



Volume 104

2019

p-ISSN: 0209-3324

e-ISSN: 2450-1549

DOI: <https://doi.org/10.20858/sjsutst.2019.104.10>



Journal homepage: <http://sjsutst.polsl.pl>

Article citation information:

Mantič, M., Kulka, J., Faltinová, E., Kopas, M., Lumnitzer, J. Simulation analysis of rope belaying system. *Scientific Journal of Silesian University of Technology. Series Transport*. 2019, **104**, 107-117. ISSN: 0209-3324. DOI: <https://doi.org/10.20858/sjsutst.2019.104.10>.

**Martin MANTIČ¹, Jozef KULKA², Eva FALTINOVÁ³, Melichar KOPAS⁴,
Ján LUMNITZER⁵**

SIMULATION ANALYSIS OF ROPE BELAYING SYSTEM

Summary. This article describes a technical proposal of anchoring determined for a horizontal belaying system, which was developed to increase the safety of crane operators and maintenance staff in their movements and work at heights. This belaying system can be installed either on the common, already existing footbridge of the overhead travelling crane or on the crane track. Loading of the steel wire rope was investigated by the simulation figurines during various assumed loading regimes. The figurines were attached to the rope belaying system by means of the standard personal protective equipment and the calculation process was realised using the non-linear dynamic FEM analysis.

Keywords: rope, safety, non-linear dynamic FEM analysis, simulation.

¹ Faculty of Mechanical Engineering, Technical University of Košice, Letná 9 Street, 042 00 Košice, Slovak Republic. Email: martin.mantic@tuke.sk

² Faculty of Mechanical Engineering, Technical University of Košice, Letná 9 Street, 042 00 Košice, Slovak Republic. Email: jozef.kulka@tuke.sk

³ Faculty of Mechanical Engineering, Technical University of Košice, Letná 9 Street, 042 00 Košice, Slovak Republic. Email: eva.faltinova@tuke.sk

⁴ Faculty of Mechanical Engineering, Technical University of Košice, Letná 9 Street, 042 00 Košice, Slovak Republic. Email: melichar.kopas@tuke.sk

⁵ Faculty of Mechanical Engineering, Technical University of Košice, Letná 9 Street, 042 00 Košice, Slovak Republic. Email: jan.lumnitzer@tuke.sk

1. INTRODUCTION

Technical solution of the problems, which were presented in this article, resulted from a requirement concerning safe entrance to the crane-operator's cab of a bridge crane as well as safe maintenance of the crane and crane track. It is necessary to emphasise an important fact that entry 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. Taking into consideration the above-mentioned facts, it was developed in an original horizontal rope belaying system, which is presented and analysed in this article, in the form of a created simulation model. Under real conditions, this horizontal belaying system (HBS) should be anchored using one of the three possibilities:

- a) anchoring between the steel columns
- b) anchoring between the concrete columns
- c) anchoring without the columns by means of own supporting structure

Bearing capacity of the anchorage equipment of type C (this is the category of the proposed equipment), which is considered as the value of dynamic force, has to be 12 kN at least in accordance with the technical standard STN EN 795. It was necessary, as the first step, to investigate what 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 and deflection of the rope during loading by the vertical force 12 kN, which is acting in various distances from the supports, using a pre-load in the rope with the values from the interval 0.2 kN ÷ 20 kN. At the same time, it was calculated as change of the rope pre-load value due to an increase or decrease of the ambient temperature. The value of the anchorage rope diameter, which was used for the calculations and also in the simulation model, was 14 mm.

Various relevant aspects of the steel wire ropes were presented in the corresponding literature. The publications [1, 2, 3] dealt with steel wire ropes, taking into consideration the general principles of their operation and safety. Possible causes of rope damage are described in professional works [4, 5, 6, 7, 8]. Similarly, analyses of the stress state and operational loading, as well as failure analyses of the steel wire ropes, are shown in publications [9, 10, 11, 12]. Described in these papers [13, 14, 15], are the mathematical and geometrical models developed for a computer simulation of the steel wire ropes. The dynamic non-linear simulations, which were performed using the Finite Element Methods (FEM), are presented in the articles [16, 17, 18, 19, 20].

Original methods developed for the solution of questions concerning mechanical vibrations and detection of failures occurring in the mechanical systems are illustrated in the publications [21, 22].

2. MATERIALS AND METHODS

There are two possibilities in the case that the rope belaying system is anchored along the crane track:

- anchoring to the steel columns of the hall (the distance between the columns was 12 m and 18 m)
- anchoring to the supporting concrete columns of the hall (the distance between the columns also was 12 m and 18 m)

Connection of the steel wire rope to the steel column of the hall was achieved by means of the anchorage point, which was fixed to the sidewall of the column, according to Fig. 1.

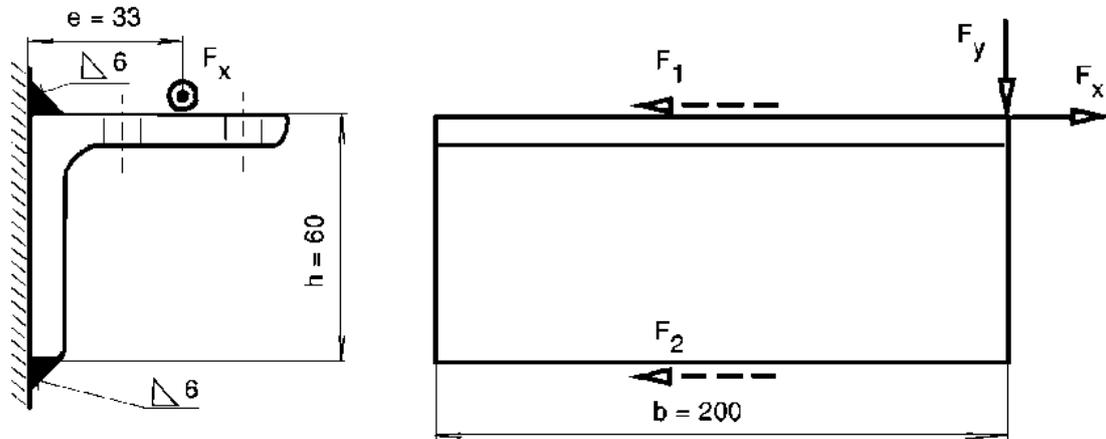


Fig. 1. Connection of the horizontal belaying system to the sidewall of the column

Connection of the rope to the concrete column of the hall (two concrete pillars arranged side-by-side) was realised by means of the connecting bolts with the thread M12 in order to tighten the auxiliary construction of the anchorage point, according to Fig. 2.

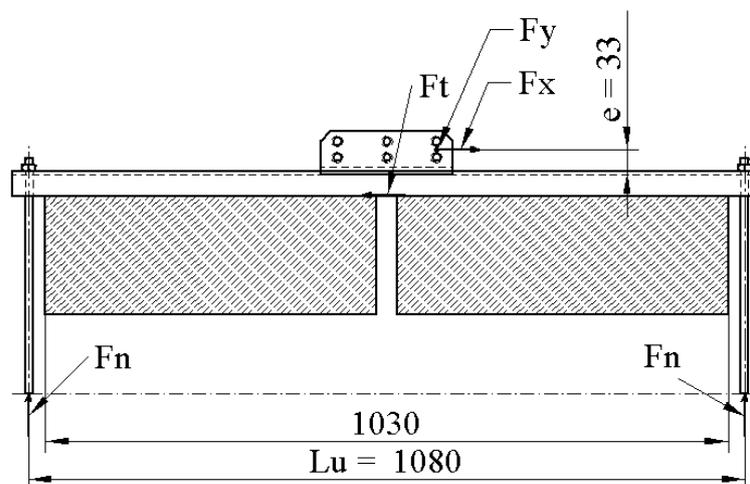


Fig. 2. Anchorage to the double concrete column

There was a proposed new, own-developed supporting structure determined for movement of the crane operating personnel or maintenance staff on the crane, whereby the distance between the neighbouring supports was 5 m (Fig. 3).

The technical standard STN EN 795 defines the bearing capacity for the analysed anchorage equipment of type C as the dynamic force with the minimal value 12 kN. Other conditions, which must be fulfilled according to Chapter 4.3.3 from the given technical standard, are as follows:

- the minimal strength of the rope has to be two-times higher than the highest acceptable force, which occurs during the capturing of a fall

- all other supporting components and anchorage guide have to be dimensioned with regard to a double-value of the force, which occurs in these parts during the capturing of a fall.

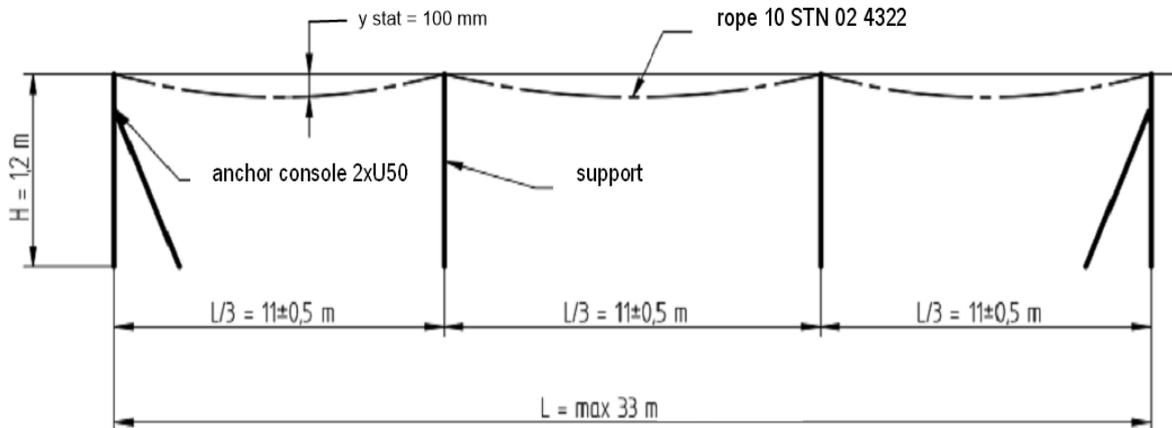


Fig. 3. Own-developed construction situated on the walkway of the crane

The individual loading-level values, which were applied in the strength calculations, respected the above-mentioned technical standard.

2.1. Simulation of loading for the HBS during fall of persons – computational model

Calculation of loading for the HBS was realised according to the crane user requirement, taking into consideration the real loading conditions, that is, maximally 3 persons are moving on the walkway at the same time and the maximal weight for each of them is 100 kg. The calculation procedure was performed for the most unfavourable arrangement of the HBS, using the steel wire rope with diameter $\varnothing 14$ mm [21] and with span 18 m, whereby there is a possibility that several workers are moving together within one section. The computational model was created using the MSC Motion software, which is specified for the solution of dynamic systems.

Mechanical characteristics of the belaying (anchoring) rope and suspension component were simulated by a system of individual mass points that represents the weight of the ropes and connecting elements. The stiffness characteristics of the ropes are represented in the model by means of the springs with the stiffness values corresponding to the applied components, obtained by measuring. The persons (their human bodies) are simulated by means of the anthropometric figurines. The complete computational model is illustrated in Fig. 4.

Two stereometric computational models with different simulation of figurine properties were created to represent a real situation. Both models were investigated for various pre-load values of the belaying ropes. The individual computational models are marked as follows:

- **La14-18m-XXkN-LZ** – model with the stiff figurines
- **Lb14-18m-XXkN-LZ** – model with the flexible figurines

where:

L means application of the rope belaying system

a or **b** means the method, which is currently used for simulation of the figurines (a - stiff, non-flexible figurines, b - flexible figurines)

14 is the belaying rope diameter (given in mm)

$18m$ is the belaying rope span (in m)

$XXkN$ is the rope pre-load value (there were used the values 5, 10, 15 and 20 kN),

LZ means the rope suspension component

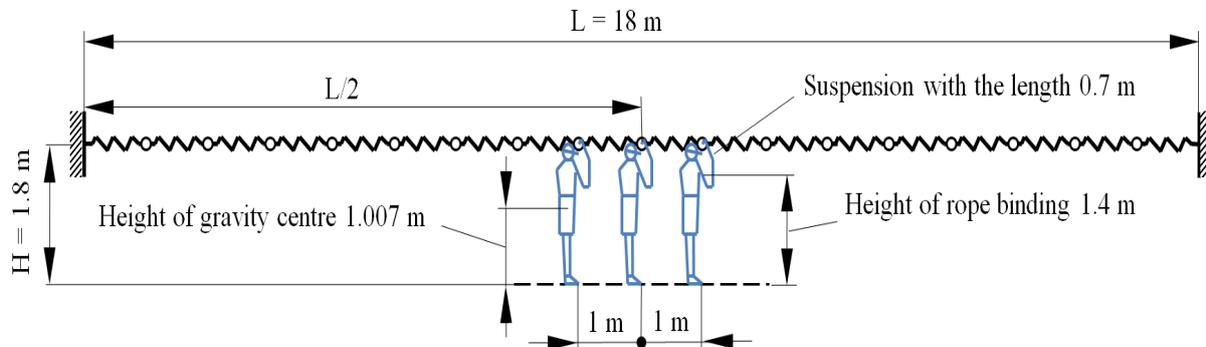


Fig. 4. Model of the belaying system with the figurines

These are the defined geometrical parameters of the analysed belaying system:

- anchorage height of the belaying system above the base is 1800 mm
- length of the rope suspension components is 700 mm
- the free length of the suspension rope before a fall of the figurine is 120 mm + overhang of the rope ystat, max caused by the own weight of the rope
- point of connection of the suspension rope to the figurine is situated 1400 mm above the base

The stiff figurines used in the models “*La...*” with the weight 100 kg were situated in the middle of span and with the mutual distance 1 m. The height of the figurine is 1800 mm and the height of the figurine gravity point is approx. 1007.3 mm. The distance of the figurines from the belaying rope in the horizontal plane was 0.42 m (Fig. 5).

The figurines used in the models “*Lb...*” are flexible in the waist around the transversal axis. The figurine waist is positioned in the height 0.98 m from the figurine foot. A possible back-bend of the figurine was eliminated using a bind between the bottom part of the figurine and the figurine body (Fig. 6).

The calculation process considered such sequence of the occurrences, by which the middle figurine was falling as the first and the other figurines were falling gradually in the time interval 0.2 s. The most unfavourable situation assumed a free movement of the figures without mutual collisions during a falling.

2.2. Elaboration of the calculated results

Considering the fact that eight (8) computational models were investigated, the elaborated results of the performed computational analyses are summarised in Tables 1 and 2, using the undermentioned designation of the individual values.

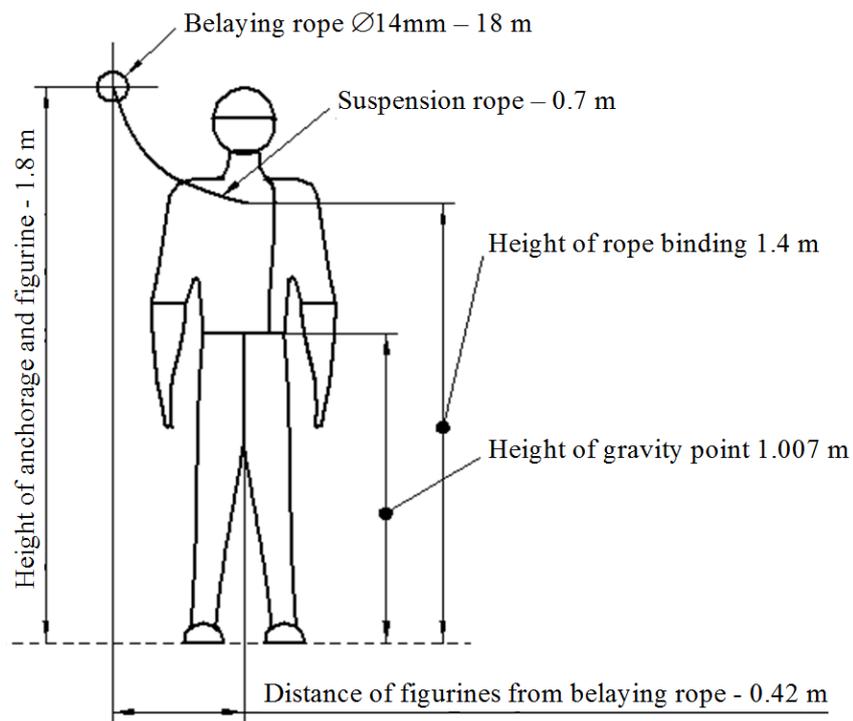


Fig. 5. Model of the stiff figurine

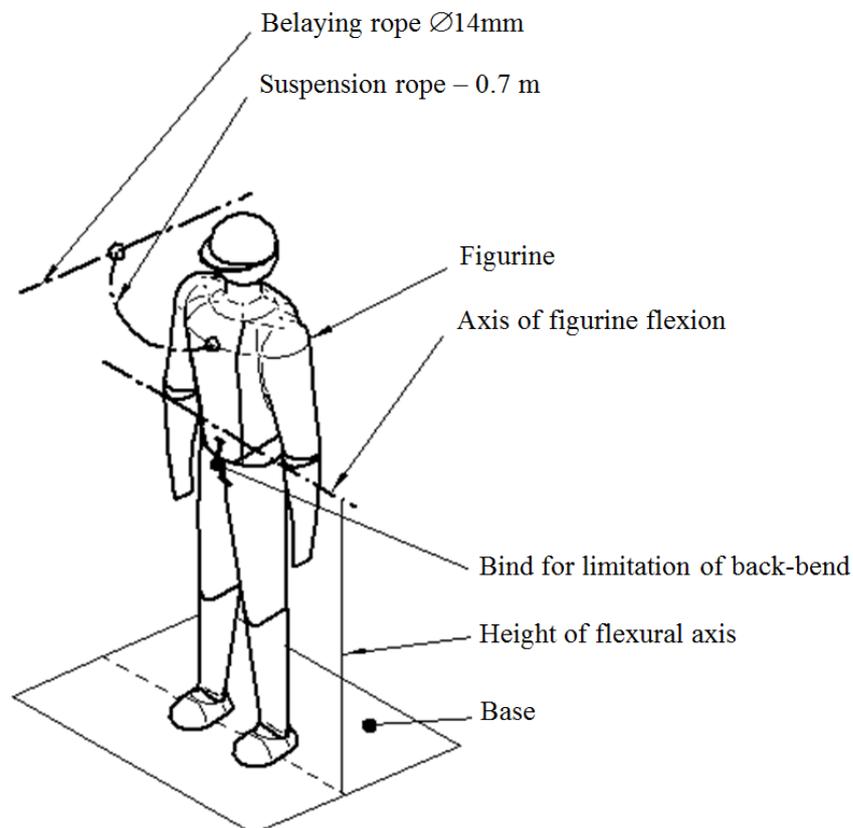


Fig. 6. Model of flexible figurine

The designation of the used input parameters is:

| | |
|--------------|---|
| G [kg] | weight of the figurine |
| n | number of the figurines |
| l_z [mm] | length of the suspension component |
| h_z [mm] | height of free figurine movement (free fall) |
| k_z [N/mm] | stiffness of the suspension component (obtained from measurement in rope test-room) |
| k [N/mm] | stiffness of the belaying rope calculated from modulus of elasticity for the rope with the length 18 m (the modulus of elasticity value $E = 55835$ MPa is obtained from measurement in rope test-room) |
| F_o [kN] | pre-load of the belaying rope |

The designation of the calculated values is:

| | |
|---------------------|---|
| l_{zmax} [mm] | maximal prolongation of the suspension component |
| F_{z1} [kN] | the first dynamic response of tensile force in the suspension component at beginning of the figurine fall (after tension of the suspension component) |
| F_{zmax} [kN] | maximal dynamic force in the suspension component (mostly the second response) |
| F_{omax} [kN] | maximal force in the belaying rope (pre-load + dynamic response) |
| $y_{stat,max}$ [mm] | maximal static overhang of the belaying rope (in fact, it is the first dynamic deflection of the rope caused by its own weight; the figurines are motionless) |
| $y_{stat+dyn}$ [mm] | the highest calculated deflection of the belaying rope after fall of the figurines |

It is possible to state, according to the results presented in Tables 1 and 2, as well as after comparison of the forces F_{omax} with the total deflections $y_{stat} + dyn$ that if the pre-load value is less than 20 kN. Hence, the maximal dynamic force (occurring in the belaying rope) does not exceed the value 30 kN, which is the maximal value of a force that is acceptable with regard to the anchorage of the belaying rope.

Tab. 1

The results obtained and elaborated from calculations for the models
La14-18m-XXkN-LZ

| Model | Load - stiff figurines | | | Suspension component - rope of personal protective equipment | | | | |
|------------------|------------------------|-----|------------|--|--------------|-----------------|---------------------|----------------------|
| | G [kg] | n | h_p [mm] | l_z [mm] | k_z [N/mm] | l_{zmax} [mm] | F_{z1} [kN] | F_{zmax} [kN] |
| La14-18m-5kN-LZ | 100 | 3 | 120 | 700 | 85,7143 | 38,14 | 1,35 | 3,26 |
| La14-18m-10kN-LZ | 100 | 3 | 120 | 700 | 85,7143 | 39,9 | 1,17 | 3,47 |
| La14-18m-15kN-LZ | 100 | 3 | 120 | 700 | 85,7143 | 41,438 | 1,28 | 3,57 |
| La14-18m-20kN-LZ | 100 | 3 | 120 | 700 | 85,7143 | 36,3 | 1,33 | 3,13 |
| Model | Load – stiff figurines | | | Belaying rope $d = 14$ mm, $L = 18$ m | | | | |
| | G [kg] | n | h_p [mm] | k [N/mm] | F_o [kN] | F_{omax} [kN] | $y_{stat,max}$ [mm] | $y_{stat+ dyn}$ [mm] |
| La14-18m-5kN-LZ | 100 | 3 | 120 | 214,5615 | 5 | 21,53 | 98,62 | 806,15 |
| La14-18m-10kN-LZ | 100 | 3 | 120 | 214,5615 | 10 | 25,13 | 45,00 | 708,00 |

| | | | | | | | | |
|------------------|-----|---|-----|----------|----|-------|-------|--------|
| La14-18m-15kN-LZ | 100 | 3 | 120 | 214,5615 | 15 | 25,26 | 33,80 | 632,39 |
| La14-18m-20kN-LZ | 100 | 3 | 120 | 214,5615 | 20 | 28,61 | 25,39 | 531,51 |

Tab. 2

The results obtained and elaborated from calculations for the models
Lb14-18m-XXkN-LZ

| Model | Load - stiff figurines | | | Suspension component- rope of personal protective equipment | | | | |
|------------------|---------------------------|---|---------------------|---|-----------------------|-------------------------|----------------------------|-----------------------------|
| | G [kg] | n | h _p [mm] | l _z [mm] | k _z [N/mm] | l _{zmax} [mm] | F _{z1} [kN] | F _{zmax} [kN] |
| Lb14-18m-5kN-LZ | 100 | 3 | 120 | 700 | 85,7143 | 37,86 | 1,35 | 3,23 |
| Lb14-18m-10kN-LZ | 100 | 3 | 120 | 700 | 85,7143 | 32,31 | 1,88 | 2,76 |
| Lb14-18m-15kN-LZ | 100 | 3 | 120 | 700 | 85,7143 | 30,67 | 1,718 | 2,64 |
| Lb14-18m-20kN-LZ | 100 | 3 | 120 | 700 | 85,7143 | 33,99 | 1,658 | 2,90 |
| Model | Load – flexible figurines | | | Belaying rope d = 14 mm, L = 18 m | | | | |
| | G [kg] | n | h _p [mm] | k [N/mm] | F _o [kN] | F _{o max} [kN] | v _{stat,max} [mm] | v _{stat+ dyn} [mm] |
| Lb14-18m-5kN-LZ | 100 | 3 | 120 | 214,5615 | 5 | 21,38 | 98,62 | 802,42 |
| Lb14-18m-10kN-LZ | 100 | 3 | 120 | 214,5615 | 10 | 24,645 | 50,55 | 755,00 |
| Lb14-18m-15kN-LZ | 100 | 3 | 120 | 214,5615 | 15 | 28,383 | 33,80 | 733,12 |
| Lb14-18m-20kN-LZ | 100 | 3 | 120 | 214,5615 | 20 | 30,054 | 25,39 | 634,16 |

Figures 7, 8 and 9 illustrate the time behaviours of the calculated values F₀, F_z and y for the model “La14-18m-5kN-LZ” (stiff figurines, pre-load level 5 kN).

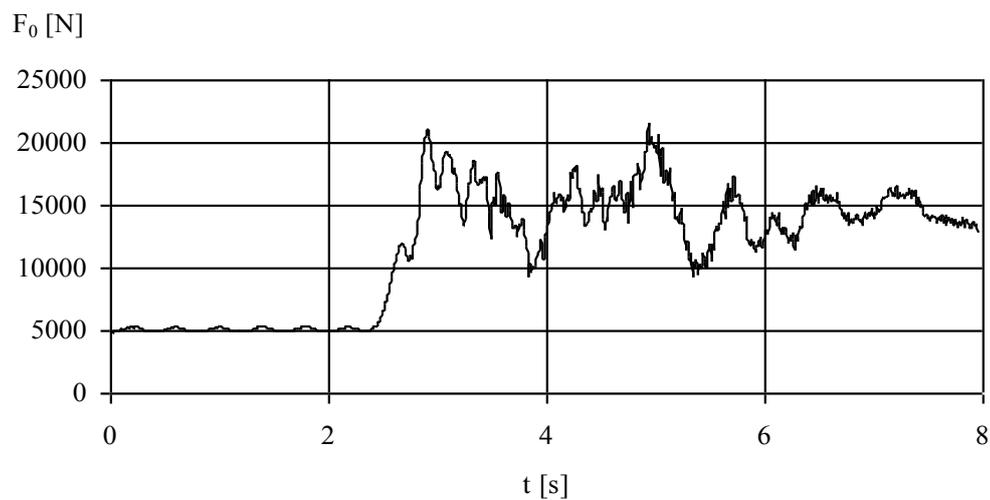


Fig. 7. Time behaviour of the tensile force in the belaying rope

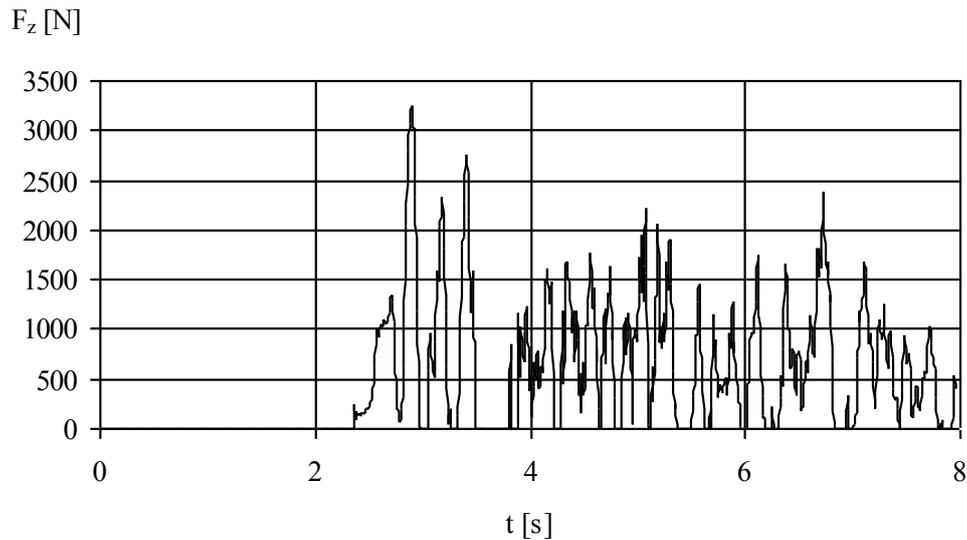


Fig. 8. Time behaviour of the tensile force in the suspension rope

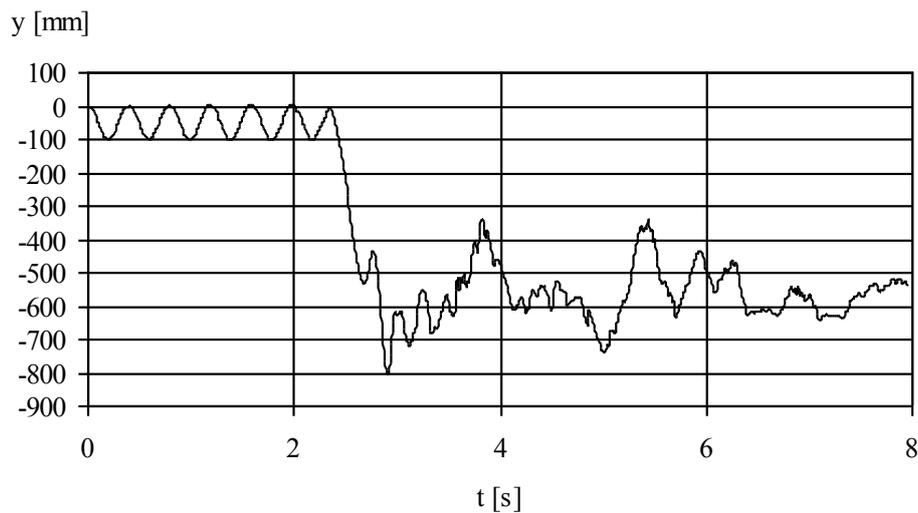


Fig. 9. Time behaviour of the overhang for the belaying rope in the middle of span

4. CONCLUSION

The analyses presented in this work were performed based on information obtained from measurement of the stiffness characteristics concerning the steel ropes or suspension components of personal protective equipment used in the horizontal belaying system and from measurement of the samples provided from the submitter of the given task. According to the calculated results, it is possible to conclude that the dynamic loading, which occurs during stoppage of the fall of two or three persons, is less than the values determined by the technical standards [23] and [24]. If the pre-load value is less than 20 kN, then the dynamic force, which is arising in the belaying rope, does not exceed the value 30 kN, which is the maximal acceptable force with regard to the anchorage of the belaying rope.

In view of the above-mentioned facts presented in the form of the results obtained from the performed simulation process, it is possible to point out that the analysed horizontal belaying system is a suitable technical equipment that increases the safety of the crane service and maintenance.

Acknowledgements

This article was elaborated in the framework of the Grant Project VEGA 1/0110/18.

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Received 11.05.2019; accepted in revised form 17.08.2019



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