

Effect of Repeated Loading on Textile Rope and Webbing Characteristics in Personal Equipment Protecting Against Falls from a Height

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Abstract

Horizontal anchor lines manufactured from fibre ropes and textile webbing are important elements of equipment protecting against falls from a height. Their mechanical properties determine the process of a fall arresting. The simultaneous use of some components of the protective equipment by more than one user is possible and desirable under specific conditions. This paper presents testing methods and a test stand for the measurement of load-elongation characteristics under static and dynamic conditions. The testing methods simulate the functioning of the equipment during the fall of consecutive users. The results indicate significant differences between the load-elongation characteristics obtained in the first versus subsequent loading tests, as well as between characteristics obtained under static and dynamic conditions. The paper also presents how the changes in rope and webbing characteristics described affect the ability of protective equipment to absorb the kinetic energy of a person falling from a height. Data obtained in the present study are useful for the development of numerical models for horizontal anchor lines.

Key words: *personal protective equipment, falls from a height, flexible anchor lines, webbing, fibre rope, elongation, repeated loading, horizontal protective lines.*

Introduction

Falls from a height still remain some of the most important causes of serious accidents at work in Poland, occurring predominantly in such sectors as the construction industry, manufacture, transport, and warehousing. The scale of the problem has been confirmed by data published by the Central Statistical Office [1] and the Polish National Labour Inspectorate [2]. One of the more effective and common methods of countering this hazard is the use of personal equipment protecting against falls from a height.

Personal systems designed to arrest the fall of a user from a height consist of three main elements [3, 4]:

- anchor component,
- connecting and shock-absorbing component,
- full body harness.

The anchor component is the part of a fall protection system that is connected directly to structural elements of the worksite. It is designed to transfer the dynamic forces generated during fall arrest to structural elements of appropriate mechanical strength. Examples of such equipment [5, 6] include horizontal anchor lines and rails, movable anchor points, etc.

The connecting and shock-absorbing component is the link between the anchor

element and full body harness. The main purpose of this element is to arrest the person's fall and to alleviate its consequences. Such alleviation is understood mainly as a reduction in the dynamic forces acting on the person's body during fall arrest, as well as minimisation of the fall distance. Examples of equipment which is currently in common use include lanyards with textile shock absorbers [7 - 9], retractable fall arresters [10], and self-locking guided fall arresters on a rigid or flexible anchor line [11].

The full body harness [12] is the last element of a personal fall protection system. Its task is to ensure an appropriate, safe position of the user's body during and after fall arrest and to distribute the dynamic forces to those parts of the body that are more resistant to injuries.

Practice in Poland and other European Union member states has shown that the simultaneous use of some components of personal fall protection equipment by more than one user is theoretically possible and desirable under specific conditions. This concerns mainly horizontal anchor lines, which are designed to enable workers to move around in a horizontal direction while safeguarding them from falls from a height [6, 13]. Such a situation is possible if the anchor line is more than a few meters long, and the work to be done requires the presence of more than one worker. The requirements placed on protective equipment

under such circumstances are completely different from those applicable in situations where there is only one user. Such requirements concern, in particular, mechanical strength parameters and load-elongation characteristics.

Horizontal anchor lines during fall arresting are loaded by vertical forces in one or several points. This creates a force acting along the anchor line, which causes its elongation. For this reason designing horizontal anchor lines made of textile materials, such as ropes and webbing, for equipment protecting against falls from a height requires knowledge of their load-elongation characteristics to conduct equipment performance modeling and numerical analysis as well as to assess the forces acting on the human body during fall arrest and the distance over which the fall arrest is effected. For that purpose, in 2014 the Central Institute for Labour Protection–National Research Institute launched a project aiming, among others, to determine the properties of textile ropes and webbing used as horizontal anchor lines in situations of cumulative loads which simulate arresting the fall of more than one user. This paper presents the initial test results of load-elongation characteristics of textile materials obtained. These results form a basis for the creation of numerical models needed for the prediction of protective equipment performance during fall arrest.

■ Current state of knowledge

The CEN/TC 160 Technical Committee of the European Committee for Standardization, which deals with protective equipment against falls from a height, developed draft document FprCEN/TS 16415:2012 [14], presenting requirements and testing methods for fall protection anchorage devices designed for simultaneous use by more than one user. The document describes, amongst others, the requirements and testing methods applicable to horizontal anchor lines made of textile materials (ropes and webbing) and focuses mainly on mechanical strength parameters for static and dynamic conditions. However, there are no design data allowing one to predict the performance of such protective equipment during fall arrest.

The currently applicable European standards (EN) concerning equipment protecting against falls from a height also fail to provide information that might be helpful in solving this problem. The standardized methods of measuring the maximum fall arresting force and falling distance [5, 15, 16] apply only to the case of single loading of the equipment tested.

The problem of the consequences of loading textile webbing used in fall protection equipment under dynamic conditions was addressed by the Health and Safety Laboratory (HSL) in the United Kingdom [17]. The most important issue analysed there was the effect of the loading velocity on the mechanical strength of textile webbing. Tests showed that the mechanical strength of such materials decreases significantly with an increase in the loading velocity.

The mechanical characteristics of textile materials such as ropes and webbing used in fall protection systems have been

Table 1. Materials used in the test samples.

Symbol	Material and structure	Type
A	Polyamide braided rope of 12 mm diameter	PA/12/E-16
B	Polyester core rope of 11 mm diameter	LB 101 29
C	Core rope of 12 mm diameter, - braid – polyamide fibre - core – aramid fibre	LB 201 FLR
D	Three-strand twisted polyester rope of 12 mm diameter	PES 12-A-Z/KG/200
E	Three-strand twisted polyester rope of 14 mm diameter	PES 14-A-Z/KG/200
F	Polyamide dynamic climbing core rope of 11 mm diameter	Tendon trust D11OTTO 1S 200R
G	Polyamide webbing of 45 mm width	TS 325/45
H	Polyamide webbing of 45 mm width	TS 608/25
I	Polyamide webbing of 20 mm width	TS 608/20

Table 2. Values of coefficient k_s obtained on the basis of $F(s)$ characteristics.

Material symbol	Rope/webbing type	k_{s1}	k_{s2}	k_{s3}	k_{s4}	k_{s5}
		kN				
A	PA/12/E-16	22.5	75.6	110.5	140.8	168.7
B	LB 101 29	68.0	199.4	269.6	306.2	353.0
C	LB 201 FLR	42.6	126.3	179.8	227.0	264.1
D	PES 12-A-Z/KG/200	30.9	147.3	193.5	238.1	271.3
E	PES 14-A-Z/KG/200	24.8	89.7	122.0	153.7	188.5
F	Tendon trust D11OTTO 1S 200R	20.7	70.2	97.8	120.3	145.1
G	TS 325/45	43.0	96.7	134.3	167.6	200.2
H	TS 608/25	32.7	85.3	118.5	151.8	186.0
I	TS 608/20	30.7	86.9	126.9	159.5	189.4

investigated in several publications [18, 19] which present methods of measuring load-elongation characteristics $F(s)$ and discuss the results obtained and their application in numerical models and numerical simulations of the fall arrest performance of connecting and shock-absorbing elements. However, the above studies concern only single loading and provide no direct clues for the solution of the problem considered in this paper.

A problem similar to the one presented herein is discussed in publication [20], concerning climbing ropes, which models the performance of dynamic moun-

taineering ropes during “jerks” that occur while arresting the fall of a single climber.

■ Tested ropes and webbing

Special test samples were prepared for measuring the $F(s)$ characteristics of selected textile materials – ropes and webbing used in horizontal anchorage systems for personal fall protection equipment. The samples were approximately 2 m long and terminated in loops for mounting in both the testing machine and dynamic test stand. The loops were formed by sewing or braiding, depending on the material type, and could be at-

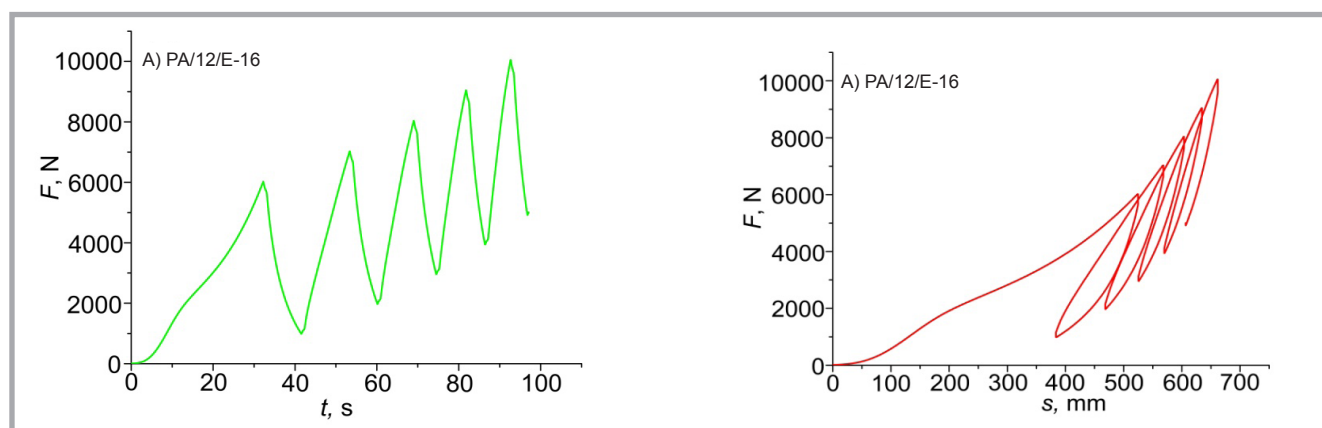


Figure 1. Load-time $F(t)$ and load elongation $F(s)$ characteristics of textile ropes (A) under static conditions, to be continued on pages 112 and 113.

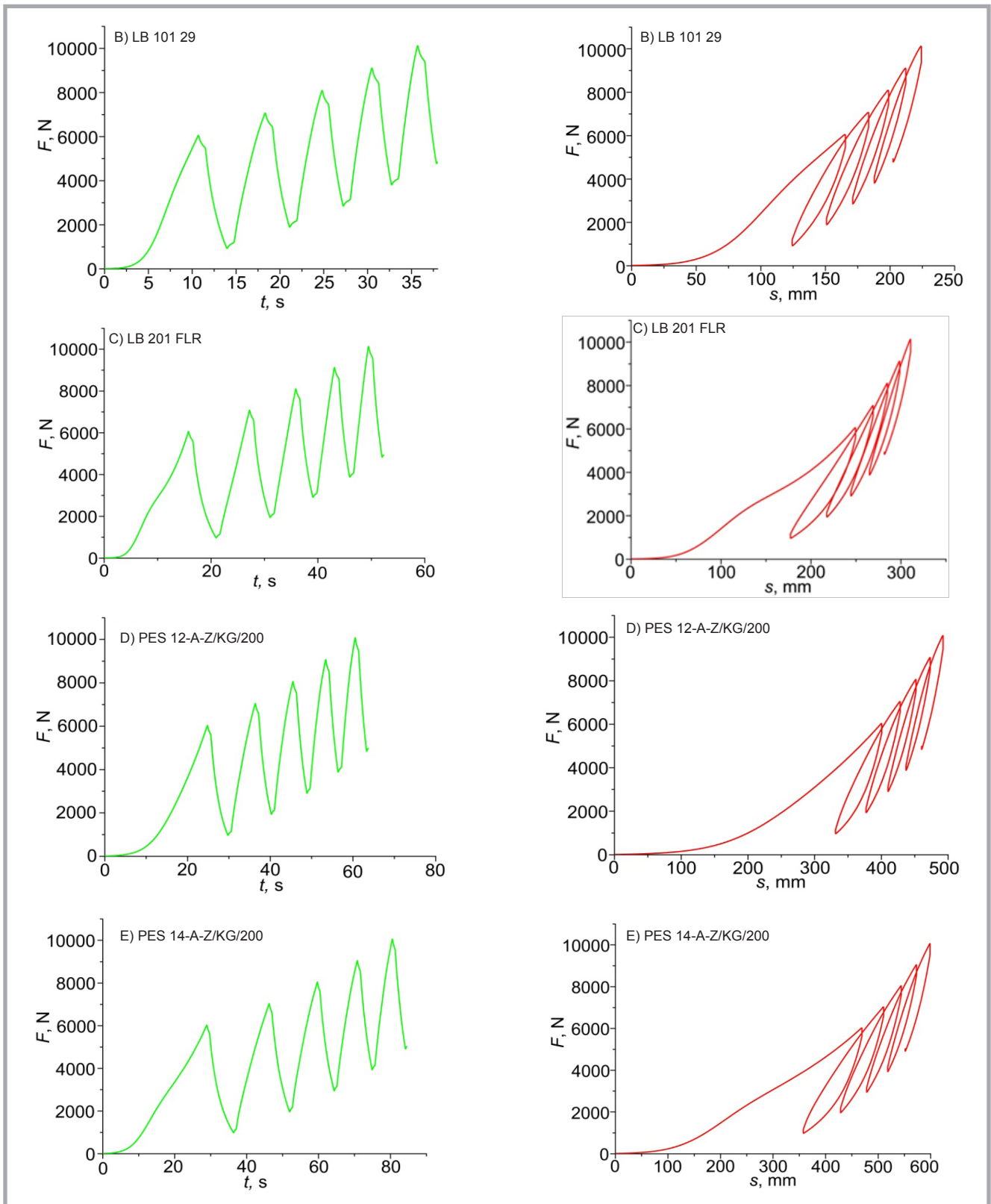


Figure 1. Load-time $F(t)$ and load elongation $F(s)$ characteristics of textile ropes (B - E) under static conditions, to be continued on the next page.

tached to bolts of 20 mm diameter. The loop construction guaranteed a mechanical strength comparable with that of the material – whether rope or webbing.

The test samples were made of materials listed in **Table 1** (see page 111).

Determination of $F(s)$ characteristics under static conditions

$F(s)$ load-elongation characteristics were investigated with the use of a Zwick ZS-100 testing machine (Germany)

equipped with a specially designed control program. The program simulated the loading of protective equipment during consecutive fall arrests of its users. The consecutive stages of loading of the ropes and webbing in the testing machine were as follows:

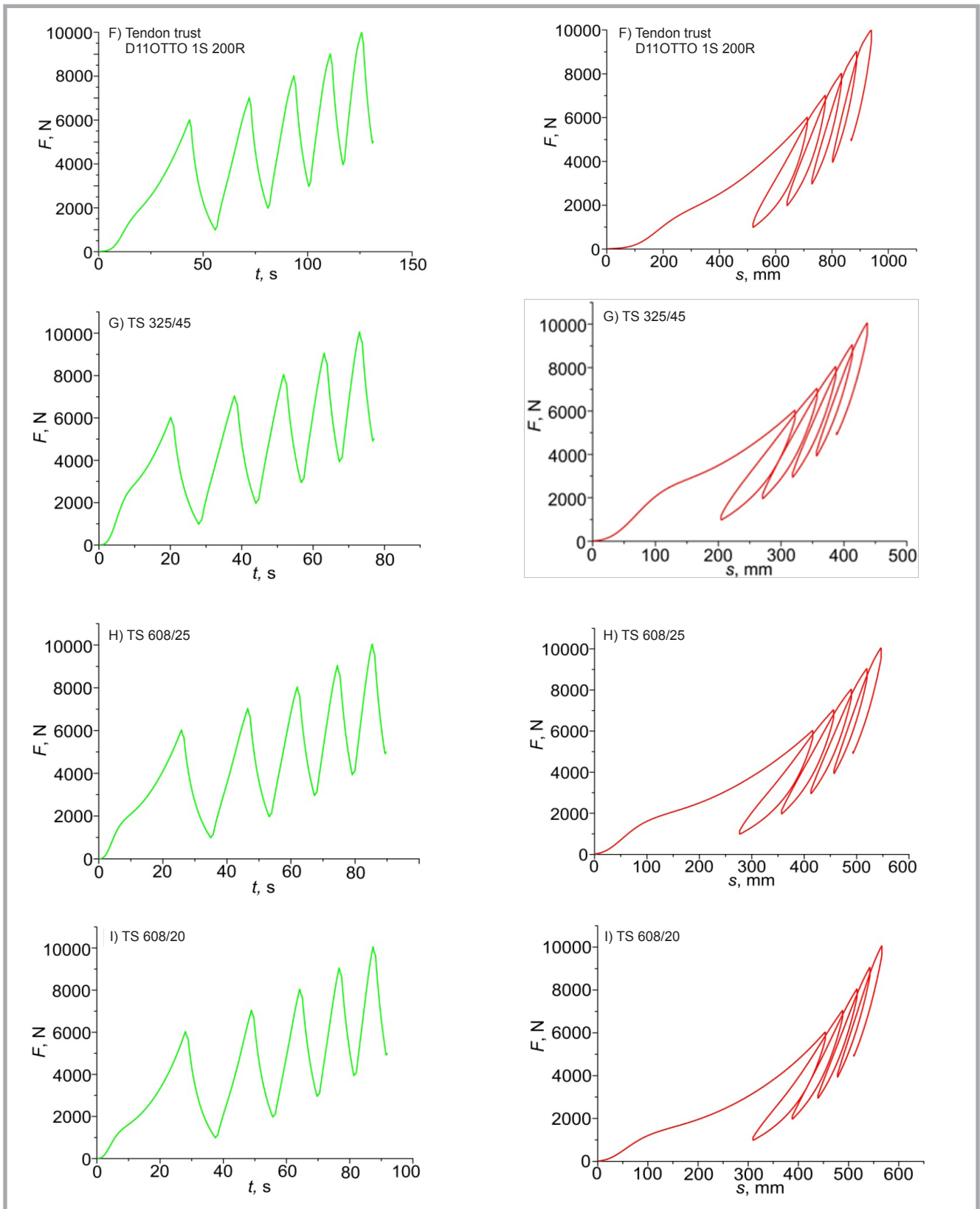


Figure 1. Load-time $F(t)$ and load elongation $F(s)$ characteristics of textile ropes (F) and webbing (G - I) under static conditions.

- stage 1: an initial 10 N load, stretching with constant velocity up to 6.0 kN, unloading to 1.0 kN;
 - stage 2: stretching with constant velocity from a load of 1.0 to 7.0 kN, unloading to 2.0 kN;
 - stage 3: stretching with constant velocity from a load of 2.0 to 8.0 kN, unloading to 3.0 kN;
 - stage 4: stretching with constant velocity from a load of 3.0 to 9.0 kN, unloading to 4.0 kN;
 - stage 5: stretching with constant velocity from a load of 4.0 to 10.0 kN, unloading to 5.0 kN.
- During the loading and unloading cycles, the sample length and tensile force acting

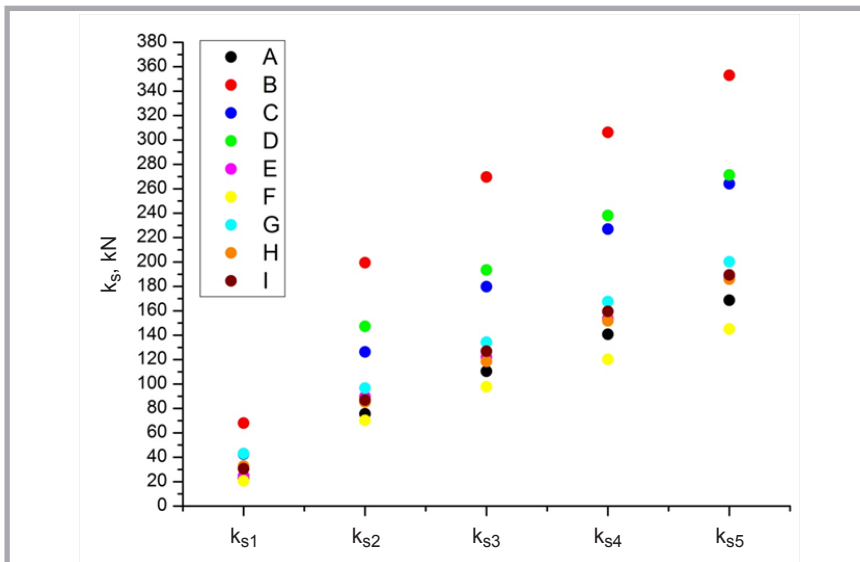


Figure 2. Values of coefficient k_s at consecutive loading steps for materials A to I under static conditions.

at a given time were recorded in parallel. A constant testing machine traverse speed of 1000 mm/min was used. The test results are shown in graphical form in **Figures 1** (see pages 111 - 113).

The graphs presented reveal that the slope of force increases in subsequent loading stages. Such an effect results from changes in the structure of the textile material due to the loading force. In order to describe that phenomenon in quantitative categories, the following coefficient k_s was defined:

$$k_s = \frac{\Delta F}{\Delta S / S_0} \quad (1)$$

where, ΔF – increase in loading force at a given loading stage, ΔS – increase in elongation at a given loading stage, S_0 – baseline length of the sample at the beginning of each loading stage.

The definition of coefficient k_s assumes that nonlinearities of the $F(s)$ character-

istics are negligible. Values of coefficient k_s for all the materials and loading stages tested are presented in **Table 2** (see page 111) and **Figure 2**.

Determination of $F(s)$ characteristics under dynamic conditions

The next step in the assessment of changes in textile ropes and webbing characteristics involved tests performed under dynamic conditions. The results of static tests demonstrated that the most significant differences in the values of coefficient k_s for all the samples tested occurred between the first and second loading tests. Therefore the dynamic tests focused on two consecutive loads with the weight of falling objects being 100 kg each. The tests were conducted on the test stand presented in **Figure 3**.

A test sample – a rope or webbing (10) of approx. 2.0 m length, terminating in

loops, was attached to the rigid element of the test stand (1) and loaded initially with a test weight of 1 kg (11). During the test, the fall of the test weight (12a) was effected first, and the rope elongation and force acting on that rope were recorded. Elongation was measured with an extensometer (6, 7, 8, 9) and digital high-speed camera (Germany) (13) coupled with a computer (1). Tema-motion [20] and Origin ver. 9.5 software [21] was used to determine the line elongation from photos recorded by the camera. After the cessation of test weight vibrations (12a), another test weight was dropped (12b), and the rope elongation and force acting on that rope were recorded. The time interval between the test weight drops did not exceed 1 min. Thus the second loading of the rope followed the first dynamic loading and coincided with a static loading as a result of suspending the first test weight (12a) of 100 kg.

The heights of free falls of test weights (12a) and (12b) were chosen so as to avoid breaking of the test samples and maintain their kinetic energy, at the end of the free fall, at a similar level. Heights of the free falls applied were contained in the range of 0.5 to 1.0 m and depended on the kind of test sample. As a result the initial velocity of elongation during the first and second fall arrest was at the same level.

Examples of the time courses of rope elongation and the forces acting on the rope recorded during the tests are presented in **Figure 4** (see page 116).

Load-elongation characteristics $F(s)$ based on time courses are presented in **Figures 5** (see page 116).

The recorded time courses and $F(s)$ characteristics obtained on their basis notably show that the slope of the characteristics obtained for arresting the fall of the second test weight is significantly greater than that obtained in the first test. For quantitative characterisation of the above effect, as in the case of static tests, coefficient k_d was calculated according to the equation previously defined. The calculation results are presented in **Table 3** and **Figure 6**.

Discussion and conclusions

In summary, the stand developed for dynamic tests and the testing method proposed allow one to determine the $F(s)$ load-elongation characteristics of fall

Table 3. Values of coefficient k obtained on the basis of $F(s)$ characteristics determined under dynamic conditions.

Material symbol	Rope/webbing type	k_{d1}	k_{d2}
		kN	
A	PA/12/E-16	141.0	310.1
B	LB 101 29	88.4	209.2
C	LB 201 FLR	191.3	306.0
D	PES 12-A-Z/KG/200	51.6	131.5
E	PES 14-A-Z/KG/200	31.7	71.8
F	Tendon trust D11OTTO 1S 200R	27.0	54.6
G	TS 325/45	63.1	93.9
H	TS 608/25	32.8	64.4
I	TS 608/20	37.1	72.9

protection equipment components under consecutive loads simulating the process of arresting falls from a height.

Tests of textile ropes and webbing conducted under static conditions demonstrated that the $F(s)$ load-elongation characteristics are significantly dependent on their structure and material they are made of, i.e., the type of synthetic fibres. The highest k_{s1} coefficient values were obtained for core ropes, ropes containing aramid fibres, and polyamide webbing. The static tests also demonstrated that consecutive loading cycles with increasing values of the loading force result in an increase in coefficient k_s , i.e., the slope of the $F(s)$ characteristics. This is caused by changes in the structure of the textile materials [19]. The most significant differences in the values of coefficient k_s are observed between k_{s1} and k_{s2} , which means that the organization of the textile structure is affected most by the first loading.

A comparison of the results of tests conducted under static and dynamic conditions shows a significant effect of the loading velocity on the slope of $F(s)$ characteristics (which increases). In the case of identical test materials, the values of coefficient k_{d1} obtained under dynamic conditions were always higher than their counterparts k_{s1} calculated on the basis of tests conducted under static conditions. Differences between coefficients k_d and k_s are presented in **Table 4**.

The difference in this respect was the most significant for ropes A and C, which is consistent with the results presented in publications [18, 19]. The differences between coefficients k_d and k_s for other materials were smaller, especially for webbing G, H and I. The first loading of the *objects tested* caused important changes in their structures which resulted in a significant reduction in the differences between coefficients k_d and k_s . For objects D, E, F, G, H and I, coefficient k_{s2} was greater than and k_{d2} . Summing up these results it should be stated that in numerical fall arrest performance simulations of textile elements of fall protection systems, models ought to be used taking into account loading velocity. This recommendation especially concerns the first loading of fibre ropes and webbing. Considering the results presented from the point of view of equipment protecting against falls from a height, it should

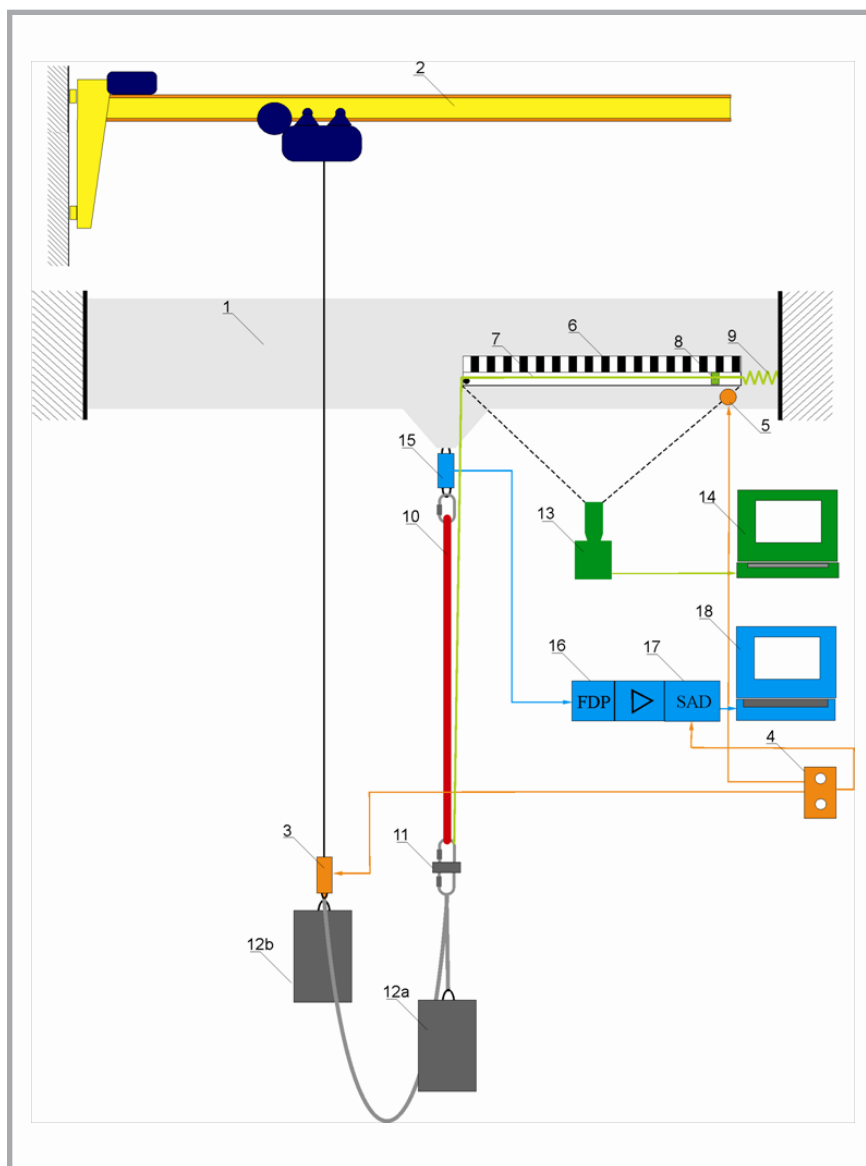


Figure 3. Stand for testing load-elongation characteristics of ropes under dynamic conditions; 1 – rigid frame, 2 – wall crane, 3 – electromagnetic latch, 4 – latch release and measurement synchronisation system, 5 – laser diode, 6 – extensometer scale, 7 – tie, 8 – indicator, 9 – tie tensioning element, 10 – rope tested, 11 – weight of 1 kg, 12a and 12b – test weights of 100 kg each, 13 – high-speed digital camera, 14 – computer coupled with a camera, 15 – force transducer, 16 – filter and analog amplifier, 17 – data acquisition system (DAS), 18 – computer operating the DAS.

be concluded that changes in the slopes of $F(s)$ characteristics directly translate into parameters of arresting the user's fall

from a height. This means that, in practice, if the equipment is simultaneously used by more than one user, in the case

Table 4. Differences between coefficients k_d and k_s .

Material symbol	Rope/webbing type	$k_{d1} - k_{s1}$ $k_{d2} - k_{s2}$	
		kN	
A	PA/12/E-16	118.5	234.5
B	LB 101 29	20.4	9.8
C	LB 201 FLR	148.7	179.7
D	PES 12-A-Z/KG/200	20.7	-15.8
E	PES 14-A-Z/KG/200	6.9	-17.9
F	Tendon trust D11OTTO 1S 200R	6.3	-15.6
G	TS 325/45	20.1	-2.8
H	TS 608/25	0.1	-20.9
I	TS 608/20	6.4	-14.0

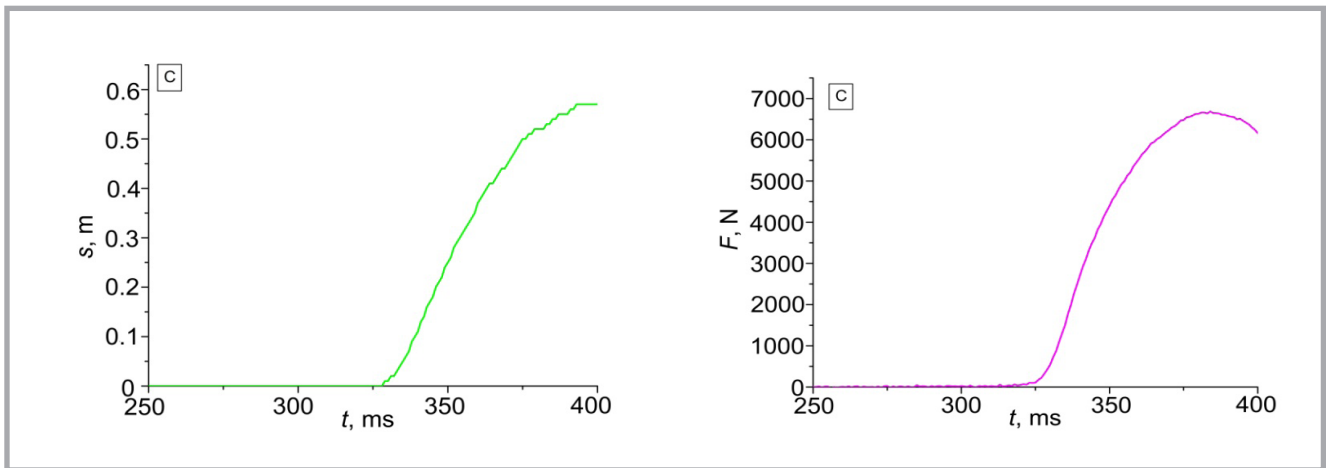


Figure 4. Sample time courses of elongation and the force acting on rope C during dynamic loading.

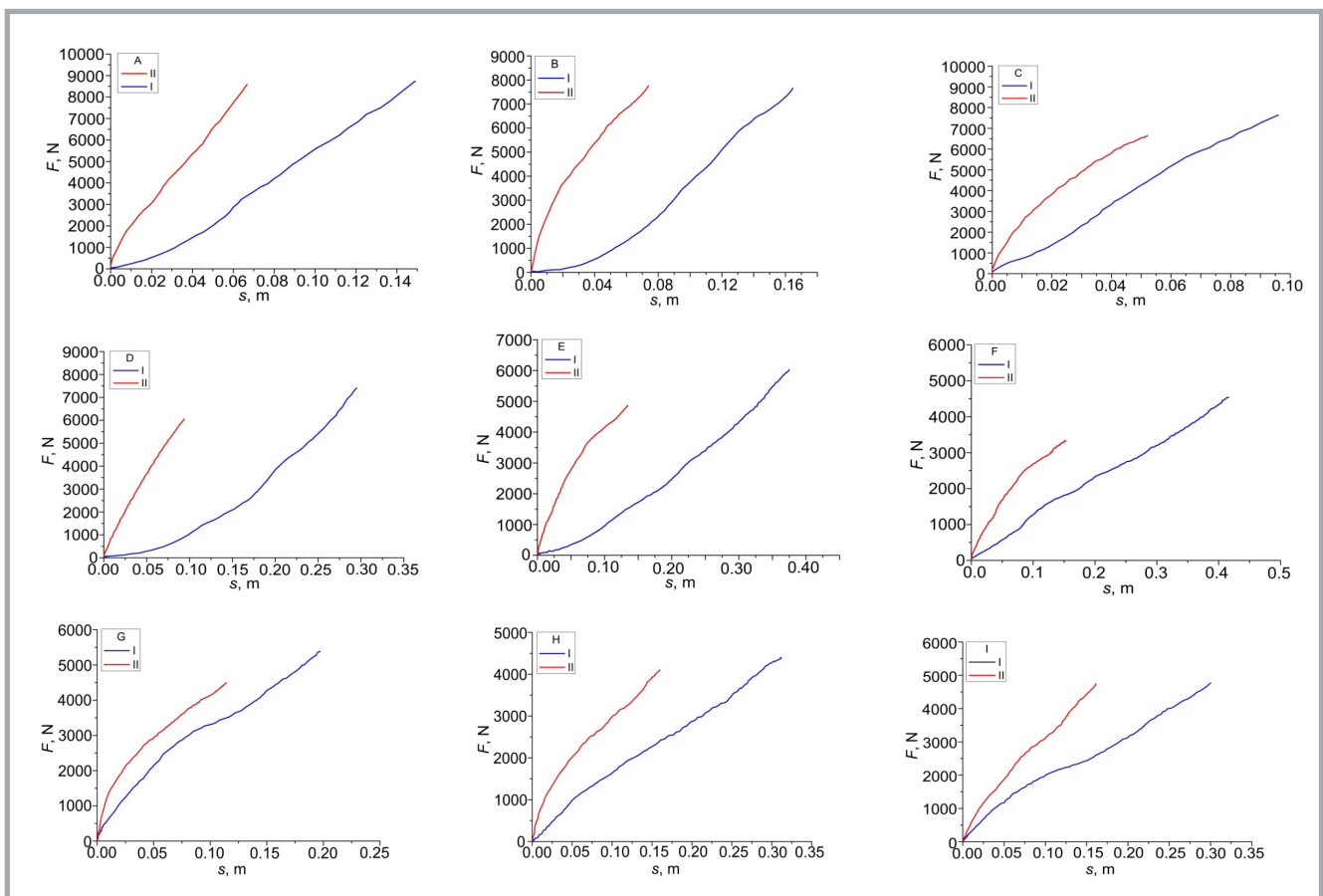


Figure 5. $F(s)$ characteristics of textile ropes (A - F) and webbing (G - I) obtained on the basis of dynamic tests; I - first loading, II - second loading.

of the second person the fall arrest will involve a higher breaking force and will be effected over a different distance. To characterize those parameters in a quantitative way, the following parameter was defined:

$$E_6 = \int_0^{s_6} F(s) ds \quad (2)$$

where, E_6 – energy absorbed by the rope/webbing being stretched, given that the

tensile force reaches the value $F = 6$ kN [8, 10, 11], s_6 – elongation for $F = 6$ kN condition, $F(s)$ – load-elongation characteristics.

The results of calculations for rope/webbing segments of 5 m length and $F(s)$ characteristics obtained under dynamic conditions are presented in Figure 7.

The data presented in the graph confirm that the textile materials studied exhibit

better shock-absorbing properties during the first fall arrest. The best shock-absorbing properties, both during the first and second fall arrest, were shown by ropes F and E, characterised by the greatest dynamic elongation. At the same time, in those cases differences between shock absorption in the first and second loading were the greatest. Fibre rope C, characterised by the smallest dynamic elongation, exhibited the lowest shock-

absorbing properties both during the first and second fall arrest. The data presented in **Figure 9** show that in the case of rope C the difference between shock absorption in the first and second loading is also the smallest.

The data presented showed that the shock-absorbing properties of the materials tested are not sufficient. Furthermore these properties are deteriorated in the successive fall arrest. This means that in some construction-related horizontal anchor line solutions it is necessary to use additional technical devices, e.g., individual shock absorbers, compensating for changes in their characteristics due to a previous fall of another user.

The test results presented indicate some mechanical phenomena important from the point of view of the safety of users of fall protection equipment and constitute the first stage of research aimed at developing numerical models of horizontal anchor lines made of textile materials. They will be used for simulations of the performance of such equipment during fall arrest in both single and multi-span systems. In this approach to the problem it will be possible to make an optimal choice of the kind of a rope or webbing for different constructions of horizontal anchor lines and the number of users. The results of this work will be presented in the next publication.

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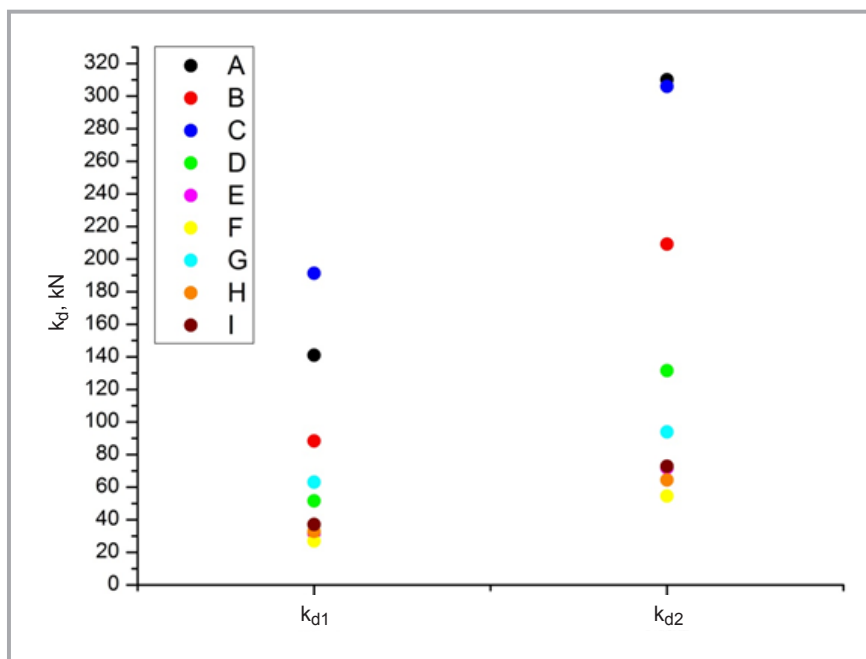


Figure 6. Values of coefficient k_d at consecutive loading steps for materials A to I under dynamic conditions.

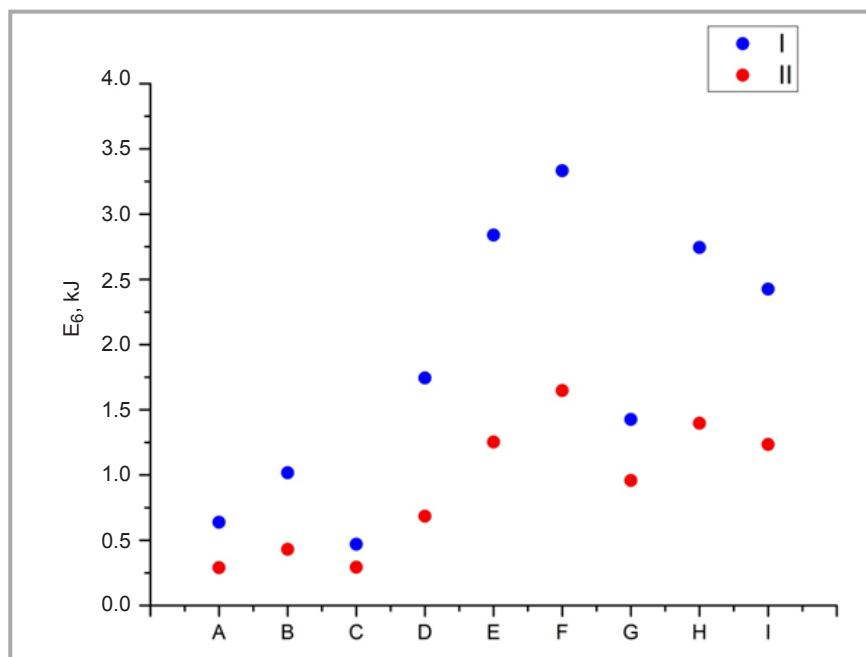


Figure 7. E_6 energy values for 5 m segments of textile ropes and webbing obtained under dynamic conditions: I – first loading, II – second loading.

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- Hexachlorocyclohexane (lindane)
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