Krzysztof Baszczyński,
Marcin Jachowicz

Load-Elongation Characteristics of Connecting and Shock-Absorbing Components of Personal Fall Arrest Systems

Central Institute for Labour Protection - National Research Institute
Department of Personal Protective Equipment
ul. Wierzbowa 48, 90 -133 Łódź, Poland
E-mail: krbas@ciop.lodz.pl

Abstract
The process of arresting a fall from a height by protective equipment is characterised by two most important values: the arrest force and the distance over which the fall arrest occurs. The time course of these values is determined primarily by the mechanical parameters of the connecting and shock-absorbing components of the fall arrest system, such as textile energy absorbers, retractable type fall arresters and guided type fall arresters. The paper presents the methods of testing used up till now to determine the properties of connecting and shock-absorbing components. Their disadvantages are demonstrated and a new method allowing to determine the load-elongation characteristics of connecting and shock-absorbing components containing textile elements is described. The method presented and test stand are based on simultaneous measurements of the force acting in the object investigated and its elongation. For measurements of elongation under dynamic conditions, an extensometer equipped with a high speed camera was used. The results of tests performed under static and dynamic conditions on objects made of fibre rope and webbing used in equipment protecting against falls from a height are presented. The results obtained demonstrate significant differences between these characteristics, which confirms the effect of the loading velocity on the mechanical parameters of textile elements used as parts of personal fall arrest systems. Therefore data allowing to develop numerical models of connecting and shock-absorbing components were obtained.

Key words: *personal protective equipment, falls from a height, connecting component, shock-absorbing component, webbing, fibre rope, elongation, performance test.*

Introduction

Data concerning casualties of accidents at work in Poland presented in the report of the Chief Labour Inspector, summing up the activity of PIP (Polish National Labour Inspectorate) in 2010 [1], show that 'slips, stumbles and falls' were the causes of accidents at work, which resulted in the deaths of 104 workers. The above figure accounts for 19.3% of all fatal accidents reported in Poland at various worksites in 2010. As follows from information published by the Labour and Living Conditions Division of the Central Statistical Office [2], there were 44 deaths due to falls from a height in Poland in 2010, predominantly in such sectors as civil end power engineering.

The above data indicate unequivocally that the problem of workers' safety at worksites located at height is still far from being solved satisfactorily. Therefore there is still a need for the improvement of equipment protecting workers under such conditions and for methods of its application. As demonstrated by the practice of works conducted at height, the methods of ensuring workers' safety, especially in such sectors as civil engineering, power engineering and telecommunications, still basically rely on the use of personal protective equipment [3 - 7].

The personal fall arrest system consists of three basic components: the anchorage component, the connecting and shock-absorbing component and full body harnesses [8]. The connecting and shock-absorbing component is a link between the worksite construction and full body harnesses worn by the worker. Its main task is to arrest the fall of the subject and to reduce its effects. Examples of equipment currently used include: lanyards with textile energy absorbers [5, 6], retractable type fall arresters [7] and guided type fall arresters on a flexible anchorage line [4]. Most types of such equipment contain fibre ropes or textile webbing of length ranging from a few dozen centimeters to a few dozen meters. The properties of the connecting and shock-absorbing component are crucial for the process of fall arrest and, consequently, for the worker's safety. The most important values characterising this process are:

- the arrest force counteracting the fall,
- the distance over which the fall arrest is exerted.

The arrest force [9], transferred through the safety harnesses to the human body, directly affects the level of loads such as acceleration and pressures, which may cause internal injuries, fractures, etc. The fall arrest distance is defined as the distance over which the velocity of the falling subject is reduced to zero. To eliminate any injuries while falling over that distance, the vertical drop pathway must be free of dangerous objects, e.g. construction elements of the worksite [10 - 13].

To guarantee safety to the users of such equipment, it is important to know these values, which must not exceed those regarded as safe [4, 6, 7]. This information is indispensable to both manufacturers at the stages of the design and construction of protective equipment and to users during its installation at the worksite and its use. In this case, the possibility of numerical simulation is particularly important [14] to predict the performance of the equipment during fall arrests with various baseline parameters, e.g. the body weight of the falling subject and the distance of free fall. The prerequisite for conducting such simulations is the application of a suitable numerical model.

In view of the importance of this problem, in 2011 the Central Institute for Labour Protection - National Research Institute (CIOP-PIB) undertook a project aimed primarily at developing numerical models for selected connecting and shock-absorbing components. The first stage of the project was focused on the testing methodology and its application to determine mechanical characteristics for textile webbing and ropes used in protective equipment, which is presented in this paper.

Objectives for the numerical model

The primary objective of the creation of a numerical model of selected connecting and shock-absorbing components, e.g. self locking arresters on flexible anchorage lines and long vertical anchorage lines, was the possibility of its application for the simulation of phenomena taking place during fall arrest, which are important from the point of view of labour safety. It means that the model helps to obtain the time course of the fall arresting force as well as the distance over which the fall arrest is affected. The model should refer to the macro scale and does not describe the phenomena taking place inside the rope or textile webbing, such as friction between fibers. Taking into consideration the preliminary studies [14] and literature data [15], the model was presumed to be based on non-linear Kelvin – Voigt and Maxwell models. The model is presented in ***Figure 1***.

The following model parameters were adopted:

- load-elongation characteristics of the connecting and shock-absorbing component,
- length of the connecting and shock-absorbing component,
- weight of the object whose fall is arrested,
- velocity of the object at the beginning of the fall arrest.

For an ultimate definition of the model structure and identification of its parameters, i.e. non-linear differential equation coefficients, it is necessary to obtain appropriate data by means of laboratory tests. It was presumed that these data will be the time courses of:

- the force acting at the anchorage point of the particular connecting and shock-absorbing component while it is arresting the fall of a rigid test mass,
- elongation of the connecting and shock-absorbing component during the rigid test mass fall arrest, and
- load-elongation characteristics of the connecting and shock-absorbing component for various loading velocities, from static to dynamic conditions.

State of the art and testing methodology for connecting and shock-absorbing components used to date

The European Standards (EN) currently applicable concerning equipment protecting against falls from a height, designed for application in an industry, require testing for the maximum value of the force acting during fall arrest and the distance over which the fall arrest is exerted. According to the standardised test methods [16 - 18], it is required that the maximum value of the arrest force should be determined at the anchorage point of the connecting and shock-absorbing component during the fall of a rigid weight of 100 kg mass, and the distance of fall arrest should be defined as the difference in weight location before and after the drop. As a result, the value determined in this way is a sum of the distance of free fall and permanent deformation of the protective equipment. In this situation there is no information concerning the elongation of the equipment taking place in the course of fall arrest. European Standard EN 892:1996 [19], concerning mountaineering equipment, confirms the faults of this method because it requires tests of the dynamic elongation of the ropes.

The evident shortcomings of that method prompted various laboratories to undertake studies in which the elongation of the connecting and shock-absorbing components of fall arrest systems was determined under dynamic conditions [20 - 22]. Most frequently, accelerometers installed in the test mass whose fall was arrested by the equipment investigated were used for that purpose. Such studies focused mainly on the maximum value of the elongation. The methodologies using accelerometers, i.e. involving the application of algorithms of double integration of the acceleration time signal, have a significant disadvantage due to the error resulting from the difficulty in the precise determination of the initial moment of fall arrest. Nevertheless data [20] illustrating maximum values of protective equipment elongation under dynamic load conditions corresponding to fall arrest were obtained.

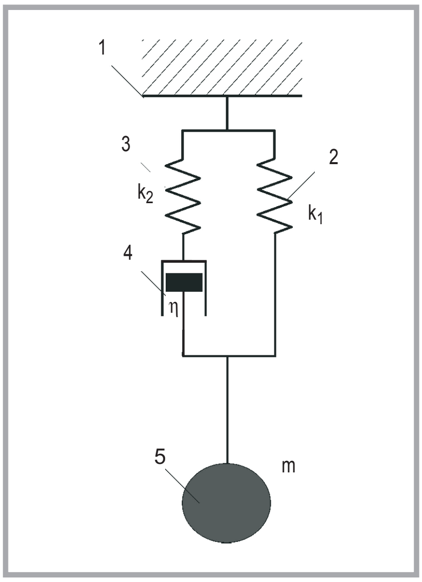

Figure 1. *Rheological model of the connecting and shock-absorbing component with long textile elements. Notes: 1 - rigid anchorage structure, 2, 3 - nonlinear spring, 4 - viscous damper, 5 - falling rigid mass.*

The problem of consequences associated with loading textile webbing used in equipment protecting against falls from a height under dynamic conditions was addressed by the Health and Safety Laboratory (HSL) in the UK. The most important issue analysed there was the effect of the loading velocity on the mechanical strength of textile webbing [23]. As a result of the tests performed , it was demonstrated that the strength of these materials decreased significantly with an increase in the loading velocity. The testing method presented in the report [23] involved the use of a high speed camera and line-scan camera allowing to record the maximum elongation of the object at the moment of break.

Test objects

For the purpose of characterisation of connecting and shock-absorbing compo-

Table 1. Textile materials used for preparation of the test objects

Symbol	Material and construction	Type	Application
L1	Polyamide webbing, 45 mm width	TS 325/45	lanyards, energy absorbers, harnesses
L2	Polyamide webbing, 25 mm width	TS 608/25	retractable type fall arresters
L3	Polyamide webbing, 20 mm width	TS 608/20	anchorage systems
L4	Webbing of 45 mm width : - polyamide mantle - aramide core	--------------	full body harnesses
L5	Three strand polyamide fibre rope, 12 mm diameter	PA 12-A-Z/KG/200	lanyards, self locking arresters on flexible anchorage line
L6	Three strand polyamide fibre rope, 16 mm diameter	PA 16-A-Z/KG/200	lanyards, self locking arresters on flexible anchorage line
L7	Three strand polyester fibre rope, 12 mm diameter	PES 12-A-Z/KG/200	lanyards, self locking arresters on flexible anchorage line
L8	Three strand polyester fibre rope, 14 mm diameter	PES 14-A-Z/KG/200	lanyards, self locking arresters on flexible anchorage line
L9	Braided polyamide fibre rope, 12 mm diameter	PA/12/E-16	lanyards for firefighters
L10	Mountaineering dynamic rope, 8.1 mm diameter	Ice Line	mountaineering equipment - half rope
L11	Polyamide core rope, 11 mm diameter	LB 101 29	lanyards
L12	Core rope of 12 mm diameter, - polyamide mantle - aramide core	LB 201 FLR	lanyards

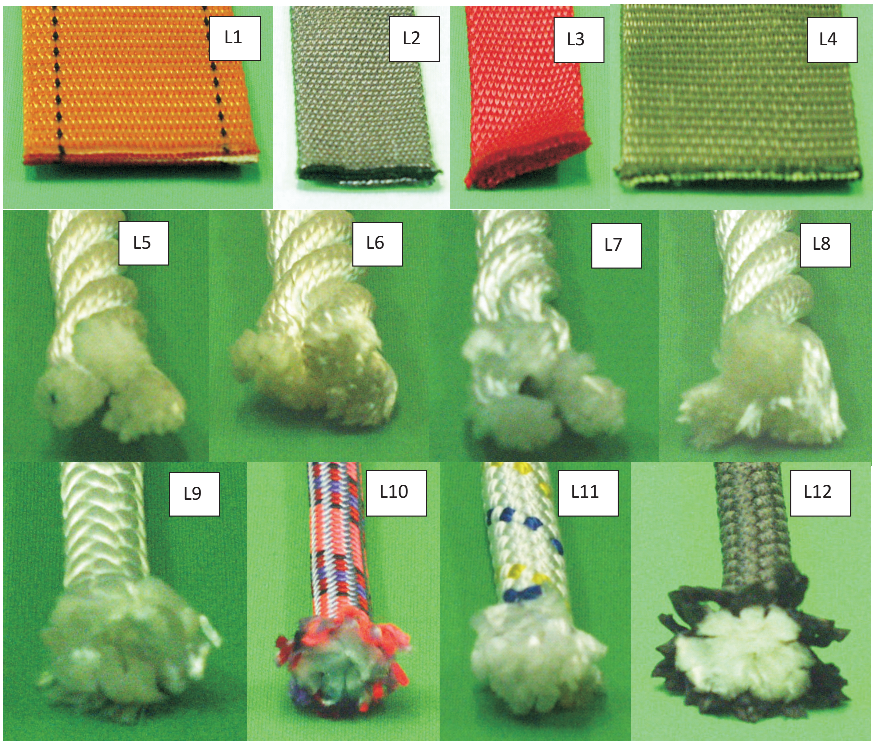

Figure 2. *Textile materials used for preparation of the test objects.*

nents, test objects made of textile materials, i.e. ropes and webbing used in the production of personal systems protecting against falls from a height, were prepared. The webbing and ropes selected represented various constructions and materials. These objects were 2 m long and ended with loops making it possible to introduce a bolt of 20 mm diameter to attach them to the strength-testing machine jaws. Depending on the material type, the loops were formed by sewing (braided ropes and webbing) or by splicing (three strand ropes). The methods of termination applied were consistent with those used in the production of protective equipment and ensured no perceptible damage of the test objects when they were loaded with tensile forces up to ca. 12 kN. The test objects were made of materials specified in ***Table 1***.

Cross-sections of the materials used are presented in ***Figure 2***.

Test methods and test stands

Determination of load-elongation characteristics of the objects described in ***Table 1*** required performing tests involving simultaneous measurements of the object load and its elongation. Tests performed within two ranges of loading velocity: static and dynamic were designed. In the first case, the loading velocity was constant, falling within the 10 ÷ 1000 mm/min range, and resulted from the current methodology of testing personal equipment protecting against falls from a height based on EN 364:1992 [16]. In the second case, the loading velocity was variable, with values changing from ca. 6 to 0 m/s. This corresponds to the variable loading velocity of the connecting and shock-absorbing component during the arrest of the fall of a rigid test mass from ca. 2 m height.

Studies of load-elongation characteristics of the objects described above under static conditions were conducted using a Zwick Z100/SW5A type testing machine. They involved the extension of the object with constant velocity and simultaneous recording of the tensile force and distance between the machine jaws, corresponding to the elongation of the object. Three values of the loading velocity: 1000; 100 & 10 mm/min were used in the study.

Studies of load-elongation characteristics under dynamic conditions were conducted using a test stand specially prepared for that purpose at CIOP-PIB, whose diagram is presented in ***Figure 3***.

The main mechanical element of the stand is a rigid frame (1), complying with the requirements of EN 364:1992 [16] with respect to rigidity and resonant frequency. The rigid frame is intended to anchor one end of the test object (10) while arresting the fall of the test mass (12). The second end of the test object (10) is connected to a preload-mass of 2 kg (11). This mass allows to reduce the axial clearance in the test equipment and straighten the object (10). The test mass (12) is connected to the object (10) through the preload-mass and Kevlar rope of 2 m (18). This solution guarantees that the test object (10) is straight irrespective of the height of the free fall of the test mass and reduces its pendulum motion during a fall arrest. The Kevlar rope (18) does not influence the dynamic load because its rigidity is significantly higher than that of the test objects (10) .

A type U9B-20kN force transducer (15) (Hottinger, Germany), installed in the axis of the symmetry of the frame, measures the force acting in the connecting and shock-absorbing component (10) during the test mass (12) fall arrest. The test stand is equipped with a power winch (2), whose hook is connected to a quick release device (3), making it possible to get hold of the test mass (12) as well as to lift and lower it to obtain the fall distance required. Opening the quick release device (3) is, owing to device (4), synchronised with the start of the KUSB 3116 measuring system (17) (Keithley, USA), recording the force signal from the transducer (15), and a laser diode (5) located in the visual field of a MotionBlitz EoSens Cube7 high speed camera (13) (Mikrotron, Germany). On the rigid frame of the stand (1), a mechanical extensometer, which measures the elongation of the object during the fall arrest of the test mass (12), is installed. The extensometer consists of a body of millimeter scale (6), over which a pointer (8) moves, connected to a piece of string (7). One end of the string is attached to a preload-mass of 2 kg (11), and the other to a spring (9), ensuring its constant tension . The extensometer string is made of polyamide braided rope of ca. 2 mm in diameter, which allows to avoid measurement errors resulting from its extension and inertia. As shown in ***Figure 4***, the extensometer (6) together with the pointer (8) and laser diode (5) is within the visual field of the camera (13).

The camera (13) is coupled with a computer (14) which is used for programming the desired mode of the camera, as well as for saving and processing the images recorded by the camera. The force transducer (15) is connected through a low-pass filter, whose characteristics comply with the requirements of RfU CNB/P/1.024 [24], to an amplifier (16) (Hottinger, Germany), which is connected to the measuring system coupled with the computer (17). In this case, the computer plays the role of programmer of the working mode of the measurement system, recorder of the time signal of the force, and a processor allowing the analysis and visualisation of the results.

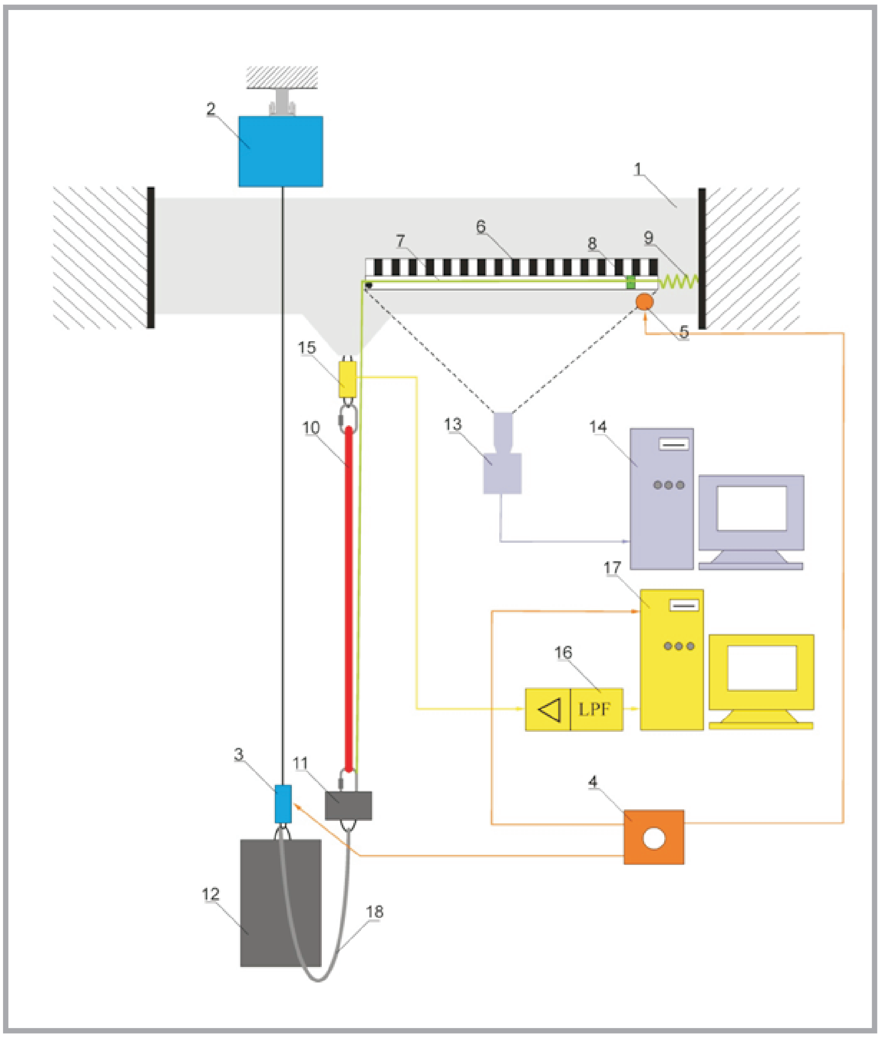

Figure 3. *Test equipment.* ***Notes****: 1 - rigid frame, 2 - power winch, 3 - quick release device, 4 - synchronization device, 5 - laser diode, 6 - extensometer, 7 - string, 8 - pointer, 9 - spring, 10 - tested object, 11 - preload - mass of 2 kg, 12 - test mass, 13 - high speed camera type MotionBlitz EoSens Cube7 (Mikrotron, Germany), 14 - personal computer, 15 - force transducer (Hottinger, Germany), 16 - low-pass filter with amplifier (Hottinger, Germany), 17 - KUSB 3116 type measuring system (Keithley, USA) with personal computer, 18 - Kevlar rope.*

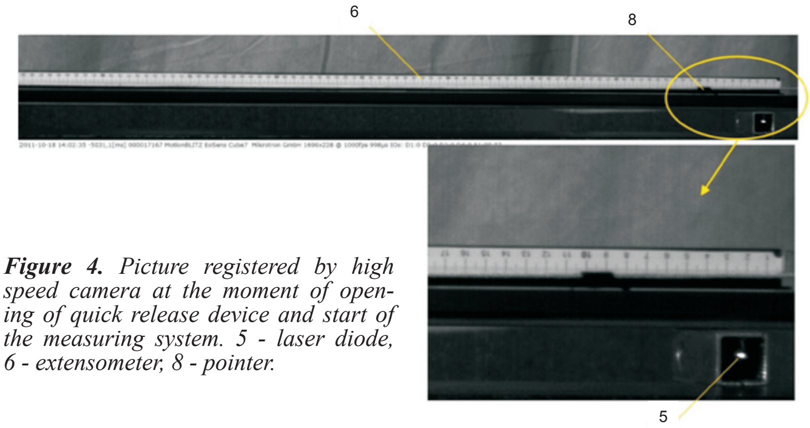

Figure 4. *Picture registered by high speed camera at the moment of opening of quick release device and start of the measuring system. 5 - laser diode, 6 - extensometer, 8 - pointer.*

The tasks of the computer software, which is an integral part of the test stand, include:

- Setting the working mode of the measurement system (17).
- Setting the working mode of the high speed camera (13).
- Processing of images recorded by the camera (plotting the time signal of the extensometer pointer – corresponding to the elongation of the test object).

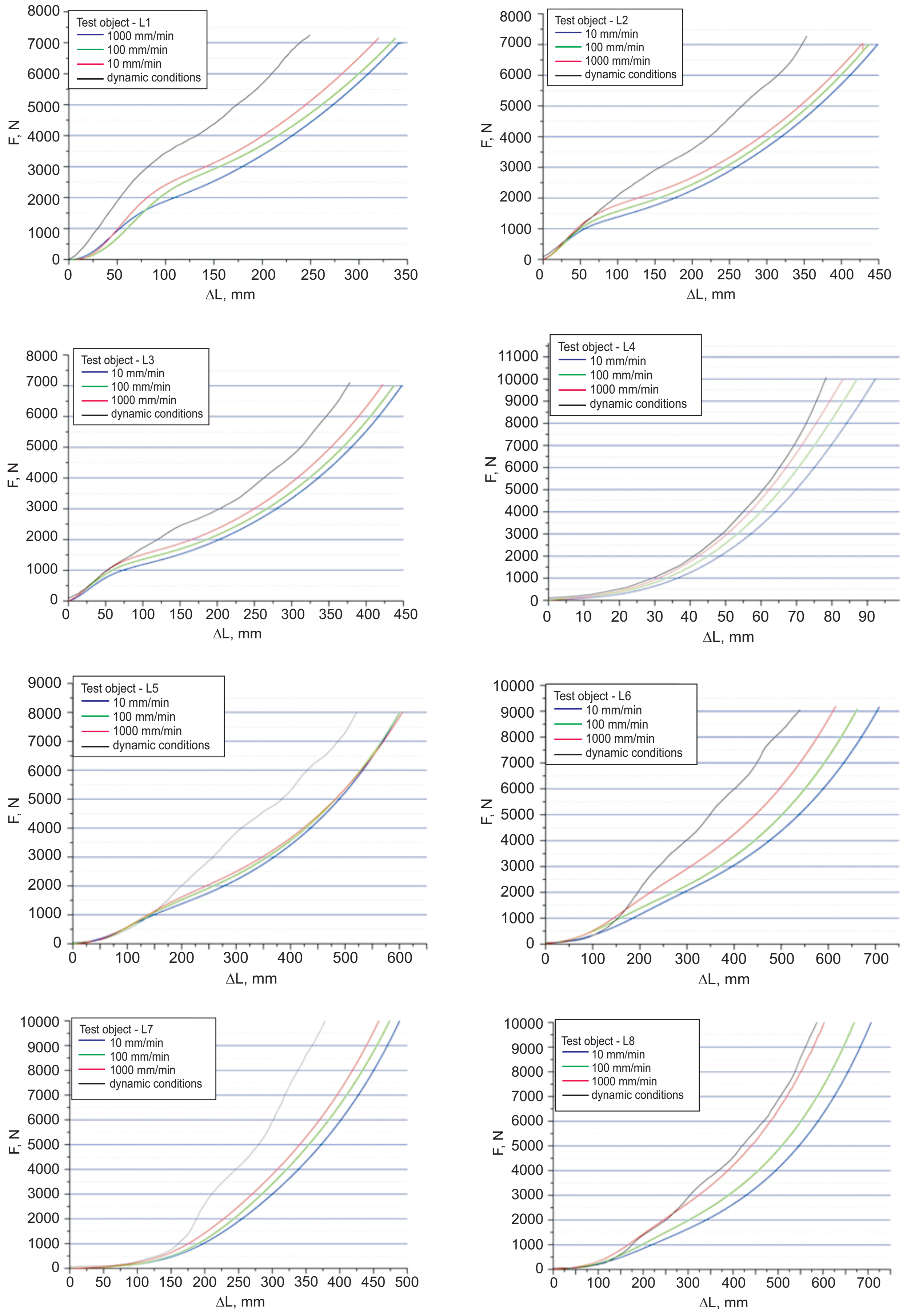

***Figure 5.** Load - elongation characteristics of the test objects according **Table 1**.*

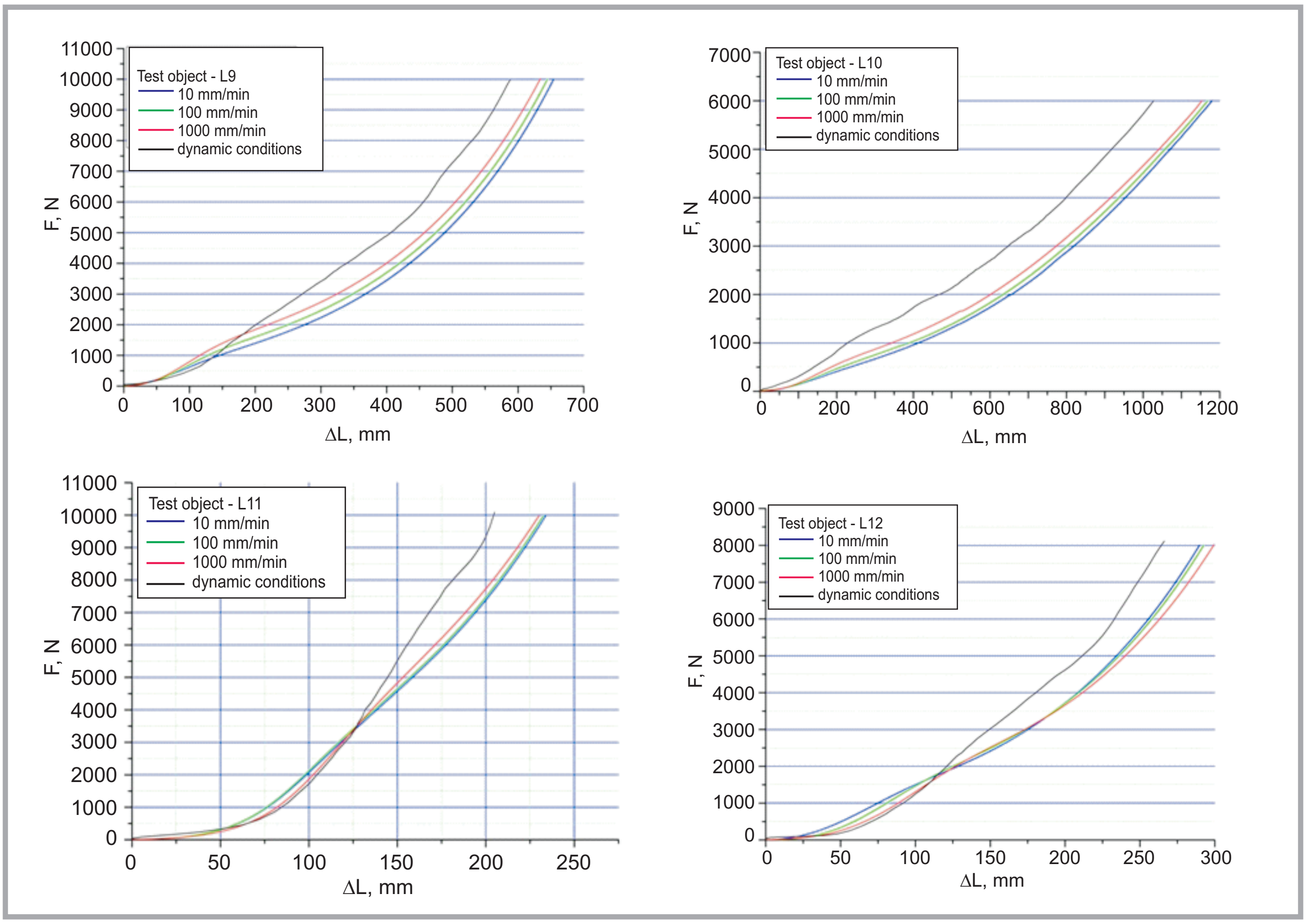

***Figure 5.** Continued.*

- Creating, on the basis of the time signals of the loading force and elongation recorded, the load-elongation characteristics of the test object.

The following settings of the instruments constituting parts of the test stand were adopted for the needs of studies of the test objects:

- force analog signal sampling frequency: 1 kHz,
- filtration of the force analog signal by means of the low-pass filter (cutoff frequency 60 Hz (-3 dB)) with characteristics specified in RfU CNB/P/1.024 [24],
- force measurement range: 0.1 ÷ 20 kN,
- observation time of the force signal: ca. 6 s,
- camera speed: 1000 frames/s,
- test object elongation measurement range: 0.0 ÷ 1.0 m,
- test mass free fall distance: 1.0 ÷ 2.0 m.

Test results and their analysis

Using the test stands and testing methods presented, the load-elongation characteristics of the test objects made of materials listed in ***Table 1*** were studied. The results are presented in the form of graphs in ***Figures 5*** and ***6***.

The characteristics shown in the figure were obtained on the basis of averaged data from three measurements. For the research methodology used, the expanded uncertainty of the elongation measurement amounts to $U_L = \pm 2.75$ mm, and that of the force measurement $U_F = \pm 50$ N (for F = 6 kN).

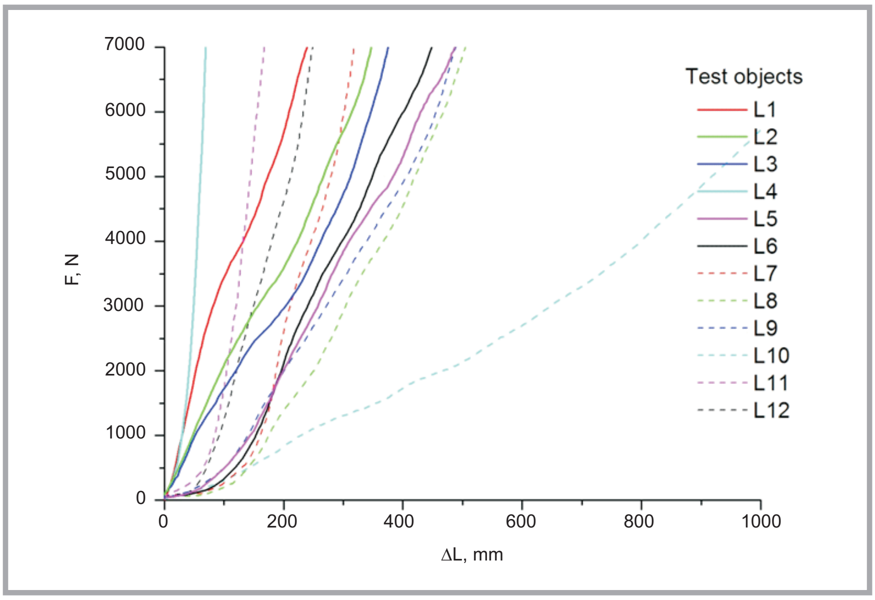

***Figure 6.** Load - elongation characteristics from the dynamic tests.*

***Table 2.** Relative elongation of the test objects under a load of 6 kN; where: V_0 - the test mass velocity at the beginning of the fall arrest*

Symbol of the object	Relative elongation of the test objects, %			Dynamic conditions	
	Velocity of the load:				
	10 mm/min	100 mm/min	1000 mm/min	V_0, m/s	%
L1	15.5	15.1	14.1	4.43	10.5
L2	20.5	20.0	19.4	4.43	15.8
L3	20.9	20.3	19.5	4.43	17.3
L4	3.8	3.5	3.4	4.43	3.2
L5	26.6	26.4	26.5	5.42	21.5
L6	29.5	27.5	24.9	5.42	20.0
L7	20.2	19.2	18.5	5.42	15.1
L8	29.4	27.5	24.2	5.42	23.3
L9	26.6	26.0	25.2	5.42	22.9
L10	59.0	58.4	57.6	6.26	51.4
L11	8.9	8.8	8.7	5.42	7.8
L12	12.8	12.9	13.2	4.43	11.6

As follows unequivocally from the graphs presented, the load-elongation characteristics are closely correlated with the rate of load increase, which means that as the rate of load increase goes up, the elongation of the object for the particular force value decreases. Such an effect is already notable in the case of tests carried out under static conditions, and it becomes even more pronounced for dynamic conditions. For analysis of the results obtained, ***Table 2*** contains relative elongation values of the test object (related to the initial length of non-loaded objects, i.e. 2.0 m) obtained as a result of a 6.0 kN force. The 6 kN value was adopted because this is the maximum value of the force that can act in the connecting and shock-absorbing component during fall arrest [4, 6, 7].

Analysis of the results presented in ***Table 2*** allows to make the following observations:

- the highest elongation values were obtained for object L10 – mountaineering dynamic rope,
- the lowest elongation values were obtained for textile webbing marked with symbol L4, containing in its structure aramide fibres characterised by low elongation potential.
- elongations obtained under dynamic conditions (during fall arrest) for the test objects fell within the 3.2 to 51.4% range.
- differences in elongations of the test objects obtained as a result of a 10 mm/min loading velocity under dynamic conditions fell within the 0.6 to 9.5 % range. The most significant of these differences was obtained in the case of three strand polyamide rope of 16 mm diameter (object L6),
- the course of load-elongation characteristics is dependent on the material of which the test object is made, as well as on its construction (see ***Figure 1*** and ***Table 1***),
- for most of the test objects studied (L2, L3, L4, L5, L6, L7, L8, L9, L11), significant differences between the characteristics determined under static and dynamic conditions are observed for the loads exceeding 1 kN.
- in the range of loads analysed, the preliminary angle between the load-elongation characteristics and x-axis increases with an increase in the load.

It should be emphasised that the tests performed in this work were not aimed at evaluation of the particular samples from the point of view of their application.

Conclusions

The analysis of the results allows to make conclusions concerning both test methods, the test stands and properties of the materials used in the production of connecting and shock-absorbing components for personal fall arrest systems. The main conclusions are as follows:

- The measurement method presented allows to obtain the time signals of the force and elongation of connecting and shock-absorbing components during a fall arrest as well as the load-elongation characteristics. This data allows to identify the structure of the numerical model and coefficients of the equations describing this model.
- The form of load-elongation characteristics of the textile ropes and webbing tested correlates significantly with the material they are made of i.e. the synthetic fibre type, and their construction. Construction variations due to the instability of conditions of the manufacturing process (e.g. torsional strength acting when the rope is being twisted) may result in significant changes in the protective parameters of the final product, e.g. flexible anchorage line.
- The load-elongation characteristics of textile ropes and webbing used in personal fall arrest systems correlate significantly with the rate of force increase.
- For the textile ropes and webbing tested, increasing the dynamic load causes a slope increase in the load-elongation characteristics.
- The test results presented confirm that the numerical model of the connecting and shock-absorbing component should contain the element that characteristically depends on the loading velocity.
- The application of load-elongation characteristics obtained from tests carried out under static conditions for developing the methods of use and installation of textile connecting and shock-absorbing components of personal protective equipment may lead to incorrect estimation of the maximum force acting on the user during fall arrest and of the distance over which that force is exerted. Consequently the user may be exposed to hazardous mechanical factors, such as forces, acceleration, pressures, etc. Because of this the load-elongation characteristics obtained from dynamic tests should be used for these purposes.

The test results presented also point to mechanical phenomena important from the point of view of ensuring safety to the users of personal equipment protecting against falls from a height. In view of the results obtained, there is a need to verify the requirements and testing methods specified in the standards harmonised with the EU directive [25] with respect to determination of elongations of connecting and shock-absorbing components. Changes should be introduced to include measurements under dynamic conditions, providing more accurate simulation of the actual conditions of fall arrest.

As was mentioned in the introduction, the results presented are the initial stage of a project aimed at developing numerical models for selected connecting and shock-absorbing components, which will be used for simulation of the performance of such equipment during fall arrest. These models will be a tool supporting the design of new constructions of equipment protecting against falls from a height and the methods of its installation and use.

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