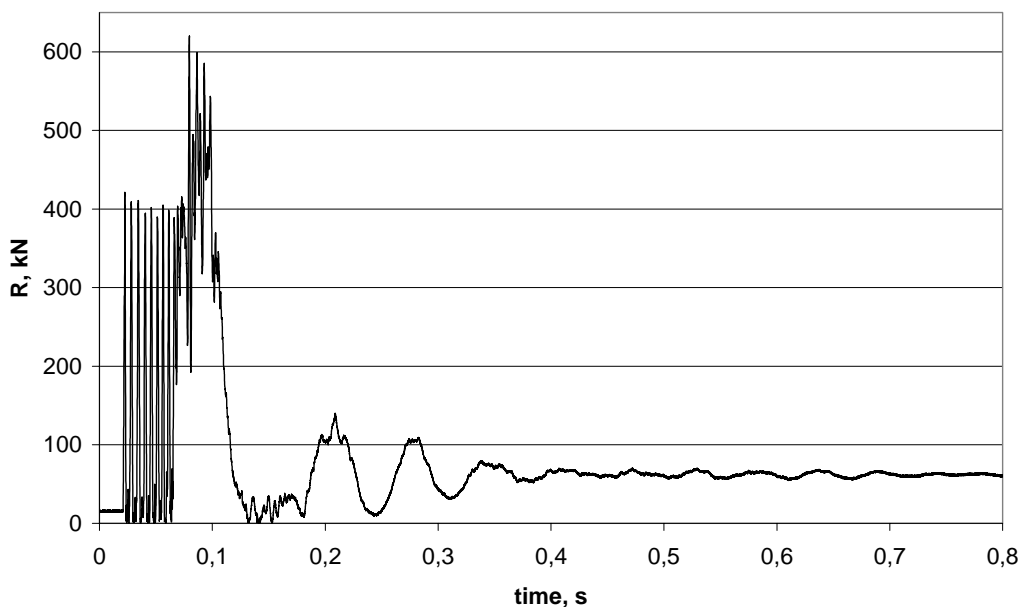
Fig. 9. Operational characteristic of the frictional joint with the resistance wedge assembled
in a distance of 0.1 m from the initial edge of displacing section

In order to determine the influence of resistance wedge on the change in value of axial forces
in the bolts of stirrups characteristics of changes in values of these forces for the frictional joints
with and without the resistance wedge are presented in a Figure 10. These characteristics were
determined for the frictional joints loaded with an impact mass falling from the height of 0.5 m
at initial values of axial force in each of the bolt of stirrup amounting to 82,5±2,5 kN.

In a case of the frictional joint with the resistance wedge we note an increase of values of
axial forces in the bolts of stirrups during a yield, what influences on the increase of value of the
force with which the cooperating sections are pressed against. It causes that load capacity of the
frictional joint increases with decreasing yield capacity, what in a case of dynamic loadings has
to be admitted as an advantage of the construction of a joint with the resistance wedge.

Dependences describing average percentage changes in values of axial forces in the bolts of
stirrups of the frictional joints with and without the resistance wedge after stabilization of a joint
(after time of 0.15 s from the beginning of a contact of an impact mass with the joint) towards
the initial values of these forces, are presented in a Figure 11.

On the basis of obtained results one can state that application of the resistance wedge in
the frictional joint causes an increase of values of axial forces in the bolts of stirrups without the
necessity of additional tightening up of bolts, what in a case of joints without the wedge is nec-
essary to ensure of proper pressing force of cooperating sections. Limitation of a drop of values
of axial forces in the bolts of stirrups after the occurrence of a yield in the joint influences also
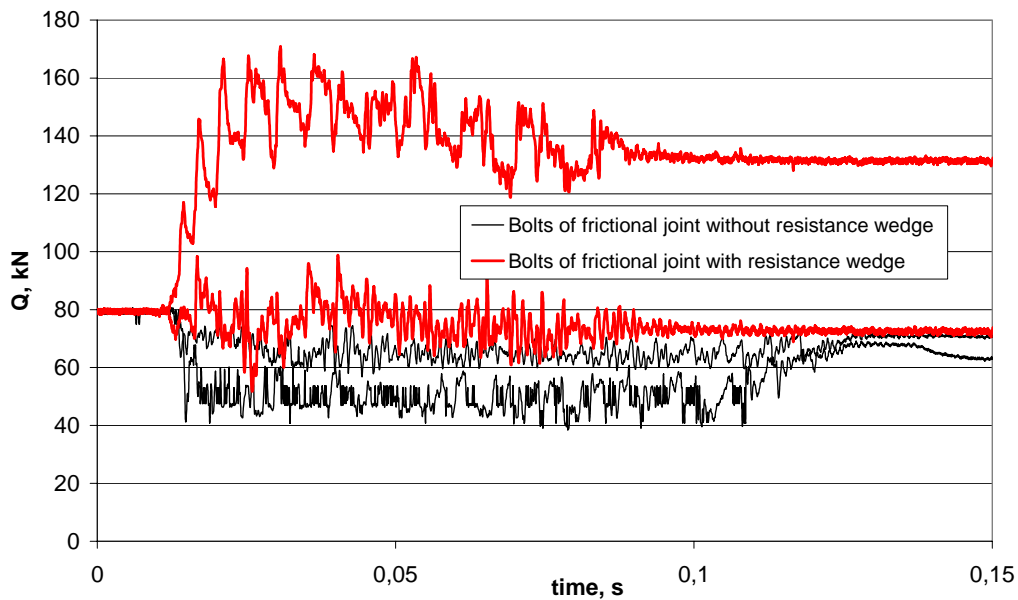on the maintenance of proper load capacity of the joint.

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Fig. 10. Change of value of axial forces in the bolts of stirrups for the frictional joint with
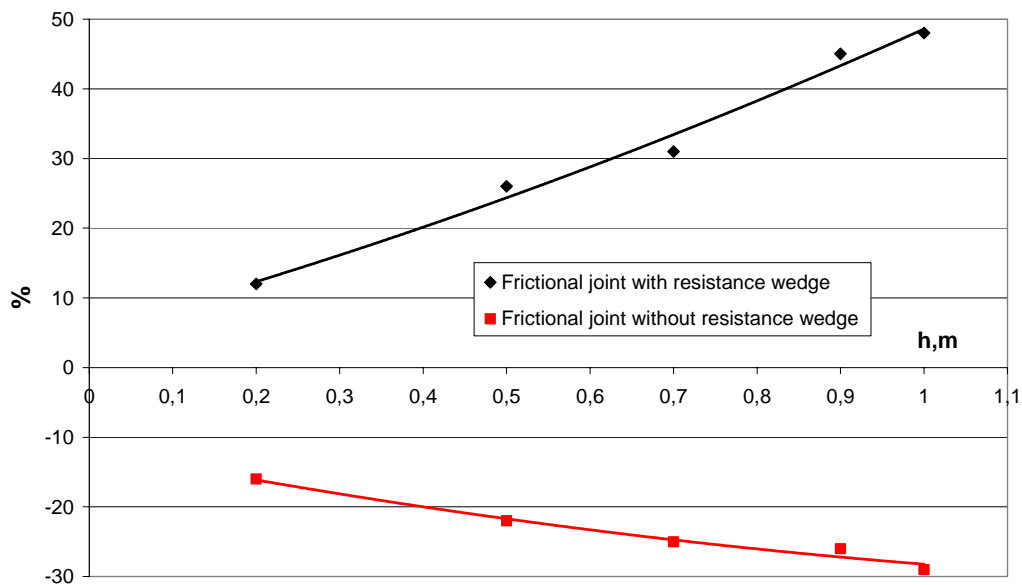and without the resistance wedge

Fig. 11. Changes of mean values of axial forces in the bolts of stirrups for the frictional joint with
and without the resistance wedge

5. Model tests of frictional joints with the resistance wedge

In order to describe analytically an operation of the frictional joint with the resistance wedge physical and mathematical models were developed. In a Figure 12 physical model and scheme of the frictional joint with the resistance wedge are presented.

At development of the physical model a discontinuous motion with a dry friction (Brodny 2011b; Leine et al., 1998; Nakano & Maegawa, 2009) and results of modelling of mechanized supports presented in work (Szweda, 2001) was taken into consideration.
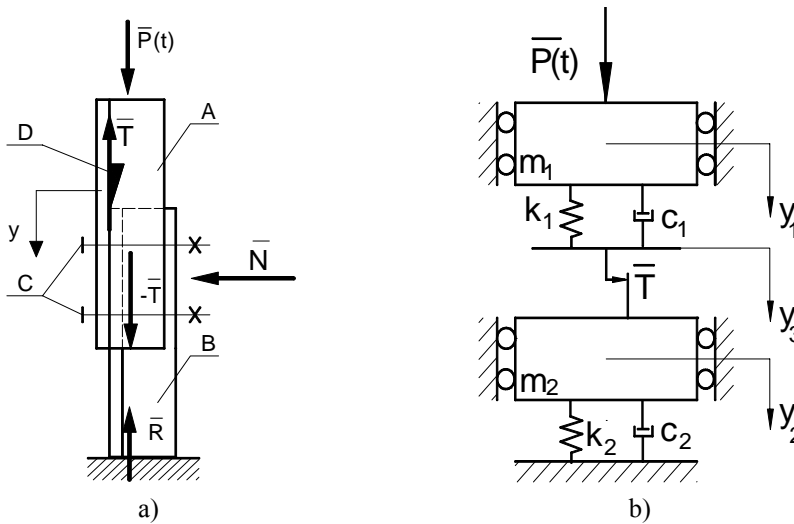

Fig. 12. Scheme (a) and physical model (b) of the frictional joint with resistance wedge

In this system frictional joint was modeled as two focused masses of cooperating sections (m_1 and m_2) each enlarged by the mass of one stirrup. Sections are pressed against with a force N, whose value is equal to the total value of axial forces in the bolts of stirrups.

Mathematical model, describing the movement of masses m_1 and m_2, and massless element around their equilibrium position forced by the loading $P(t)$ takes a form of a system of equations:

$$m_1 \cdot \ddot{y}_1 + k_1 \cdot (y_1 - y_3) + c_1 \cdot (\dot{y}_1 - \dot{y}_3) = P(t)$$
$$m_2 \cdot \ddot{y}_2 + k_2 \cdot y_2 + c_2 \cdot \dot{y}_2 - T = 0 \tag{1}$$
$$k_1 \cdot (y_1 - y_3) + c_1 \cdot (\dot{y}_1 - \dot{y}_3) - T = 0$$

where:
$k_1 = k_2$ — elasticity coefficients of sections, N/m,
$c_1 = c_2$ — damping coefficients of sections, kg/s.

To describe friction force the Coulomb's model was used. Value of friction force T is dependent on the pressure force N and on the value of static (μ_{st}) and kinetic (μ_k) friction coefficients between the surfaces of contacting sections. However, application of the resistance wedge causes that resistances to motion in the joint are much higher than resulting from the action of static and kinetic friction forces. Therefore, resistances connected with the action of resistance wedge were taken into consideration in equations describing the friction force. Distribution of friction force increased by the resistances connected with the action of resistance wedge is presented in a Figure 13a.
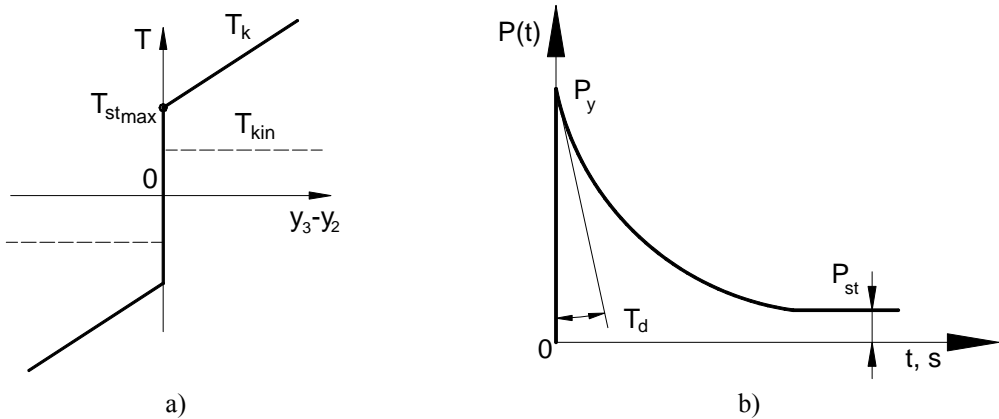

Fig. 13. Characteristics of friction force (a) and external force (b) acting on the frictional joint

General equation describing the changes in value of friction force with considered resistances connected with an operation of the resistance wedge has following form:

$$T = \begin{cases} T_{st_{max}} \cdot \mathrm{sgn}(W) & \text{for } \dot{y}_3 - \dot{y}_2 = 0 \text{ and } y_3 - y_2 = 0 \text{ and } |W| = T_{st_{max}} \\ W \cdot \mathrm{sgn}(W) & \text{for } \dot{y}_3 - \dot{y}_2 = 0 \text{ and } y_3 - y_2 = 0 \text{ and } |W| \langle T_{st_{max}} \\ T_k \cdot \mathrm{sgn}(\dot{y}_3 - \dot{y}_2), & \text{for } \dot{y}_3 - \dot{y}_2 \neq 0 \text{ and } y_3 - y_2 \neq 0 \text{ and } |W| \rangle T_{st_{max}} \end{cases} \quad (2)$$

where: $W = k_1(y_1 - y_3) + c_1(\dot{y}_1 - \dot{y}_3)$; $T_{st_{max}} = N \cdot \mu_{st}$; $T_k = f(a, y_3 - y_2)$

a — coefficient of increase of resistances to motion in the frictional joint.

Coefficient of increase of resistances to motion in the frictional joint is contingent on the geometrical parameters of the resistance wedge and on the magnitude of a yield in the frictional joint.

In analyzed model it was assumed, that its value will change from 0 to 0.3, what means that value of the friction force during a yield will not decrease below the maximum value of static friction force ($T_{st\,max}$).

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External active force $P(t)$ acting on the frictional joint with the resistance wedge is a result of composition of two exponential functions (Fig. 13b) and is describe by following equation:

$$P(t) = (P_y - P_{st}) \cdot e^{-\frac{t}{T_d}} + P_{st}(1 - e^{-\frac{t}{T}}); \quad \text{for} \quad T_d \gg T \tag{3}$$

where:

P_y — maximum value of dynamic impulse, kN,
P_{st} — value of fixed static loading, kN,
T_d — time constant of dynamic impulse decay, s,
T — time constant of component impulse decay, s.

Value of force transmitted through the frictional joint, which characterizes reaction of the base was determined from following relationship:

$$R(t) = c_2 \dot{y}_2 + k_2 y_2 \tag{4}$$

Developed mathematical model was subjected to numerical analysis, whose results allowed to determine the dynamic characteristics of the frictional joint with the resistance wedge determining the changes in value of force transmitted through the frictional joint ($R(t)$).

In order to determine the influence of the resistance wedge on the operation of the frictional joint, dynamic characteristics of the frictional joints with and without the resistance wedge are presented in a Figure 14.
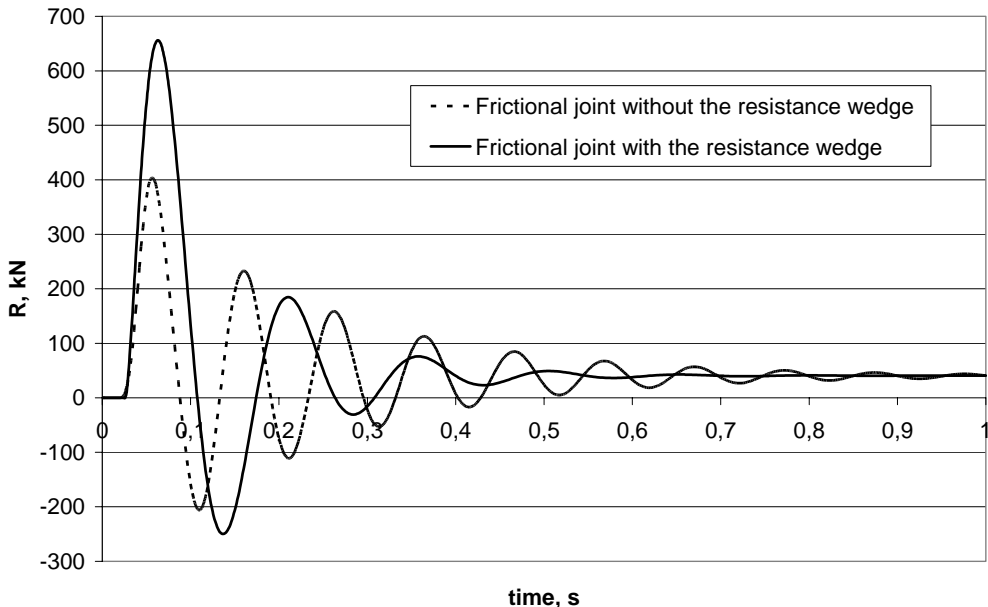

Fig. 14. Dynamic characteristics of the frictional joint with and without the resistance wedge

Analyzing obtained characteristics, one can state that similarly as in a case of stand tests, application of resistance wedge causes an increase of value of force transmitted through the frictional joint. The wedge causes an increase of resistances to motion, what according to equations (2) causes an increase of value of friction force in the frictional joint, what in turn influences on the increase of value of external force necessary to generate a yield in the joint.

Analyzing dynamic operational characteristics of the frictional joint with the resistance wedge obtained on the basis of stand tests of joint loaded with an impact of the mass (Fig. 6) and numerical analysis (Fig. 14), one can state that their similarity in the range of the course and obtained values. Maximum value of force (R_{max}) transmitted through the frictional joint with the resistance wedge, determined on the basis of numerical analysis amounts to 760 kN, and from the stand tests 785 kN.

Particular phases of frictional joint's operation determined on the basis of these characteristics are also similar. Differences between them result from simplifications of the model and the way of its loading. Due to permanent connection of mass elements of the frictional joint's model with the base, the value of force transmitted through the joint reaches negative values, and there not occur vibrations related to the breaking away of the joint from the base. Limitation of changes in value of force transmitted through the frictional joint, especially in the initial phase of loading, results also from the fact of acceptance of the external loading's characteristics in a form of one dynamic impulse.

Therefore, it can be assumed that developed model in correct way represents the real system in the range of determination of value of maximum force transmitted through the frictional joint, and of the damping time of this force.

Developed mathematical model of the frictional joint with the resistance wedge creates great possibilities of simulation of an influence of joint's parameters on its characteristics.

6. Summary and conclusions

Conducted studies and results obtained on their basis unequivocally indicate, that application of the resistance wedge as an additional constructional element in the frictional joint influences in significant way on its operational parameters.

Both in a case of static and dynamic loading in the frictional joints with the resistance wedge, an increase of value of force transmitted through them occurred, towards the joints without the resistance wedge.

Increase of values of forces transmitted through the frictional joint with the resistance wedge, so also its load capacity, with preservation of yield capacity, is a result of an increase of resistances to motion in the joint during the yield, and has to be admitted as positive effect of application of the resistance wedge.

Very significant meaning for the operation of the frictional joint with the resistance wedge, despite the decrease of values of yields in the frictional joint, has the preservation of proper yield capacity by this system.

In many cases at static loading of the frictional joint with the resistance wedge practically a continuous yield in the joint was registered. It causes that the frictional joint with the resistance wedge during a yield transmits in continuous way the external loading. Sudden unexpected large yields, which occur often in the joints without the resistance wedge, and during which the joint practically do not transmits any loading, undergo the limitation.

Such behavior is very dangerous in a case of dynamic loading of the frictional joint without the resistance wedge, because at the moment of beginning of a yield the value of force transmitted through the joint considerably decreases. Such phenomenon do not occur in a case of the joint without the resistance wedge, because shape of the wedge causes that with an increase of the displacement resistances to motion in the joint increase.

Analyzing operational characteristics of the frictional joint with and without the wedge, it has to be also emphasized that for the joint with the resistance wedge we observe greater damping of vibrations of the whole system. It is connected with the process of cutting and deformation of the resistance wedge and of deformation of cooperating sections, stirrups, and bolts.

These processes cause an increase of values of axial forces in the bolts of stirrups during the yield. It occurs in a case of static and dynamic loading of the joints, what has to be admitted as very positive phenomenon. It solves the problem of loosening of the bolts during the yields, which causes that values of forces with which the cooperating sections are pressed against, undergo the decrease. Its consequence is the unpredictable decrease of load capacity of the yielding steel frames and friction props.

Conducted studies proved also that through the change in geometrical parameters of the resistance wedge and the position of its assembly in the frictional joint related to the edge of displacing section, one can influence on the operational characteristics of the joint.

Proper selection of distances between the resistance wedge and the edge of displacing section causes, that the frictional joint can operate as late-bearing or immediate-bearing.

On the basis of stand tests physical and mathematical models of frictional joint with the resistance wedge were developed. Results obtained from the analysis of mathematical model testify on its good conformity with the real object. Especially in the range of determination of maximum values of forces transmitted through the frictional joint, obtained values do not diverge more than ca. 10 % from the values obtained in the stand tests. This testifies on the satisfactory accuracy of developed model.

Presented way of modelling of the frictional joint gives great possibilities of simulation of its operation in the field of change in the way and character of loading, and selection of physical parameters of the joint.

Despite that in the paper only the part of large amount of material obtained in stand tests and numerical analysis was presented, one can state that presented constructional solution of the frictional joint with the resistance wedge creates great possibilities of improvement of operational parameters of the frictional joints, and subsequently the whole yielding support of dog headings.

Practical application of this solution in the yielding steel frames and friction props should influence on more effective utilization of strength possibilities of frames' construction and influence on the improvement of the work safety in the mining.

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