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Jozef KUĽKA[1], Martin MANTIČ[2], Melichar KOPAS[3], Eva FALTINOVÁ[4], Leopold HRABOVSKÝ[5]

SIMULATION-EXPERTISE ANALYSIS OF ROPES USED IN THE HORIZONTAL BELAYING SYSTEM

Summary. This article deals with a dynamic simulation of the movement and fall of persons working at a height, using the rope belaying system. The input data, which are necessary for a created simulation model, were obtained from experimental measurements realised from the concrete belaying system. The simulation analyses were performed for three different values of the rope pre-load level. Consequently, the outputs from the simulations presented in this article were applied in a real design proposal of the rope anchoring arrangement for a horizontal belaying system.
Keywords: rope, horizontal belaying system, safety, FEM analysis

[1] Faculty of Mechanical Engineering, Technical University of Košice, Letná 9 Street, 042 00 Košice, Slovak Republic. E-mail: jozef.kulka@tuke.sk
[2] Faculty of Mechanical Engineering, Technical University of Košice, Letná 9 Street, 042 00 Košice, Slovak Republic. E-mail: martin.mantic@tuke.sk
[3] Faculty of Mechanical Engineering, Technical University of Košice, Letná 9 Street, 042 00 Košice, Slovak Republic. E-mail: melichar.kopas@tuke.sk
[4] Faculty of Mechanical Engineering, Technical University of Košice, Letná 9 Street, 042 00 Košice, Slovak Republic. E-mail: eva.faltinova@tuke.sk
[5] Faculty of Mechanical Engineering, Institute of Transport, Technical University of Ostrava, 17. Listopadu 15/2172 Street, 708 33 Ostrava - Poruba, Czech Republic. E-mail: leopold.hrabovsky@vsb.cz

1. INTRODUCTION

Modern methods and approaches, when applied within the individual phases of a machine whole life cycle, particularly, during the phase of projection, design, operation, repairs, maintenance and recycling, must take into consideration the safety requirements. Presently, there remains in operation, a large number of aged machines that were projected and produced several decades ago.

Although these machines are suitable enough from the viewpoint of durability and functionality, they are no longer reliable from the aspect of labour safety and health protection with regard to new safety rules; taking into consideration conditions determined for the safe movement of workers on the supporting structure of the given machine equipment. Every user of such machines and machinery has to ensure correction of occurred faults.

Operation and maintenance of overhead travelling cranes, which operate in open-air weather conditions, are typical examples with the above-mentioned problems. Entrance into the crane operator’s cab, which is usually situated at a height, as well as maintenance activities performed during the winter period, are especially dangerous with regard to the possibility of injury.

Therefore, it is necessary to install some suitable belaying system into the given working area in order to make the movement of the operating personnel safer. Described in this article, is the horizontal belaying system based on the application of steel wire ropes. This belaying system was successfully installed in a real bridge crane operation.

Various relevant aspects of the steel wire ropes are presented in the corresponding literature. The publications [1, 2] dealt with steel wire ropes, taking into consideration the general principles of their operation and safety.

Possible causes of rope damage were explained in professional works [3, 4, 5, 6, 7]. Similarly, analyses of the stress state and operational loading, as well as failure analyses of steel wire ropes have been published in other articles [8, 9, 10].

These were described in the papers [11, 12], the mathematical and geometrical models developed for computer simulation of steel wire ropes. The dynamic non-linear simulations, which were performed using the Finite Element Methods (FEM), were presented in these articles [13, 14, 15, 16, 17].

Specific approaches to the solution of mechanical vibrations as well as to the detection of failures in the various mechanical systems are illustrated in these publications [18, 19, 20].

2. MATERIALS AND METHODS

In this work, a special horizontal belaying system (HBS), the horizontal rope belaying system, which was proposed and applied in a real metallurgical plant was described and analysed. This plant consists of several production halls equipped with various kinds of bridge cranes. There exist three possibilities on how to realise anchorage of the proposed rope belaying system:

a) anchoring between steel columns.
b) anchoring between concrete columns.
c) anchoring without columns.

Bearing capacity of the anchoring equipment of the type C category (category of the proposed system), which is given as the dynamic force value, has to be 12 kN at least according to the technical standard STN EN 795. Hence, it was necessary to determine the real loading of the rope and connecting elements or more precisely, investigate what heavy loading of the rope and joining elements corresponds to this force.

There were calculated reactions in the connecting points of the main rope (that is, horizontal rope), forces in the rope as well as the deflection of the rope during loading caused by the vertical force 12 kN. This vertical force was acting in various distances from the supports using a pre-load in the rope with the values of the pre-load forces from 0.2 kN to 20 kN. Simultaneously, it calculated a change of the pre-load due to increase or decrease of the ambient temperature. The diameter of the applied main rope was 14 mm.

The calculations were performed by means of the Finite Element Method (FEM) and utilising the software product COSMOS/M, version 2.7. The main rope ∅14 was simulated using the bar elements of type TRUSS2D [21].

2.1. Calculation Methodology during Dynamic Loading of Anchorage Rope

The calculation model of HBS, which was proposed for simulation of the static and dynamic loading of the guide, is schematically illustrated in Fig.1. The horizontal guide PV (that is, the main rope) is simulated by means of two-nodal planar bar elements considering a non-linear elastic material and large displacements. These elements are specified in the software, COSMOS/M, under the designation TRUSS2D [21]. The same elements were used for simulation of the attachment rope SL.

An advantage of FEM is the possibility of relatively easy simulation concerning other related parts, which are situated within the supporting structure, taking into consideration the stiffness of the whole system. In the simplest case, it was enough to apply a solid connecting for the ends of the guide, according to Fig.1.

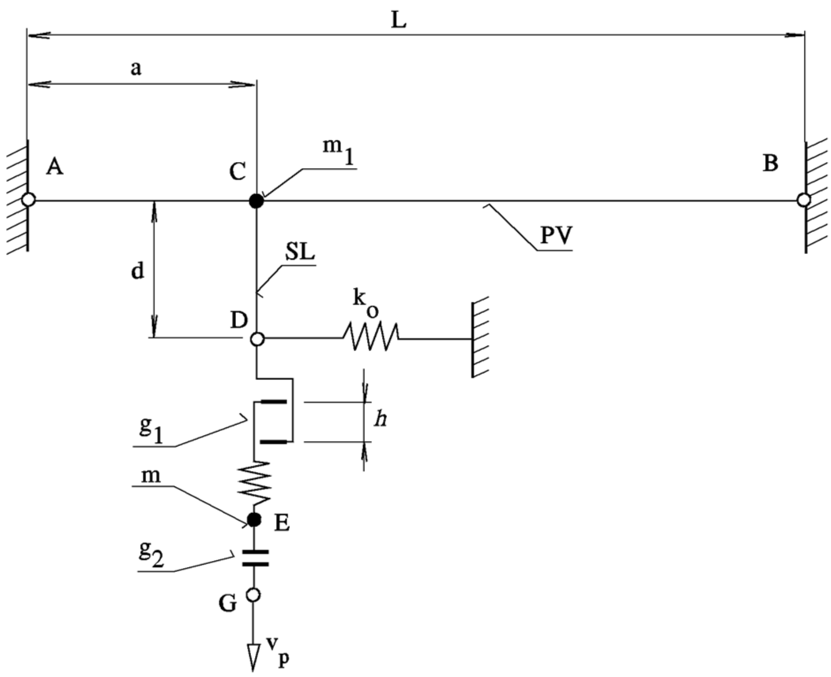

Fig. 1. Calculation model of HBS with a stiff support of guide

The calculation model also includes the single-node elements of the type MASS in order to simulate the concentrated masses that replaced a ballast weight, which represents a falling person (that is, the mass m in Fig.1) as well as to replace the snap hook m1 of the attachment rope.

Also implemented into the calculation model were elastic springs, which limits the horizontal displacements of the ballast weight in order to eliminate a singularity. The stiffness of these springs is very small (the stiffness value is k0 $\approx$ 10-5 N/mm), which means, mathematically, that a very small numerical value is substituted into the diagonal element of the stiffness matrix so that a singularity of the given matrix can be eliminated.

A free fall of the ballast weight from height h was simulated by means of the contact elements of the type GAP. These elements are two-node elements, which carry the load unilaterally, either in pressure or in tension. At the same time, it is possible to simulate the stiffness-damping characteristics of these elements in such a way that the carried force is given by the following relation:

$$F = F_0 + k(u_{rel} - u_0) - c(\,|v_{rel}|\,)^s \operatorname{sign} v_{rel} \quad , \tag{1}$$

where F_0 is pre-loading force, k is stiffness of the spring, u_{rel} is relative displacement of the nodes, u_0 is relative displacement at the beginning of the contact, v_{rel} is relative speed of the nodes, the constants c and s are the damping characteristics.

The above-mentioned properties enable the application of the GAP elements (in the case of a parallel connection) also for simulation of the fall dampers. The elastic properties of the elements were considered in this case only, whereby the value of stiffness k was chosen as the highest value with regard to a minimal influence on the dynamic response of the analysed system.

The stiffness of the element g_1, which is situated between the attachment rope and the ballast weight, was defined as 10-times higher than the stiffness of the attachment rope.

A free fall of the ballast weight was simulated using the contact element g_2 with the vertical displacement v_p, which was given in advance.

The solution of the system response consists of two phases. Overhang of the guide, which is caused by own weight, was determined in the first phase, using a static analysis and applying the given initial pre-load. The response after the fall of the ballast weight from height *h* was investigated during the second phase, utilising the dynamic analysis applied for the given configuration. The free fall of the load was simulated by a prescribed movement of the nod *G* downward, whereby the movement speed was significantly higher than the free fall speed.

The geometrical and physical non-linearity was also taken into consideration during the calculation. The geometrical non-linearity was given due to the unknown new configuration of the system in every calculation phase. Therefore, the created equations are non-linear with regard to unknown node displacements. The physical non-linearity results from a non-linear dependence between the deformation and the force in the rope.

The dynamic analyses were performed by means of Newmark's method. This implicit method enables the inclusion of the damping characteristics of the contact elements in order to simulate a fall damper. The value of time increments was chosen with regard to the accuracy and stability of the solution. Every implicit method, that is, including the Newmark's method, offers a numerical stability of calculation only in the case of linear methods. The numerical stability of the calculation process can be lost during the solution of the non-linear methods if the time step is chosen improperly, that is if it is too long.

A possible compromise offers the time increment, which is chosen from the interval 10-5 ÷ 10-4 s. This was also applied in several performed analyses of the Rayleigh damping:

$$\mathbf{C} = \alpha\,\mathbf{K}_0 + \beta\,\mathbf{M}\ , \tag{2}$$

whereby, in the matrix of damping **C**, it was considered the coefficient α, which is associated with the initial matrix of stiffness $\mathbf{K}_0$. This coefficient was chosen from the range 0.001 ÷ 0.05. The damping, which is related to the matrix of mass **M**, was neglected, so the coefficient $\beta = 0$.

The main task of this analysis was to investigate the individual characteristics of the horizontal belaying system in order to consider a necessity of changes concerning the individual constructional modifications of the given system, which is utilised in practice by the operator of the crane.

The individual analyses were based on information obtained from realised measurements, principally from information about the stiffness properties of the individual ropes and suspended components of the personal protective equipment applied in the constructional modifications of the horizontal belaying system. The tensile test was performed in the case of the attachment textile rope with the diameter 11 mm and length 570 mm, which is delivered together with the safety belts of the type TIMUS SAFETY: 048/414082023.

Working diagram of the main rope ∅14 is presented in Fig. 2, working diagram of the textile attachment rope ∅ 11 is given in Fig. 3 and the calculation of the working diagram of the same rope is shown in Fig. 4.

The loading regimes of the HBS were defined according to the technical standard STN EN 795. Evaluation of the welding joints and screw joints in the individual constructional modifications of the HBS was performed according to the STN EN 1993-1-8 (Eurocode 3: Design of steel structures. Part 1.8: Design of joints).

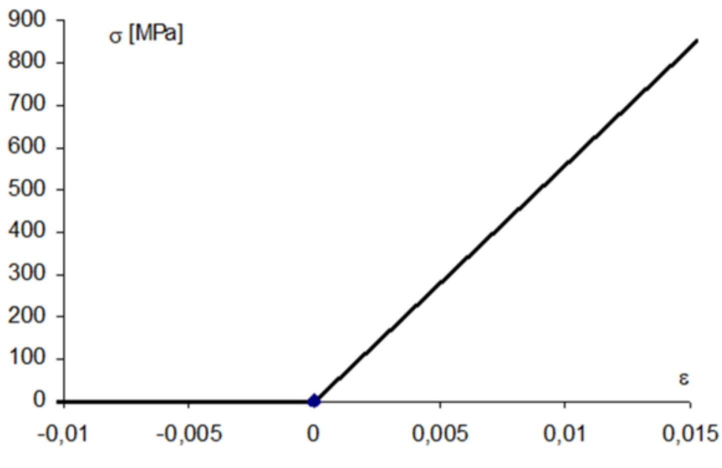

Fig. 2. Working diagram of the rope ∅ 14, used for calculation

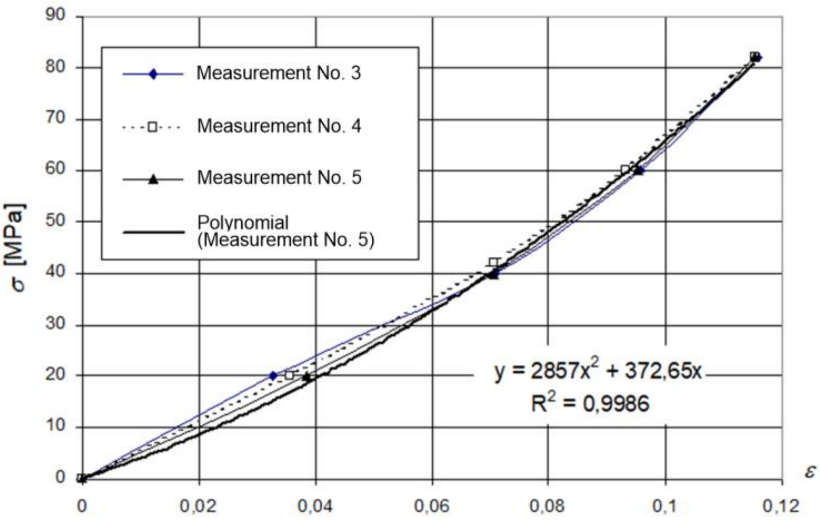

Fig. 3. Working diagram of the textile attachment rope ∅ 11

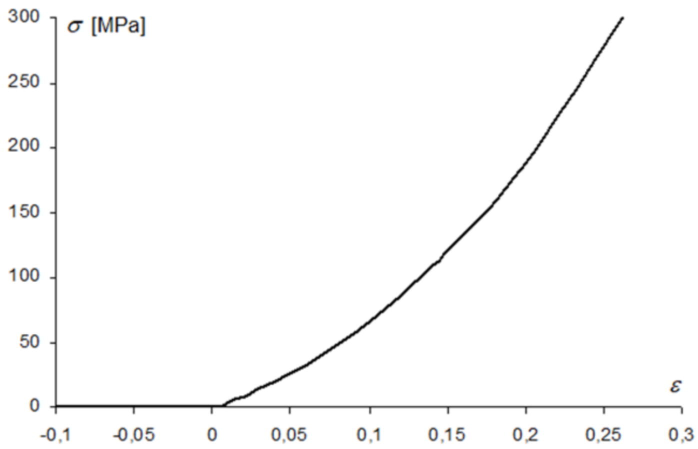

Fig.4. Calculation of the working diagram of the textile attachment rope ∅ 11

2.2. Deflection of Rope

2.2.1 Deflection of Rope Caused by Own Weight

The technical standard STN EN 795 determines a bearing capacity of the HBS of type C as the minimal dynamic force 12 kN. The main task of the performed calculations was to investigate what a heavy loading of the rope and joining elements corresponds to this force. There were calculated reactions in the connecting points of the horizontal rope, forces in the rope as well as the deflection of the rope during loading by the vertical force 12 kN. This vertical force was acting in various distances from supports using the pre-load of the rope with the values from 0.2 kN to 20 kN. Simultaneously, it was calculated as a change of the pre-load due to increase or decrease of the ambient temperature. The modulus of elasticity, EL, of the rope was measured during the tensile test, basically this value is EL = 55835 MPa. The used coefficient of thermal expansion was 1.2 x 10-5 K-1. The nominal cross-sectional area of the applied rope is 69.17 mm^2 and own weight of the rope is 0.64 kg m^{-1}, according to the catalogue of the rope producer [22]. The rope was anchored between the steel columns.

The calculations were performed by means of the FEM method, applying the software product COSMOS/M, version 2.7. The main rope ∅14 was simulated using the bar elements of the type TRUSS2D [21].

The values of the main rope deflection, which is caused by own weight and by the pre-load forces selected from the interval (0.2 kN ÷ 20 kN), are given in Tab. 1 (for the rope with span length 12 m) and in Tab. 2 (for the rope with span length 18 m). Dependence of the main rope deflection on the pre-load force is illustrated in Fig. 5.

These are the symbols used in the tables:

- $\boldsymbol{L}$ span length of the rope.
- $\boldsymbol{F_0}$ pre-load of the rope at zero deflection (that is, pre-load without acting of the weight).
- $\boldsymbol{v_0}$ deflection of the rope (deflection caused by the rope's own weight).
- $\boldsymbol{v_3}$ deflection of the rope after increase of the ambient temperature about 50 K.
- $\boldsymbol{v_4}$ deflection of the rope after decrease of the ambient temperature about 50 K.
- $\boldsymbol{R_1}$ force in the rope at the deflection v_0.
- $\boldsymbol{R_3}$ force in the rope after increase of the ambient temperature about 50 K.
- $\boldsymbol{R_4}$ force in the rope after decrease of the ambient temperature about 50 K.

Tab. 1

Deflection of the rope with span length 12 m

***L* = 12 m**						
$\boldsymbol{F_0}$ [kN]	$\boldsymbol{v_0}$ [mm]	$\boldsymbol{v_3}$ [mm]	$\boldsymbol{v_4}$ [mm]	$\boldsymbol{R_1}$ [kN]	$\boldsymbol{R_3}$ [kN]	$\boldsymbol{R_4}$ [kN]
0,2	108,5	194,3	42,7	1,042	0,583	2,648
0,4	100,6	187,7	39,2	1,124	0,603	2,830
0,6	92,9	181,0	37,5	1,217	0,625	3,018
0,8	85,5	174,1	35,2	1,323	0,650	3,206
1	78,5	167,0	33,3	1,440	0,678	3,397
1,5	63,3	148,6	29,1	1,787	0,761	3,880
2	51,6	129,1	25,9	2,191	0,876	4,365
3	36,5	89,8	21,1	3,095	1,259	5,349
5	22,4	40,4	15,4	5,036	2,799	7,334
10	11,3	14,7	9,2	10,010	7,698	12,320
15	7,5	8,9	6,5	15,000	12,690	17,320
20	5,7	6,4	5,1	20,000	17,690	22,320

The graphs in Figures 6 and 7 illustrate rope deflection and influence of the changed temperature on the pre-load value in the case of two rope lengths: 12 and 18 m. The line T 50 represents the percentage decrease of the force R_1 after continual increase of the rope temperature about 50 K, while line T –50 represents the percentage increase of this force after the decrease of the rope temperature to about 50 K. It is evident that in the case of higher pre-load level that there is reduced influence with the temperature changes.

Influence of the temperature changes are important above all for such ropes, which are installed out-of-door and exposed to weather conditions. The actual ambient temperature should be taken into consideration during the initial pre-loading of the rope.

Tab. 2

Deflection of the rope with span length 18 m

***L* = 18 m**						
F_0 [kN]	v_0 [mm]	v_3 [mm]	v_4 [mm]	R_1 [kN]	R_3 [kN]	R_4 [kN]
0,2	189,5	304,8	91,4	1,343	0,836	2,783
0,4	179,1	295,7	86,1	1,420	0,862	2,953
0,6	168,9	286,4	81,3	1,507	0,889	3,128
0,8	158,8	276,9	76,9	1,602	0,920	3,306
1	149,5	267,2	72,9	1,707	0,953	3,487
1,5	126,6	242,4	64,4	2,010	1,050	3,949
2	107,4	216,6	57,5	2,367	1,175	4,423
3	79,4	164,7	47,2	3,201	1,545	5,388
5	50,1	87,0	34,6	5,080	2,924	7,355
10	25,4	33,0	20,6	10,020	7,717	12,330
15	16,9	20,0	14,7	15,010	12,700	17,320
20	12,7	14,4	11,4	20,010	17,690	22,320

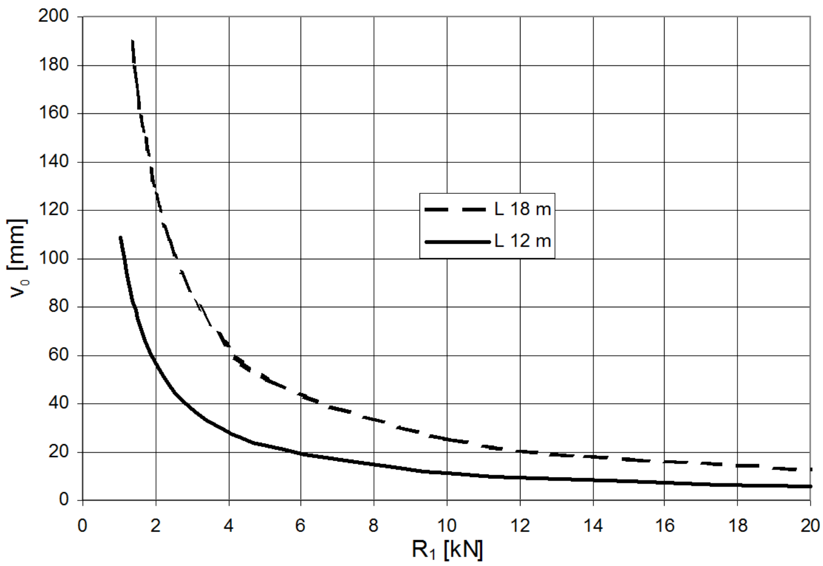

Fig. 5. Dependence of the rope ∅14 mm deflection on the pre-load force

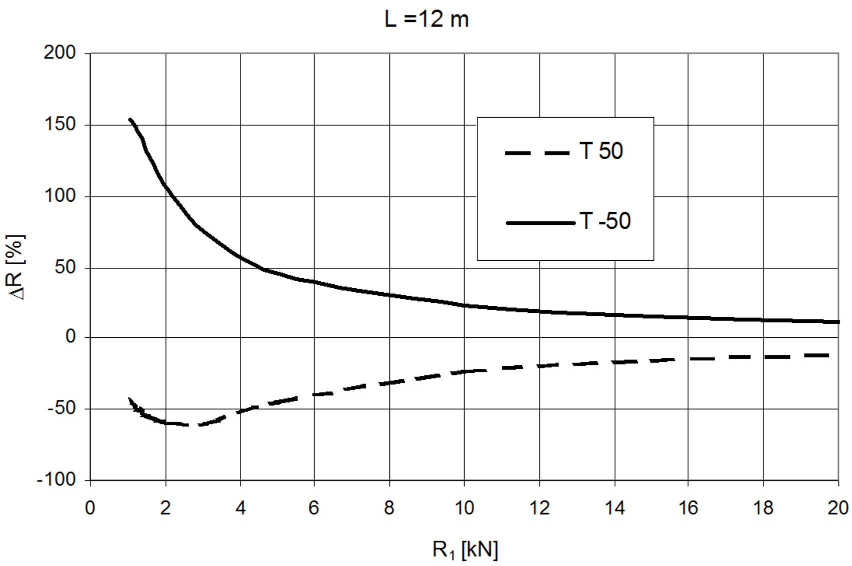

Fig. 6. Influence of changed temperature on pre-load of rope with the length 12 m

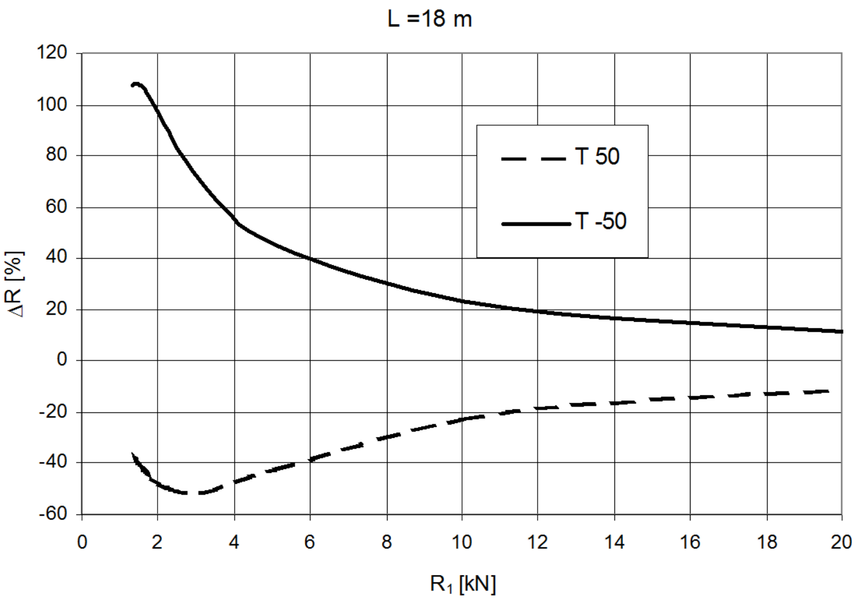

Fig. 7. Influence of changed temperature on pre-load of rope with the length 18 m

2.2.2 Deflection of Rope Caused by the Loading Force 12 kN

Deflection of the rope in the point of action for the single vertical force with the value 12 kN depends on the pre-load value R_1 and on the point of action position as well. Fig. 8 illustrates this dependence for the rope with length 12 m. The symbol a, marks the distance of the point of action from the left end of the rope. It is obvious that the position of the load influences the value of deflection quite significantly, as such an influence of higher pre-load on reduction of the deflection is non-significant.

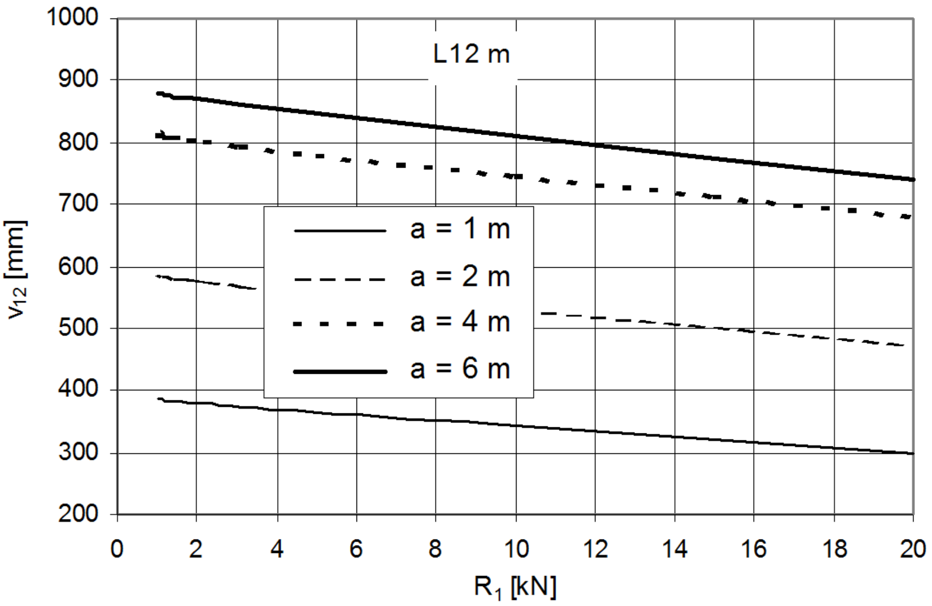

Fig. 8. Dependence of deflection on the acting point of the force 12 kN

Analogical dependence of the deflection on the load position, using various pre-load values for the rope with length 18 m, is shown in Fig. 9.

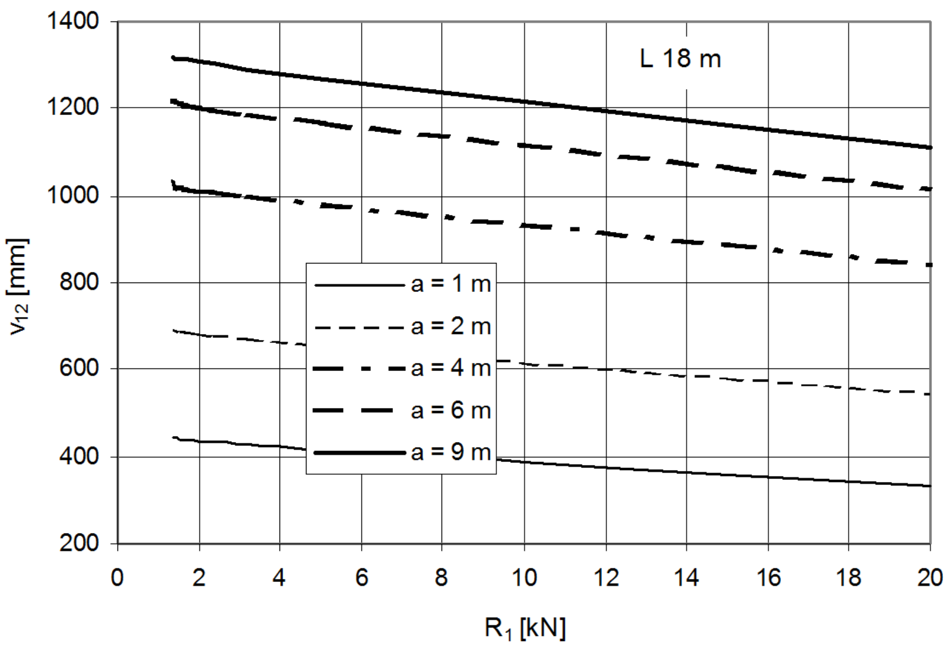

Fig. 9. Dependence of deflection on point of action position for the rope with span length 18 m

A maximal deflection is recorded if the load is situated in the middle of the span length. Dependence of the deflection on the load position (which is given by the distance a, measured from the left support) is non-linear, according to Fig. 10.

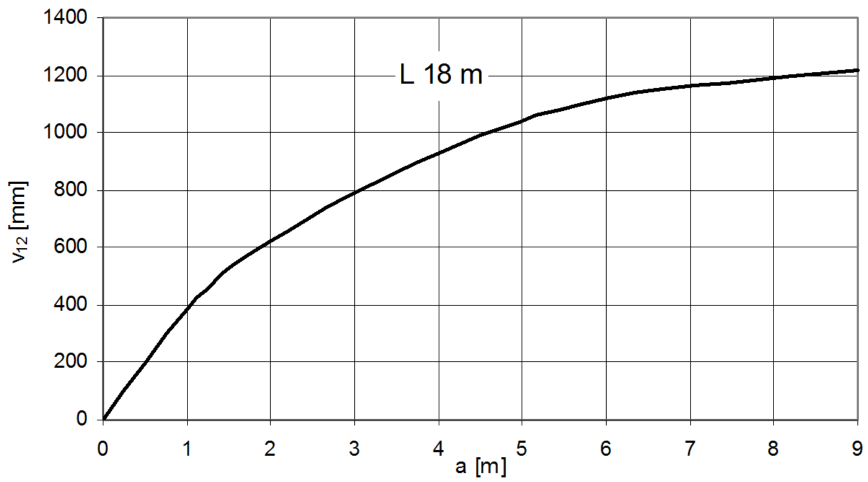

Fig. 10. Dependence of rope deflection on position of the load (using the pre-load value 10 kN and span length 18 m)

2.3. Horizontal Belaying System with Rope ∅ 14 mm

The following values of the input parameters were used in order to simulate the process of capture in the case of the falling load

- span length of the anchoring guide 12 m
- mass of the falling balance weight 200 kg
- length of attachment rope 600 mm
- number of attachment ropes 2
- free-fall height 300 mm

These values were applied during the performed calculations, the already obtained characteristics of the steel wire rope, which is used as the anchoring guide and the characteristics of the textile attachment ropes.

These mechanical properties described earlier were measured during the experimental tests. According to the calculated results, it is safe to assume that the force in the anchoring guide, as well as the force in the attachment rope, together with the maximal deflection of the balance weight, depends on the pre-load level in the anchoring guide. This is also presented as an influence of the attachment rope position on the anchoring guide.

The graphs in Figures 11, 12 and 13 illustrate the influence of the attachment rope position, which is given by the coordinate a (according to Fig. 1), on the dynamic response. The highest force Fmax in the rope of the anchoring guide occurs in such situation when the attachment rope is positioned in the middle of the guide span length (Fig. 11). Analogically, the same is true for the maximal dynamic deflection vmax of the ballast weight (Fig. 12). The highest force in the attachment rope (in this case, it is a sum of the forces in the two attachment ropes) occurs if the attachment rope is positioned at the end of the anchoring guide (Fig. 13).

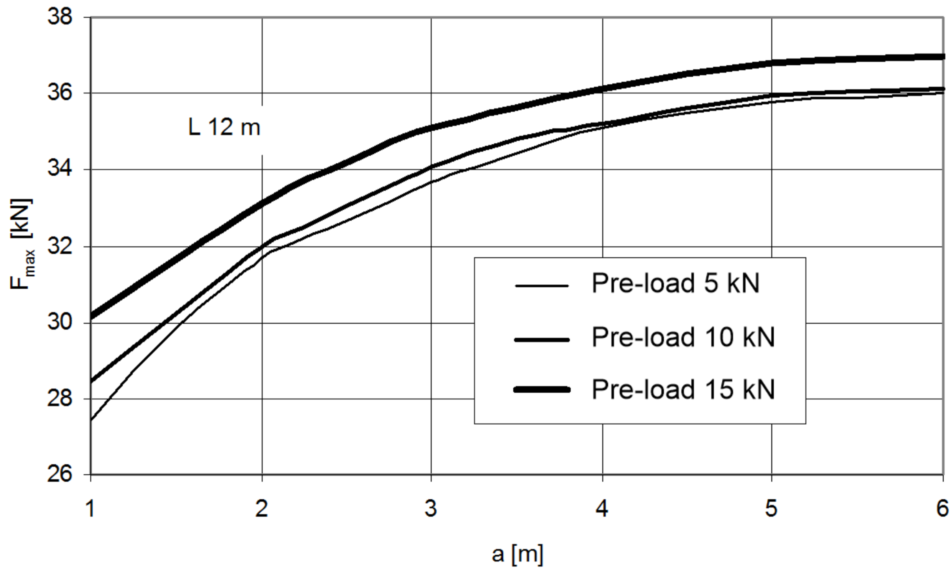

Fig. 11. Maximal force in the anchoring guide rope with the span length 12 m

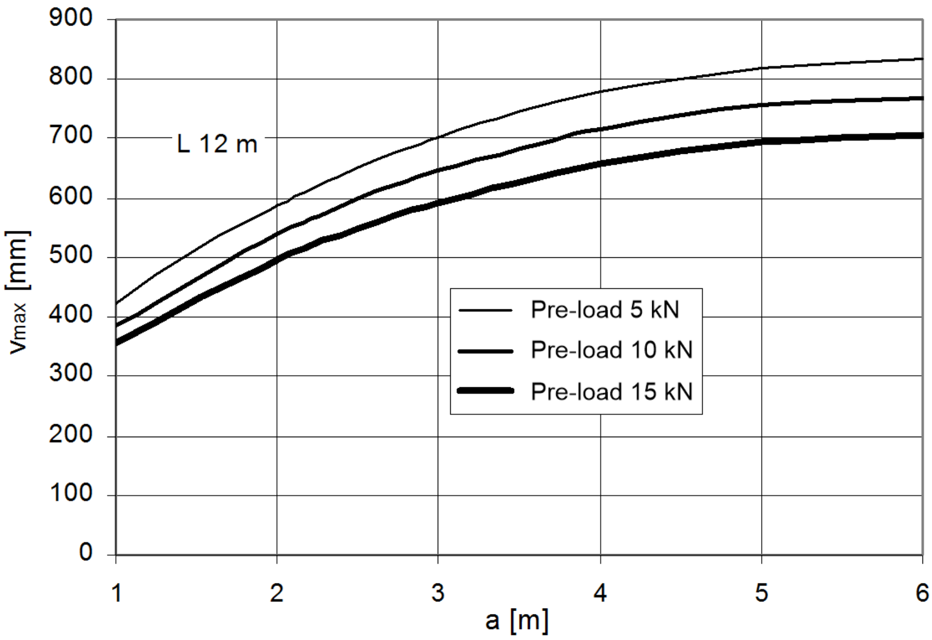

Fig. 12. Maximal deflection of the rope with the span length 12 m

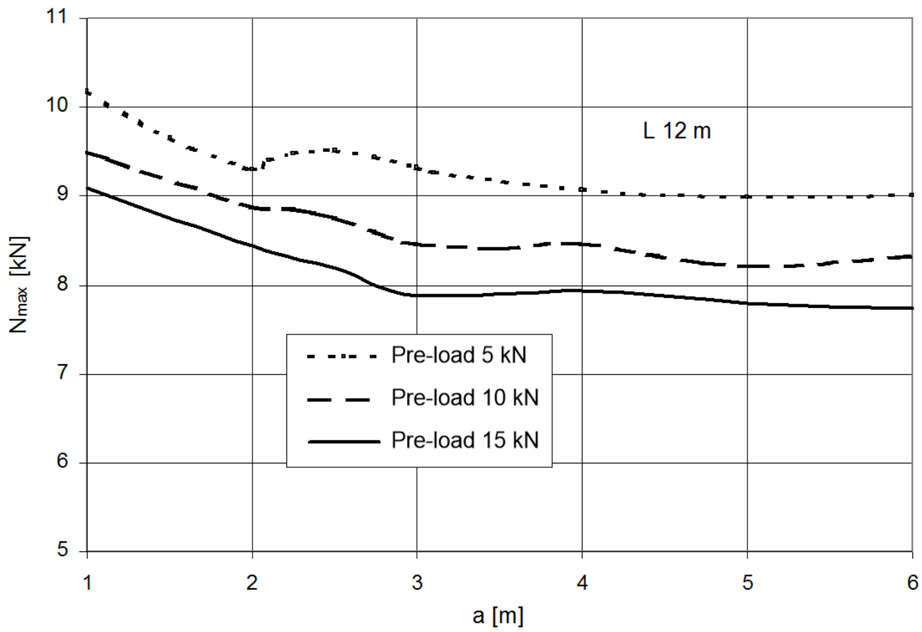

Fig. 13. Dependence of maximal force in the attachment rope on its position

4. CONCLUSION

We introduced in this article the possibility of increase labour safety of a specific machinery, installed at a height, by means of a simple design solution and by use of standard constructional components, for example, rolled shapes, rope, rope clamps, rope sockets and tensioning screws.

The presented analyses were based on information obtained from measurement of the stiffness properties of the ropes and suspension elements which were utilised in the personal protective equipment applied in the proposed design solutions of the HBS. It is presumed, according to the obtained results, loading analyses and strength calculations of the given HBS, that this system has the possibility of serving as anti-falling protection for 2 or 3 persons. Hence, the dynamic loading of the HBS will be lower than as defined in the technical standards [23] and [24].

The most unfavourable situation occurs if the vertical loading force F is acting in the middle of the span length. The limited application possibility of HBS is defined by internal prescriptions based on the above-mentioned analyses and this requires an experimental verification of the strength by means of a real test.

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