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Modelling the Performance of Selected Textile Elements of Personal Protective Equipment Protecting Against Falls from a Height During Fall Arrest

Abstract
Ropes and woven webbing used in personal equipment protecting against falls from a height determine the course of forces acting on the human body during fall arrest, as well as the fall arrest distance. This paper presents a model of a system made up of a textile connecting and shock-absorbing component and the mass constituting its load. The model is based on non-linear rheological models of visco-elasto-plastic objects developed by Maxwell and Kelvin-Voigt. The definite structure of the model is described with a non-linear differential equation, enabling numerical analysis of its performance. Identification of the model parameters was carried out utilising a software package allowing to analyse the static load-elongation characteristics and the time courses of a dynamic force acting during fall arrest. The paper presents the results of identification of selected connecting and shock-absorbing components used in equipment protecting against falls from a height. The models identified were subjected to verification involving comparison of their numerically simulated response with the results of laboratory tests. The comparison demonstrated the correctness of the model structure and identification of its parameters. The paper also presents an example of application of the model for simulation of the performance of a connecting and shock-absorbing component during fall arrest.

Key words: *protective equipment, falls from a height, shock absorption, webbing, fibre rope, elongation, performance test.*

Introduction

Ropes and woven webbing are the basic textile materials used in personal equipment protecting against falls from a height [1, 2]. Such materials are used in the following elements of protective equipment:

- anchor devices, e.g. horizontal and vertical anchor lines [3],
- connecting and shock-absorbing components e.g. guided type fall arresters on a flexible anchorage line [4], retractable type fall arresters [5], energy absorbers [6], lanyards [7],
- full body harnesses [8], work positioning belts.

The components containing textile elements of considerable length, ranging from one to several dozen meters, require special attention. During fall arrest, these components determine the two most important values characterising that process:

- the braking force, which arrests the fall,
- the distance over which the fall arrest is affected.

The aforementioned quantities have a direct impact on the subject's safety because they influence the levels of loads such as acceleration and compression, which may cause internal injuries, fractures, etc., as well as the risk of collision with dangerous objects present in the worksite area. Knowledge of the performance of equipment during fall arrest under predictable conditions is necessary to guarantee the user's safety. In such a case, the possibility of numerical simulation of the equipment's performance during fall arrest with various baseline conditions, e.g. the subject's body weight and free fall distance, is particularly important.

Considering the importance of this problem, in 2011 the Central Institute for Labour Protection - National Research Institute (CIOP - PIB) initiated a project whose primary aim was to develop numerical models for selected textile elements of personal equipment protecting against falls from a height. The previous paper [9] was devoted to the first stage of the study, i.e. development of methodology and experimental stand for determination of load-elongation characteristics of textile webbing and ropes used in protective equipment. The paper presented is a continuation of that work and concerns numerical modelling of the performance of such textile elements and simulation of their performance under fall arrest conditions.

Rheological model of selected textile elements used in fall protection systems

Examples of connecting and shock-absorbing components of fall protection systems containing long textile elements include guided type fall arresters on a

Table 1. *Standard textile materials used in personal equipment protecting against falls from a height.*

Structure	Material	Symbol
Three strand fibre rope, 12 mm diameter	polyamide	A
Three strand fibre rope, 14 mm diameter	polyester	B
Braided fibre rope, 12 mm diameter	polyamide	C
Core rope, 11 mm diameter	polyamide	D
Webbing, 45 mm width	polyamide	E
Webbing, 20 mm width	polyamide	F

flexible anchorage line, retractable type fall arresters, vertical anchor lines and energy absorbers. The performance of such equipment during fall arrest, characterised by the course of the fall-arresting force and elongation, is determined predominantly by the textile elements, i.e. ropes and webbing [10 - 12]. Numerical analysis and prediction of the performance of such elements requires the development of an appropriate model. For the purpose of the study, standard forms of textile elements of fall protection systems were adopted, i.e. segments of 2 m length ending in loops, which, depending on the material, were sewn or braided. The textile elements were also presumed to be made of standard materials used for the production of personal equipment protecting against falls from a height. The materials are listed in ***Table 1***.

The construction and properties of the materials were characterised in paper [9], which also presents sections of ropes and webbing analysed.

To characterise the structure and parameters of the textile component model, the following assumptions were made [9, 13 - 18]:

- a system consisting of a textile element connected to a weight is modelled,
- the weight is absolutely rigid, and its dimensions are negligible,
- the model describes the motion of the rigid weight while its fall is being arrested by the textile element, i.e. during the time between the initial moment of fall and the maximum elongation (the lowest position of the weight),
- the basic values characterising the fall arrest process are the weight displacement and fall-arresting force,
- the weight moves along a vertical axis during its fall arrest,
- the model takes into account the non-linear nature of load-elongation characteristics of textile materials (ropes and webbing) used in the production of connecting and shock-absorbing components, as well as their dependence on the elongation velocity,
- the input variables of the model are as follows: *m* – weight mass, V_0 – weight velocity at the moment of fall arrest initiation, *F(S, V)* - load-elongation characteristics of the textile element, L_0 – baseline length of the component at the initial moment of the fall,
- the value of the weight velocity at the moment of fall arrest initiation (V_0) is less than 8.9 m/s,
- the maximum value of the force acting in the textile element is less than 0.5 of its breaking force,
- the model concerns mechanical quantities important from the point of view of the safety of the user and does not describe phenomena taking place inside the textile structure.

Scientific literature concerning the mechanical properties of textile materials presents various types of their models. The structures of the models depend on their application, kind of materials simulated, conditions of the load etc. The rheological models of visco-elasto-plastic objects developed by Maxwell and Kelvin-Voigt are useful tools for modelling the performance of textile material in dynamic conditions [14, 16, 18]. Taking into consideration the structures of these models, the results of the project described in paper [9] and the assumptions made, the structure of the model of a system containing a connecting and shock-absorbing component as well as a rigid weight was determined. The structure of the model is presented in ***Figure 1***.

In the model, element (1) represents an absolutely rigid construction, to which the textile element of the connecting and shock-absorbing component (2) arresting the fall of the rigid weight (3) is anchored. Element k_2 (6), with non-linear characteristics, determines the performance of the model under static load conditions, and the complex of elements k_1 (4) and η (5) plays a similar role under dynamic load conditions.

To make it possible for the model to be used in numerical simulations, it was described by means of appropriate mathematical equations. The purely elastic spring k_2 was described by the following equation:

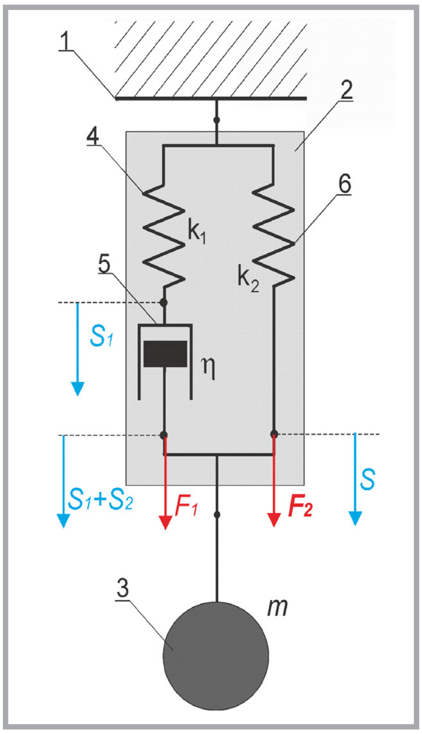

Figure 1. *Rheological model of a system comprising a connecting and shock-absorbing component and a rigid weight; 1 - rigid anchorage structure, 2 – textile element of the connecting and shock-absorbing component, 3 – rigid weight mass m, 4 - purely elastic spring k_1, 5 - viscous damper η, 6 - nonlinear spring k_2, S_1 - elongation of element k_1, S_2 - elongation of element η, S - elongation of element k_2, F_1 - force in element k_1 and η, F_2 - force in element k_2.*

$$F_2 = \left(b_0 \frac{L_{REF}}{L_0}\right)^{b_1} S^{b1} \qquad (1)$$

where:

L_0 – non-loaded component length,
L_{REF} – length of non-loaded component subjected to $F_2(S)$ characteristics test under static load conditions,
b_0, b_1 – coefficients of power function describing $F_2(S)$ characteristics,
S – elongation of element k_2,
F_2 – force in element k_2.

This formula was adopted from tests of the course of load-elongation characteristics of ropes and webbing presented in [18]. The tests proved that equation (1) described precisely the dependence between the static load and elongation of the materials mentioned in ***Table 1***.
The correlations for elements k_1 and η of the model can be presented as follows:

- purely elastic spring k_1

$$F_1 = \frac{1}{\frac{L_0}{L_{REF}} k_1} S_1 \qquad (2)$$

where:

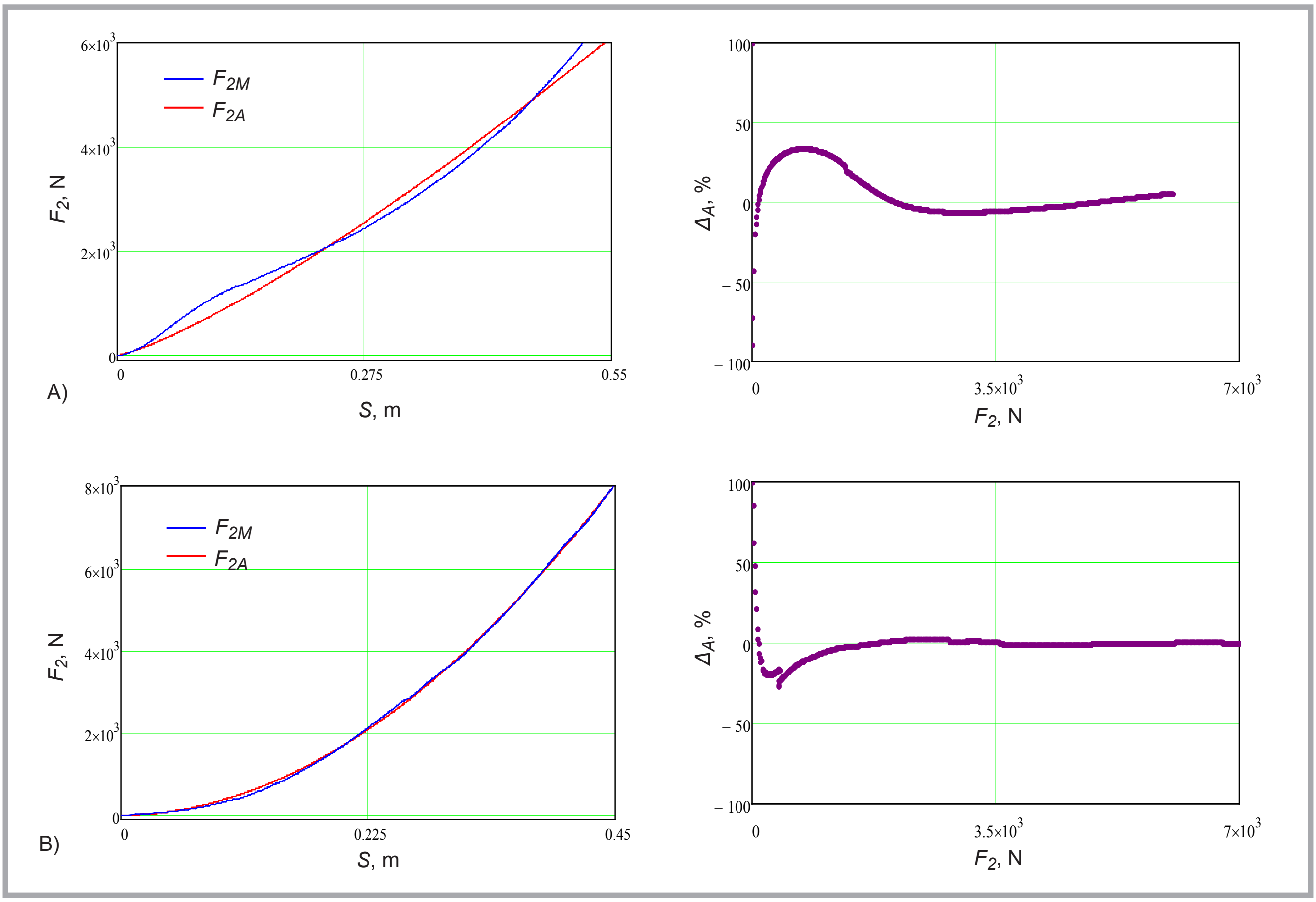

Figure 2. Approximation of characteristics $F_2(S)$ of three-strand polyamide fibre rope, 12 mm diameter (A) and three-strand polyester fibre rope, 14 mm diameter (B); F_{2M} – measured characteristics, F_{2A} – approximated characteristics, Δ_A – relative difference between F_{2M} and F_{2A}.

k_1 – linear characteristics slope coefficient,
S_1 – elongation of element k_1.

- viscous damper η

$$F_1 = \frac{\eta}{\frac{L_0}{L_{REF}}} V \quad (3)$$

where:
η – coefficient defining viscosity,
V – elongation velocity of element η.

Formulas (2) and (3), describing linear characteristics of the purely elastic spring k_1 and the viscous damper η, were adopted from [14, 16]. These types of characteristics were used in the papers cited for modelling of the performance of textile structures under cyclic loading.

The model as a whole was described with the following set of equations, characterising the motion of the rigid weight of mass m while its fall is being arrested:

$$\begin{cases} m\frac{d^2S}{dt^2} + F_2 + F_1 = Q \\ S = S_1 + S_2 \\ S_1 = \frac{L_0}{L_{REF}} k_1 F_1 \\ F_1 = \frac{\eta}{\frac{L_0}{L_{REF}}} \frac{dS_2}{dt} \\ F_2 = \left(b_0 \frac{L_{REF}}{L_0}\right)^{b_1} S^{b_1} \end{cases} \quad (4)$$

where:
m – rigid weight mass,
Q – weight gravity.

After elementary transformations of the set of ***Equations 4***, the following third order non-linear differential equation is obtained:

$$mk_1\eta\frac{d^3S}{dt^3} + m\frac{d^2S}{dt^2} + \frac{\eta L_{REF}}{L_0}(1 + k_1\eta b_1 S^{b_1-1})\frac{dS}{dt} + \left(b_0\frac{L_{REF}}{L_0}\right)^{b_1} S^{b_1} - Q = 0 \quad (5)$$

For this equation, the following baseline conditions (for $t = 0$) were defined:

- $S(0) = 0$ - initial weight displacement,
- $V(0)$ – weight velocity at the initial moment of fall arrest, calculated from the equation:

$$V(0) = \sqrt{2hg} \quad (6)$$

where:
h - distance of weight's free fall,
g - acceleration due to gravity.

- $a(0)$ = g - weight acceleration at the initial moment of fall arrest.

As a result, the mathematical equations define the model of performance of selected textile elements of connecting and shock-absorbing components during the arrest of the rigid weight's fall.

Identification of model parameters

According to previous assumptions, the structure of the model (***Figure 1***) and ***Equation 5*** concern every textile material listed in ***Table 1***. The specific properties of these materials are related to the values of the parameters (b_0, b_1, k_1, η) used in ***Equation 5***. Therefore for a complete definition of the models, their parameters (b_0, b_1, k_1, η) were identified. According to the model structure presented, the load-elongation charac-

Table 2. *Results of identification of parameters b_0, b_1, k_1, η.*

Symbol (Table 1)	L_{REF}, m	b_0	b_1	η	k_1
A	2.05	$1.295\cdot10^{4}$	1.259	$1.100\cdot10^{3}$	$1.902\cdot10^{-4}$
B	2.03	$2.684\cdot10^{4}$	2.774	$1.755\cdot10^{3}$	$1.277\cdot10^{-4}$
C	1.98	$1.581\cdot10^{5}$	1.610	$0.417\cdot10^{3}$	$1.666\cdot10^{-4}$
D	1.90	$1.712\cdot10^{5}$	1.959	$0.645\cdot10^{3}$	$5.189\cdot10^{-5}$
E	2.0	$2.537\cdot10^{4}$	1.074	$0.083\cdot10^{3}$	$1.990\cdot10^{-7}$
F	2.00	$2.428\cdot10^{4}$	1.583	$1.013\cdot10^{5}$	$8.513\cdot10^{-4}$

teristics under static conditions takes the form of ***Equation 1***. For the purpose of identification of parameters b_0 and b_1, a program of data approximation using a power function in the form (1) was used. The input data for the program were load-elongation characteristics $F_2(S)$ obtained from experiments with a testing machine working in the mode of constant elongation increase, with a speed of the beam movement of 10 mm/min [9].

A sample result of load-elongation characteristics $F_2(S)$ approximation in graphic form for elements A and B (***Table 1***) is presented in ***Figure 2***.

The results of identification of parameters b_0 & b_1 of $F_2(S)$ characteristics are presented in ***Table 2***.

The identification of parameters k_1 (2) and η (3) was based on the results of dynamic tests of textile elements used in components characterised in ***Table 1*** – the time courses of force $F(t)$ acting in the connecting and shock-absorbing component during the rigid weight's fall arrest [9, 19 - 21]. For the purpose of identification, a special computer program was developed using Mathcad software package [22].

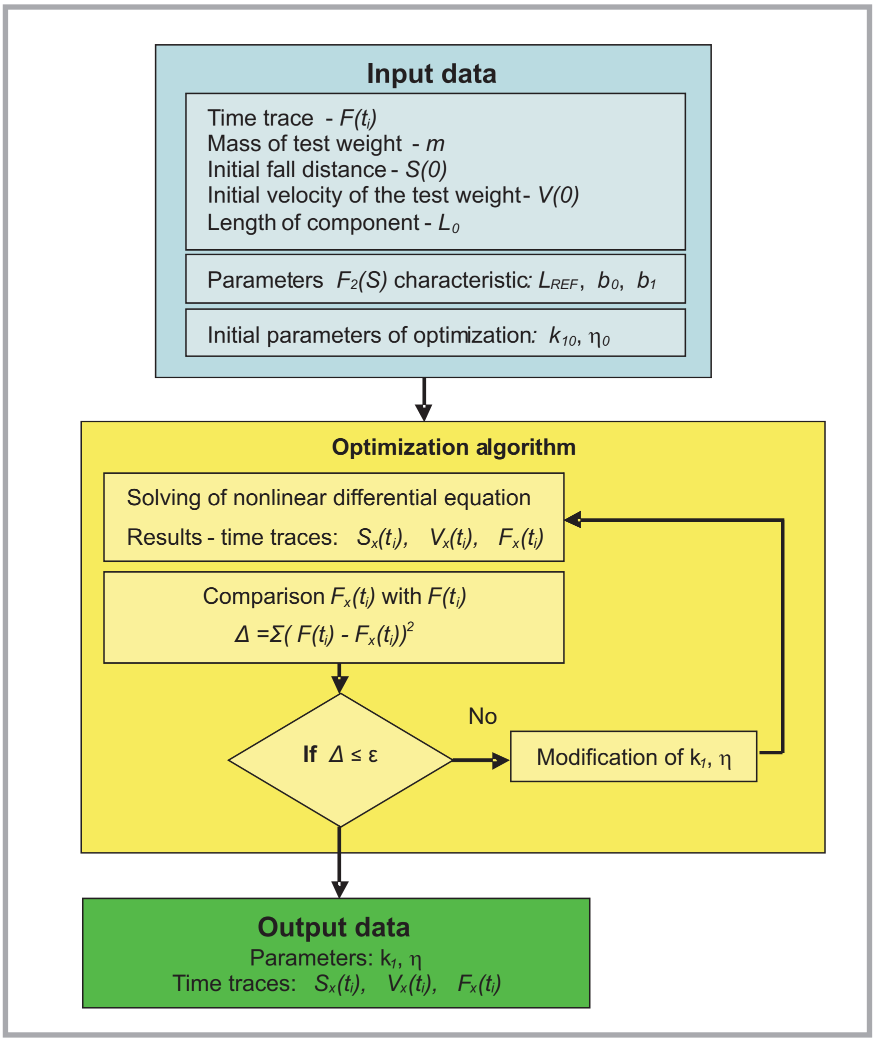

Figure 3. *Block diagram of parameters k_1 and η identification program.*

A block diagram of the program developed is presented in ***Figure 3***.

The first part of the program is a module for entering the input data, including:

- m – the rigid weight mass,
- parameters characterising the initial moment $t = 0$ of weight's fall arrest - $S(0)$, initial velocity - $V(0)$,
- parameters b_0 & b_1 of $F_2(S)$ characteristics,
- geometric parameters of components L_0 & L_{REF},
- the file with the course of force $F(t_i)$ recorded during the fall arrest test,
- initial values of the parameters identified: k_{10}, η_0.

The second part of the program is a module for the identification of parameters k_1 and η. The method of identification is based on the minimisation of the mean square error between the course samples *recorded* $F(t_i)$, and the $F_x(t_i)$ model response samples [23 - 25]. The model response is adjusted to the data obtained as a result of measurements using the conjugate gradient optimisation method, with parameters k_1 and η as the variables in the algorithm. Calculation of the response of the model $F_x(t_i)$ with the BDF (backward differentiation formula) method, after subsequent modification of parameters k_1 and η, results in a solved non-linear differential equation (5). Optimisation of parameters k_1 and η is continued as long as the error Δ between the course samples $F(t_i)$ and $F_x(t_i)$ is higher than the adopted value ε. If the error Δ is lower than or equal to ε, the actual values of parameters k_1 and η are accepted as the result of identification, and courses and maximum values of $F(t_i)$, $V(t_i)$ and $S(t_i)$ are additionally calculated. Results of the identification of parameters k_1 and η for particular types of textile elements of connecting and shock-absorbing systems are presented in ***Table 2***.

Verification of the model

The model developed was subjected to verification involving the comparison of its response with the results of fall arrest tests. The test objects were connecting and shock-absorbing systems of length L_0 = 2 m made of the materials listed in ***Table 1***. The tests involved measurement of the course of the force acting in the component while the fall of a rigid weight of mass m =100 kg was being

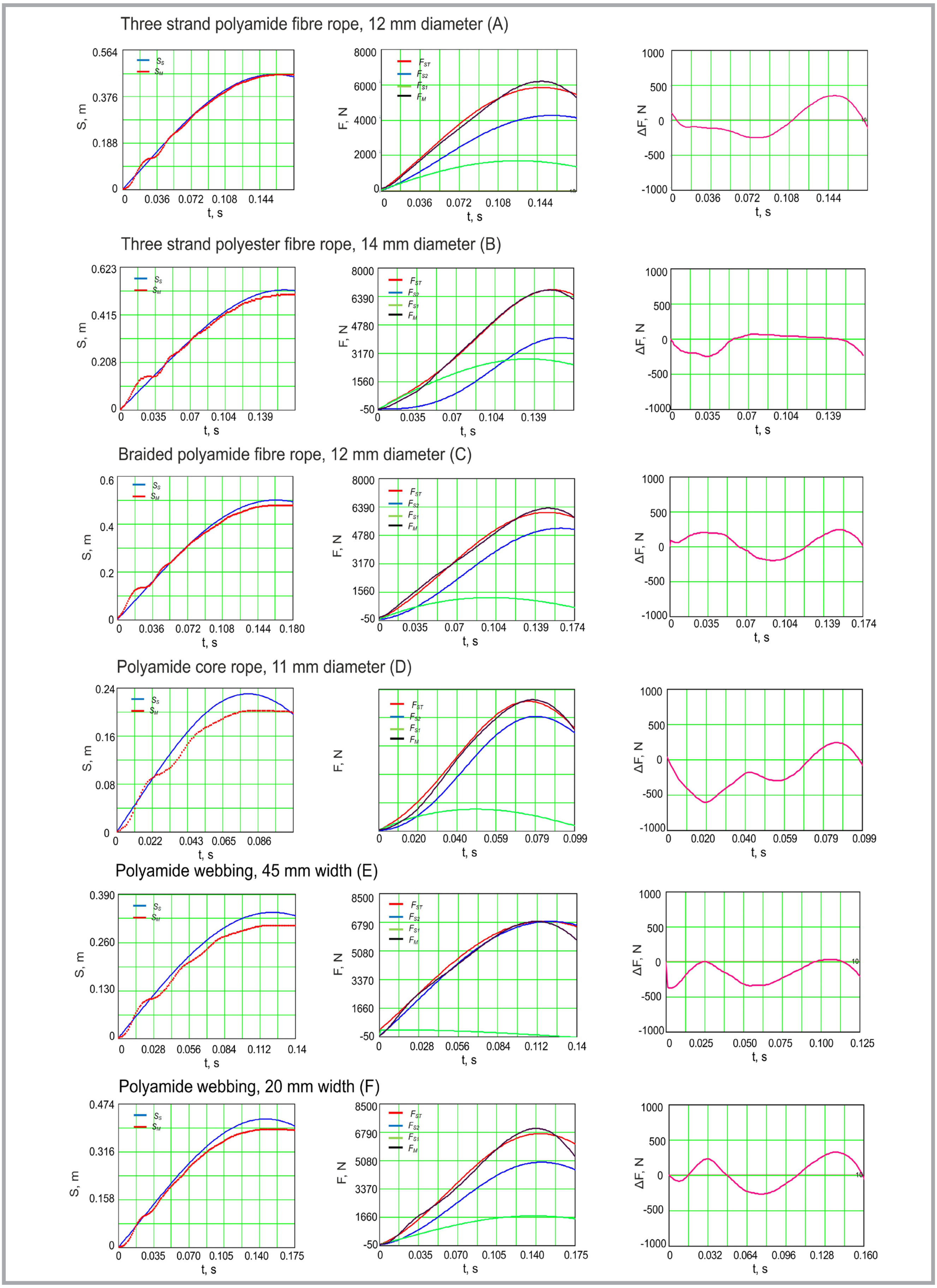

Figure 4. *Comparison of numerical simulation results with laboratory test results; S_M - measured component elongation, S_S - simulated component elongation, F_M - measured fall arrest force, F_{ST} - simulated fall arrest force, F_{S2} - simulated force in element k_2, F_{S1} - simulated force in element k_1 and η, ΔF difference between F_M and F_{ST}.*

arrested, as well as measurement of the time course of its elongation. The force acting in the component was measured by a force transducer coupled with a data acquisition system, and elongation with a digital high-speed camera [9]. Numerical simulation utilised the model developed. The results of identification presented in ***Table 2*** and the baseline conditions (*m*, V_0, L_0) are analogical to those of the laboratory tests. The verification included comparison of the time courses of:

- the component elongation: measured $S_M(t_i)$ and simulated $S_S(t_i)$ (where $S_S = S$ in ***Equation 5***),
- fall arrest force: measured $F_M(t_i)$ and simulated $F_{ST}(t_i)$ (where $F_{ST} = F_1 + F_2$).

Examples of comparisons are presented in ***Figure 4***. The graphs also include the numerically simulated time courses of forces $F_{S1}(t_i)$, (describing the force in element k_1 and η, see ***Figure 1***) and $F_{S2}(t_i)$ (describing the force in element k_2). Taking into consideration the ***Equations 1, 2*** and ***3*** the following relations can be formulated:

$$F_{S1}(t_i) = F_1 \text{ and } F_{S2}(t_i) = F_2.$$

Analysis of the results obtained can lead to the following conclusions:

- The difference between the time courses of elongation $S_M(t_i)$ and $S_S(t_i)$ does not exceed the value of 0.03 m.
- The maximum of the $S_S(t_i)$ course is always higher than that of $S_M(t_i)$, which is due to absorption of the energy of the falling weight by a non-ideal measurement system, e.g. a parallel flange beam, on which the force transducer is mounted, steel connectors at the ends of the textile element tested, etc.
- In the initial phase of the course $S_M(t_i)$ there is a characteristic oscillation due to a transverse wave generated in the test component as a result of the dynamic effect of the falling weight.
- The maximum values of the courses:
  - $S_S(t_i)$ and $S_M(t_i)$,
  - $F_M(t_i)$ and $F_{ST}(t_i)$

  are noted at the same moment. This proves that the prepared model of the textile elements listed in ***Table 1*** describes the dynamic phenomena of the fall arrest in a proper way.
- The differences between sample time courses of the $S_S(t_i)$ and $S_M(t_i)$ are the biggest in the case of core rope D and webbing E. The tests described in [9] proved that the elongation of these materials is relatively low. These results show that ***Equations 4*** prepared in a better way describe the performance of materials of high elongation e.g. A, B, C.
- The difference between sample time courses of the fall arrest force $F_M(t_i)$ and $F_{ST}(t_i)$ does not exceed 350 N.
- The maxima of the simulated courses of forces occur in the following sequence: $F_{S1}(t_i)$, $F_{ST}(t_i)$, $F_{S2}(t_i)$. The reason for such an effect, according to ***Equation 3***, is a linear correlation of force $F_{S1}(t_i)$ with the loading velocity.
- For the individual textile elements tested, the maximum values of force $F_{S1}(t_i)$ reached from ca. 0.2% to 43% of the maximum value of force $F_{ST}(t_i)$.
- The shortest force impulse increase time $F_M(t_i)$ *and* $F_{ST}(t_i)$ were noted for element D. This effect is caused by the $F_2(S)$ characteristic, which in this case increases the most rapidly [9].

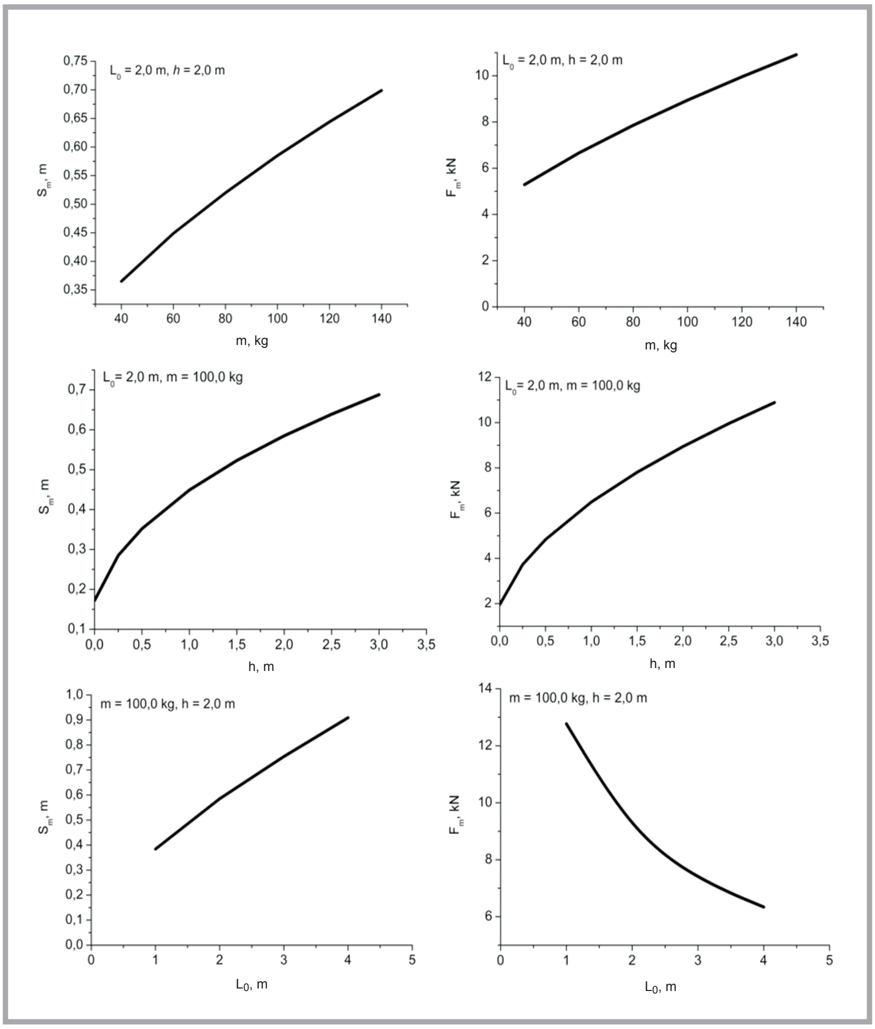

Figure 5. *Results of performance simulation of a connecting and shock-absorbing component made of three strand polyamide fibre rope (A) during fall arrest.* S_m *– maximum elongation value for the component,* F_m *– maximum fall-arresting force value.*

Conclusions

Taking into consideration the complexity of studies concerning the performance of a connecting and shock-absorbing system during fall arrest, the differences between courses $S_M(t_i)$ and $S_S(t_i)$ obtained, as well as those between $F_M(t_i)$ and $F_{ST}(t_i)$ should be regarded as acceptable, which indicates the correctness of the selection of the model structure and identification of its parameters. The correctness of the model is evidenced also by the simultaneous occurrence of maxima in courses $S_M(t_i)$ and $S_S(t_i)$ as well as $F_M(t_i)$ and $F_{ST}(t_i)$. The occurrence of the maximum in course $F_M(t_i)$ prior to the $S_M(t_i)$ maximum indicates the presence of a force component dependent on the fall arrest system's loading velocity, which has been addressed in the model developed by the introduction of elements k_1 and η. Comparison of the courses of forces $F_{ST}(t_i)$ and $F_{S2}(t_i)$ allows to observe that the use of characteristics tested under static conditions, without taking into account the effect of the elongation velocity, may lead to significant errors in most cases. Such errors may have an impact on the safety of protective equipment users. Additionally the differences between test and simulation results ($S_S(t_i)$ and $S_M(t_i)$) proved that functions (4) describe the mechanical properties of materials of high elongation in a better way. This means that for the description of the performance of low elongation materials, the new function (1) should be considered.

Summing up the conclusions presented, it can be stated that the model developed is a useful tool for the analysis and prediction of the performance of fall protection systems during fall arrest. Using appropriate software, e.g. Mathcad [22] , it is possible to simulate the quantities occurring during fall arrest effected by the connecting and shock-absorbing component selected. An example of simulation for a component containing a flexible anchorage line made of type A rope (***Table 1***) is presented in ***Figure 5***.

The graphs present the correlation between two parameters characterising the fall arrest process, most important from the point of view of human safety:

- S_m – maximum value of component elongation, corresponding to the fall arrest distance,
- F_m - maximum value of the fall arrest force

and the weight mass *m*, its free fall distance *h* and component length L_0.

The results of such simulation can provide valuable information that increases the safety of protective equipment users without the necessity of costly laboratory tests.

The investigations presented are the first step toward the modelling of the performance of textile components of personal protective equipment protecting against falls from a height during fall arrest. The model defined and the methods of identification of its parameters are the starting point for models describing not only the performance of the components but also connecting the mechanical phenomena in static and dynamic conditions with internal structures of textile materials. Taking into consideration the phenomena inside the textile structures, friction among filament fibres will complicate the structure of the models and their mathematical description. The results of these studies will be presented in the subsequent paper.

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