International Journal of Occupational Safety and Ergonomics
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tose20

Dynamic Performance of Horizontal Flexible Anchor Lines During Fall Arrest— A Numerical Method of Simulation

Krzysztof Baszczyński[a] & Zygmunt Zrobek[a]
[a] Department of Personal Protective Equipment, Central Institute for Labour Protection, Lodz, Poland
Published online: 08 Jan 2015.

INTERNATIONAL JOURNAL OF
OCCUPATIONAL SAFETY AND ERGONOMICS 2000, VOL. 6, NO. 4, 521-534

Dynamic Performance of Horizontal Flexible Anchor Lines During Fall Arrest— A Numerical Method of Simulation

Krzysztof Baszczyński
Zygmunt Zrobek

Department of Personal Protective Equipment, Central Institute for Labour Protection, Łódź, Poland

Designing fall arrest systems, which contain horizontal flexible anchor lines is an important technical problem related to the safety of people who work at a height and need horizontal freedom of movement. The article presents a numerical simulation of the dynamic performance of horizontal flexible anchor lines during fall arrest. The model of a 2-component system—a horizontal flexible anchor line and a falling rigid mass, described with a second order non-linear differential equation—is the main element of this method. This method of simulation is realised by a computer program, which allows obtaining the most important data characterising a fall arrest. The article shows laboratory tests used for the verification of this method, which turned out to be a valuable source of information and which can be used for designing fall arrest systems.

personal protective equipment against falls from a height
horizontal flexible anchor line structural anchor point
intermediate structural anchor point dynamic performance

1. INTRODUCTION

A lot of tasks performed by workers in various constructions in industry carry the risk of falling. In some cases workers need horizontal freedom of movement in getting to or in performing their jobs. Laboratory tests and practice of using equipment protecting against falls from a height proved

Correspondence and requests for reprints should be sent to Krzysztof Baszczyński, Central Institute for Labour Protection, ul. Wierzbowa 48. 90-133 Łódź, Poland. E-mail: <krbas@ciop.lodz.pl>.

that applying one anchor point could be dangerous for workers in this situation (Dolecki, 1990). Applying a single anchor point and, for example, a retractable fall arrester causes a pendulum motion of the worker when the fall occurs in the place that is horizontally remote from this point. The pendulum motion can cause the striking of elements of the constaiction and therefore can be a source of high risk of severe injuries or even death (Noel, 1991; Sulowski, 1991a, 1991b). Applying a fall arresting system comprising a rigid or flexible anchor horizontal line seems to be the best solution of this problem (Baszczyński & Zrobek, 1998; Riches & Feathers, 1998; Timmermans, 1998). If the task of a worker can be performed in a relatively short time there is no sense in using a rigid horizontal line, for example, a rail, because preparing this kind of construction is expensive and time consuming. A horizontal flexible line made from a synthetic fibre rope should be applied in this situation. Proper information concerning the dynamic performance of a horizontal flexible line is the main condition of using such a system (Miura & Sulowski, 1991; Paureau & Jacqmin, 1998).

Getting this information demands theoretical analysis (Paureau, 1998) and laboratory tests. Therefore in the years 1995-97 a research project on horizontal flexible anchor lines (HFALs) was undertaken by the Department of Personal Protective Equipment of the Central Institute for Labour Protection in Poland. This paper is based on the information generated in the course of the project and concerns a method of numerical simulation of dynamic performance of horizontal flexible anchor lines during fall arrest.

2. THEORETICAL ANALYSIS OF HFAL PERFORMANCE

The simplest construction of the system, giving a user horizontal freedom of movement, contains two basic elements: anchor points on a rigid construction and a horizontal flexible anchor line. An example of this kind of constaiction is shown in Figure 1.

The phenomena occurring during the fall of the mass m can be divided into two phases:

- free fall of the mass. The phase begins at point a, ends at point b and the free fall distance of the mass m is h;
- mass fall arrest. The phase begins at point b and ends at point c. During this phase the mass falls along distance H_m and its kinetic energy is absorbed by the HFAL, which causes the elongation of the line and increases the angle γ from value γ_0 to γ_m.

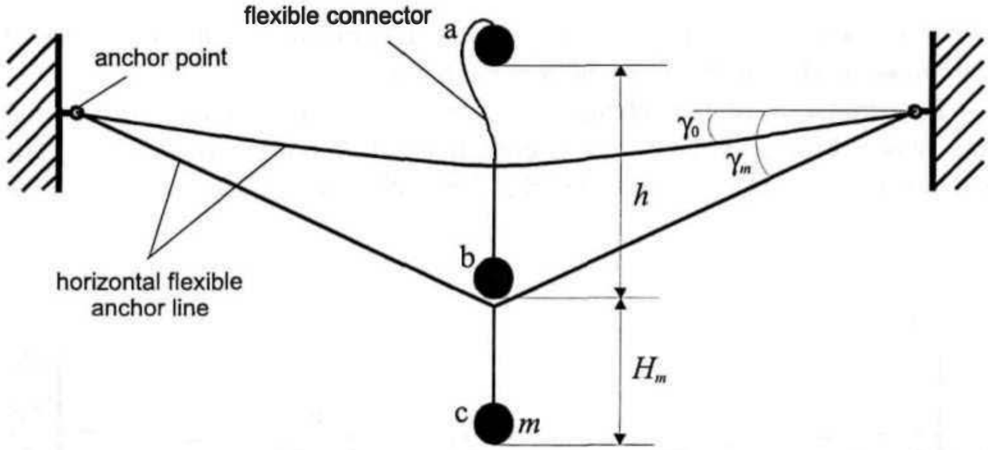

Figure 1. Fall arrest by horizontal flexible anchor lines. *Notes,* a—beginning of free fall, b—end of free fall, c—lowest position of the mass during fall arrest, *m*—mass, *h*—distance of free fall, H_m— maximum distance of fall arrest.

The following assumptions were made in order to describe the motion of **the** mass *m* during its fall arrest:

- the mass is totally rigid and its dimensions do not have to be taken into account;
- the energy absorption of anchor points is negligible and they are totally rigid;
- the flexible connector between the mass *m* and the HFAL is inextensible and its mass is negligible;
- the mass of the HFAL is negligible;
- the forces act vertically or along the rope line only;
- the HFAL is loaded at a central point between the anchor points. The laboratory tests proved that this central point is the place where the greatest values of displacement *H*m and forces acting on the ends of line are generated;
- the tension-elongation characteristic of the rope does not depend on the velocity of the elongation;
- the analysis of the HFAL performance concerns the period between the end of the mass free fall and the moment when it reaches the lowest position where its velocity is $V = 0$.

Taking these assumptions into consideration the mass motion can be described by the following equation:

$$a = g - \frac{F(H)}{m} \quad (1)$$

where *a*—acceleration of the mass, g—acceleration of gravity, m—mass of the mass, *F{H)*—arrest force acting on the mass.

Determination of the relationship between the value of the force *F* and the mass displacement *H* is a condition of solving Equation 1. The relationship can be described by the force distribution diagram shown in Figure 2.

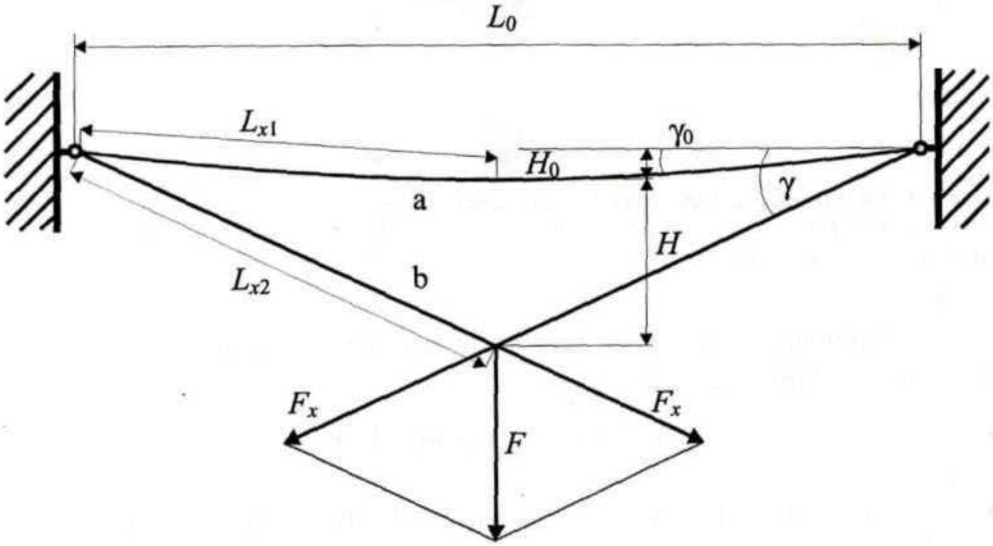

Figure 2. Distribution of the force *F* loading horizontal flexible anchor lines. *Notes.* a—initial position, b—position during fall arrest.

This force distribution can be expressed by the following set of equations:

$$\begin{cases} \dfrac{F}{2F_x} = \sin\gamma & (2) \\ \dfrac{L_0}{2L_{x2}} = \cos\gamma & (3) \\ F_x = f(L_{x2}) & (4) \\ (H_0 + H)^2 + \left(\dfrac{L_0}{2}\right)^2 = (L_{x2})^2 & (5) \\ \dfrac{2H_0}{L_0} = \tan\gamma_0 & (6) \end{cases}$$

where γ_o—initial angle of the end of the HFAL from an imaginary horizontal line, L_o—distance between anchor points, H_o—initial distance between the central point of the HFAL and the horizontal plane comprising anchor points, $f(L_{x2})$—tension-elongation characteristic of the rope used in the HFAL.

Equations 2 and 3 can be written as

$$\left(\frac{F}{F_x}\right)^2 + \left(\frac{L_0}{L_{x2}}\right)^2 = 4 \tag{7}$$

and then the force F is as follows:

$$F = F_x\sqrt{4 - \left(\frac{L_0}{L_{x2}}\right)^2}. \tag{8}$$

From Equations 4, 5, 6, and 8

$$\begin{cases} F = f(L_{x2})\sqrt{4 - \left(\frac{L_0}{L_{x2}}\right)^2} & (9) \\ L_{x2} = \sqrt{\left(\frac{L_0}{2}\tan\gamma_0 + H\right)^2 + \left(\frac{L_0}{2}\right)^2} & (10) \end{cases}$$

and then this set of equations expresses the force F by the function of the displacement H.

3. TENSION-ELONGATION CHARACTERISTICS OF ROPES APPLIED IN A HFAL

The tension-elongation characteristic of the rope in a HFAL is necessary for solving the set of Equations 9 and 10. The characteristics of this kind can be obtained from laboratory tests where a universal tensile testing machine is used. An example of a characteristic of a 14-mm diameter, three-strand polyamide rope is shown in Figure 3.

The initial length of tested rope was L_{so} = 1.93 m and the velocity of elongation 1 m/min. The test was carried out using a universal machine ZWICK Z100/SW5A (Germany). Figure 3 shows the force F_a (acting in the rope) expressed by the function of elongation ΔL_x The characteristics of

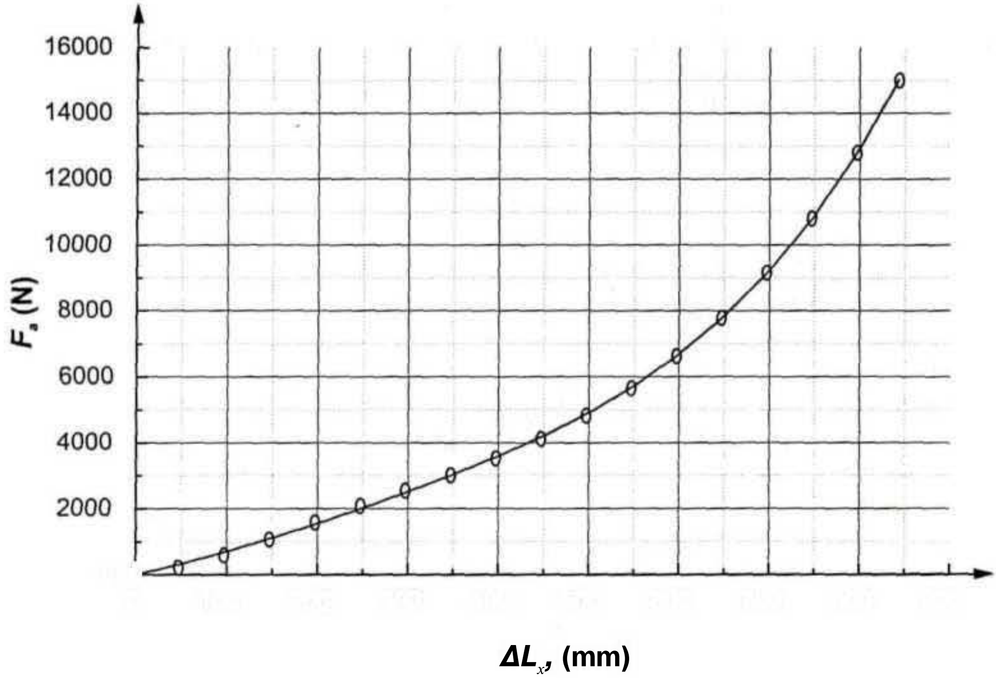

Figure 3. Characteristic of elongation of a 14-mm diameter three-strand polyamide rope. *Notes.* 0—data from measurements,———data from approximation.

this kind of polyamide and polyester ropes can be approximated with satisfactory closeness by the following function:

$$F_a = c_1\Delta L_x + c_2\Delta L_x^2 + c_3\Delta L_x^3 + c_4\Delta L_x^4 \qquad \textbf{(11)}$$

where c_1, c_2, c_3, c_4—parameters dependent on material and construction **of** the rope.

The theoretical analysis and laboratory tests proved that using Equation 11 allows obtaining relative deviations, between the data **from** the test and an approximation, not greater than ±5%. **For example, an** approximation **of** the tension-elongation characteristic of tested rope has given the following values of parameters:

c, = 5.7613, c_2 = 0.015174, c_3, = -0.000033164, c_4 = 0.0000000380.

The results of the approximation are also shown in Figure 3. In order to compute the elongation of an arbitrary initial length L_{x1} Equation 11 can be **transformed** as follows:

$$F_a = c_1 L_{so}\left(\frac{L_{x2}}{L_{x1}} - 1\right) + c_2 L_{so}^2\left(\frac{L_{x2}}{L_{x1}} - 1\right)^2 + c_3 L_{so}^3\left(\frac{L_{x2}}{L_{x1}} - 1\right)^3 + c_4 L_{so}^4\left(\frac{L_{x2}}{L_{x1}} - 1\right)^4 \quad (12)$$

where L_{so}—length of a rope test piece used in order to determine the ΔF_a ΔL_x) characteristic, L_{x1}—length of the rope when $F_a = 0$ N, L_{x2}—length of the rope loaded by the force F_a.

Equation 12 can be applied in Equation 9 where $f(L_{x2}) = F_a$.

4. COMPUTER PROGRAM

The description of HFAL performance demands determination of H, F, F_x as a function of time. This can be obtained by solving the set of Equations 1,9, 10, and 12. In order to solve this problem an iteration method and a computer program in Borland Pascal 7.0 were prepared. A flow chart of this computer program is shown in Figure 4.

The program demands an introduction of the following input data: m, Lo, γ_o, h, c_1, c_2, c_3, c_4, T_s (time of the analysis of HFAL performance), AT (time between successive values of calculated quantities). At the first step of the calculations the values of H_o and initial velocity V_o of the mass (at the beginning of a fall arrest) are determined. The value of H_a is obtained from Equation 6 and the value of V_o from the following relationship:

$$V_0 = \sqrt{2gh} \quad (13)$$

where g—acceleration of gravity, h—the free fall distance.

The values of H_Q and V_o are the initial conditions for the fourth order Runge-Kutta (RK) algorithm used for solving Equation 1, which is a second order differential equation describing the mass movement in the time domain. For calculating the values of $H\{t_i)$, $V(t_i)$, and $a(t_i)$ in successive moments t_i, Equations 9, 10, and 12 are applied. These values are stored in files. The calculations in the RK loop are continued until the period of the analysis is equal or greater than T_s.

At the next step the values of $\gamma(t_i)$ and $F\{T_i)$ are calculated from the equations

$$\gamma(t_i) = \arctan\left(\frac{2H(t_i)}{L_0}\right) \quad (14)$$

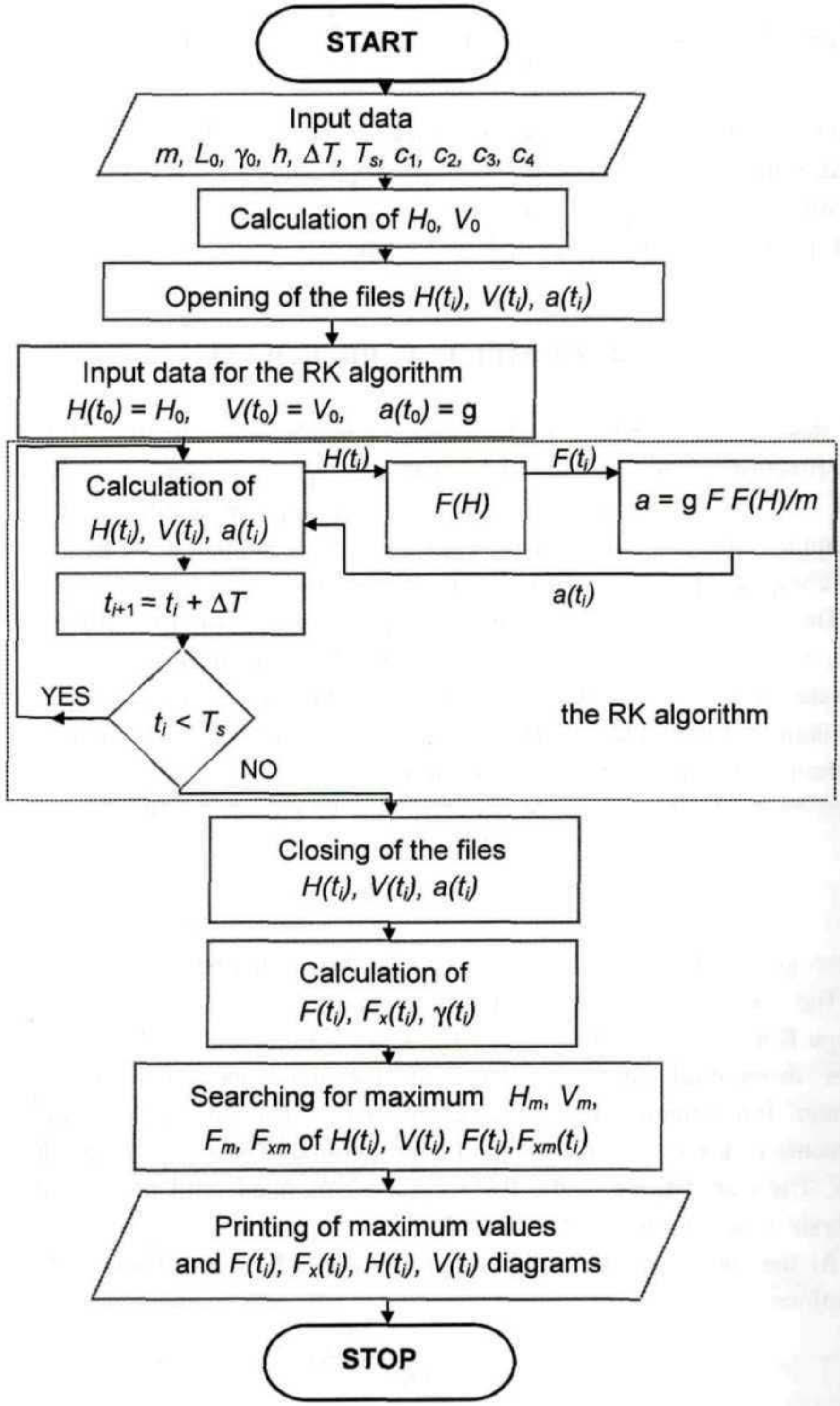

Figure 4. A flow chart of the computer program.

$$F(t_i) = m(g - a(t_i)) \tag{15}$$

and *Fjt(ti)* using Equation 2. Afterwards the maximum values of H_m, V_m, F_m, and F_{xm} are searched in the files. At the end of the program maximum values and curves are presented. An example of the curves being the results of this program is presented in Figure 5.

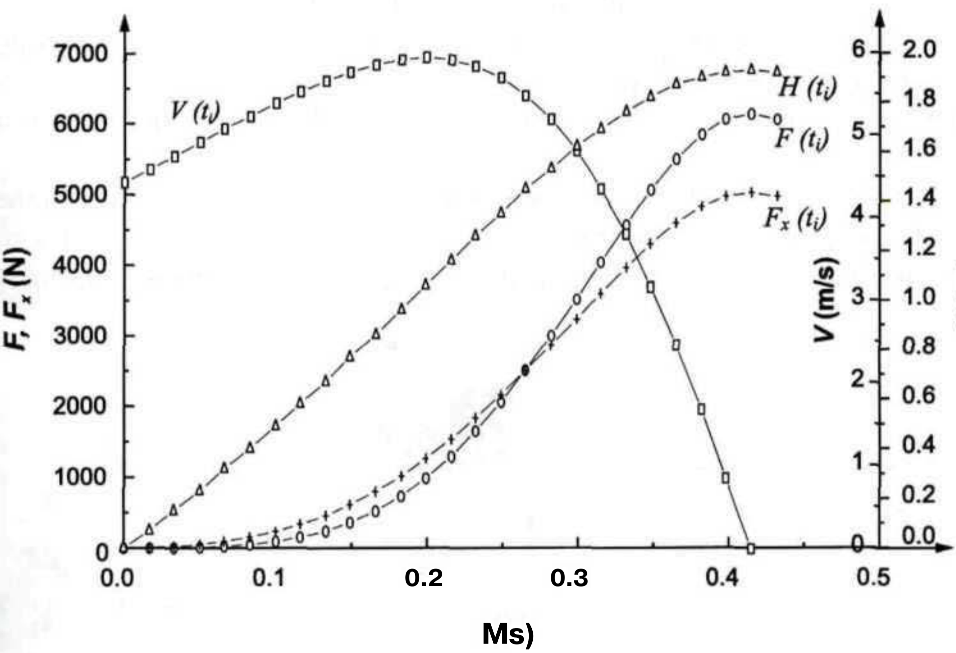

Figure 5. An example of curves obtained from the computer program.

The parameters of the calculations are a 14-mm diameter three-strand polyamide rope, L_0 - 5 m, m - 100 kg $\gamma_0 = 0°$, $h = 1$ m.

5. A COMPARISON OF COMPUTER ANALYSIS RESULTS WITH TEST RESULTS

In order to verify the prepared program several series of laboratory tests were carried out. The horizontal flexible anchor lines used in the tests were made from

- a 12-mm diameter three-strand polyamide rope,
- a 14-mm diameter three-strand polyamide rope,

- a 16-mm diameter three-strand polyamide rope,
- a 12-mm diameter three-strand polyester rope,
- a 14-mm diameter three-strand polyester rope,
- a 16-mm diameter three-strand polyester rope,

and their ends were terminated with loops.

The test stand, described in a simplified way in Figure 6, was applied for the tests. The mechanical part of the test stand consisted of 1—anchor points on a rigid construction, 2—a power winch for lifting and lowering the rigid test mass, 3—a quick release device for the rigid test mass, 5—a chain for connecting the rigid test mass with a HFAL, 6—the rigid test mass (100 kg).

In order to measure the force acting on the mass, the force acting on the HFAL ends, the displacement of the mass the test stand was equipped with a measuring system consisting of 10—a force transducer type U9B-20kN

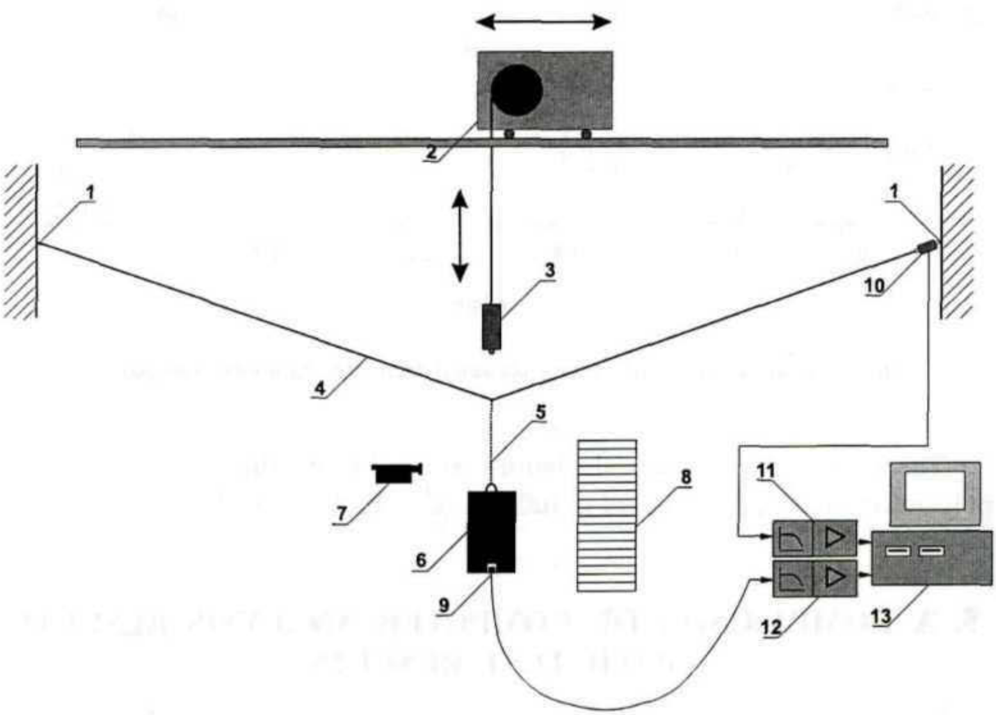

Figure 6. Horizontal flexible anchor lines test equipment. *Notes.* 1—anchor point, 2—power winch for lifting and lowering rigid test mass, 3—quick release device, 4—horizontal flexible anchor line, 5—chain, 6—rigid test mass (100 kg), 7—video camera, 8—screen, 9—accelerometer type 7267A (Endevco, USA) incorporated in rigid test mass, 10—force transducer type U9B-20kN (Hottinger, Germany), 11—amplifier type AE-101 (Hottinger, Germany) with low-pass filter, 12—amplifier type 106 (Endevco, USA) with low-pass filter, 13—a personal computer with measuring card type DAP-1200e (Datalog, Germany).

(Hottinger, Germany), 11—an amplifier with a low-pass filter type AE-101 (Hottinger, Germany) connected to a force transducer (10), 9—an accelerometer type 7267A (Endevco, USA) incorporated in the rigid test mass (6), 12—an amplifier with a low-pass filter type 106 (Endevco, USA) connected to the accelerometer (9), 13—a personal computer with a measuring card type DAP-1200e (Datalog, Germany), which allows recording force and acceleration time signals and their processing after tests.

The force acting on the HFAL ends was directly measured by the force transducer (10). The force acting on the mass was calculated from the acceleration signal from the accelerometer (9). This signal was also used for calculating the mass displacement applying a double integration algorithm. Additionally during the tests a video camera (7) and a screen (8) were applied for tracing the movements of the mass.

An example of a comparison of the results of a computer analysis with those of a test is shown in Figures 7 and 8.

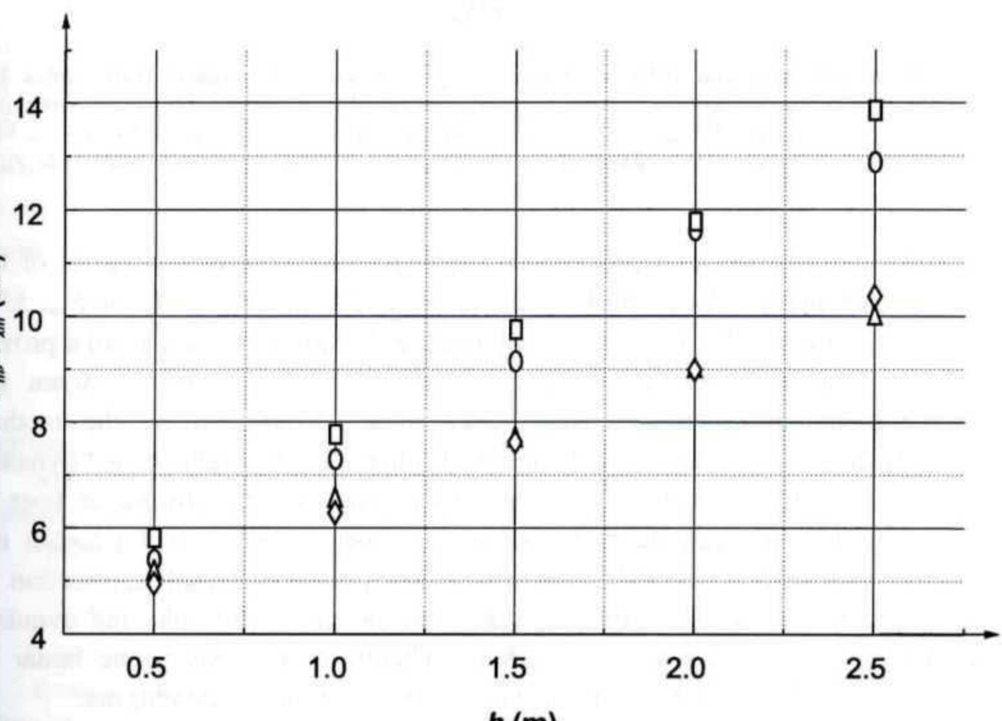

Figure 7. A comparison of the computer analysis results with those of tests. *Notes.* The parameters of the calculations and the laboratory tests: a 14-mm diameter three-strand polyamide rope, L_o= 2.8 m, m= 100 kg, γ_o = 3°; • — F_m from simulation, 0—F_m from tests, • —F_{xm} from simulation, Δ—F_{xm} from tests.

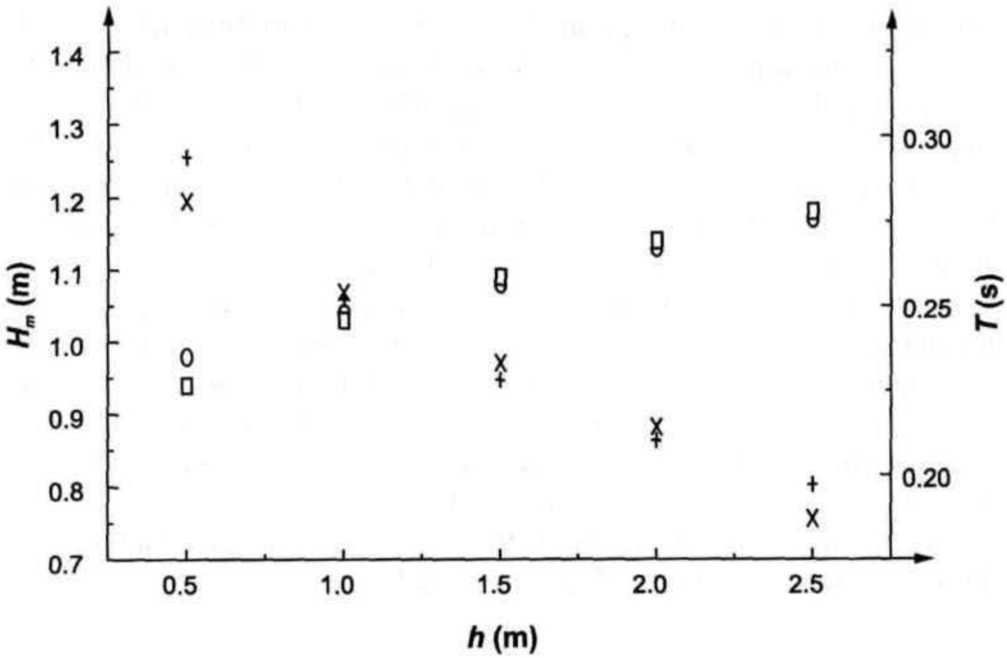

Figure 8. A comparison of the computer analysis results with those of tests. *Notes.* The parameters of the calculations and the laboratory tests: a 14-mm diameter three-strand polyamide rope, L_o = 2.8 m, m = 100 kg, γ_o = 3°; •—H_m from simulation, 0—H_m from tests, +—T_m from simulation, x— T_m from tests (where T_m is the rise time of the force F from value 0 to F_m).

The laboratory tests proved that the maximum relative deviations of the computer analysis from the test results were +7% for F_m, ±5% for F_{xm}, ±5% for H_m, ±4% for T_m. The theoretical analysis based on the test results proved that the main source of these deviations is the difference between the tension-elongation characteristic of the rope, determined by the method described in section 3, and the real characteristic related to dynamic conditions. The velocity of the rope elongation during performance tests of the HFAL can reach the value of several meters per second whereas the velocity in tests described in section 3 was 1 m/min. The determination of this characteristic in dynamic conditions is more difficult and requires applying a complicated test machine. Therefore it seems to be better to accept the determination of the characteristic in static conditions.

The other sources of the aforementioned deviations are

- measuring errors in laboratory tests,
- energy absorption by anchor points and a flexible connector.

6. CONCLUSIONS

The presented method of a computer analysis seems to be a valuable tool in predicting and estimating HFAL performance in real conditions of use. Therefore it can be applied in scientific work and designing systems protecting against falls from a height comprising HFALs. The main advantage of using this method is obtaining not only the maximum values of the fall arrest force F_m, the F_{xm} force acting on anchor points, and the fall arrest distance H_m but also the values of these quantities in every moment of the fall arrest. Additionally the method will be developed for the case where the fall can happen at any location along HFALs. The presented method can be used for predicting the test conditions in dynamic performance tests of class C anchor devices described in the European Standard EN 795:1996 (European Committee for Standardization [CEN], 1996).

The prepared computer program can be transformed in an easy way for analysing the performance of HFALs comprising wire ropes. This transformation demands changing the tension-elongation characteristic (Equation 11) of the rope. In the case of applying wire ropes their characteristics can be approximated by straight lines. It is also possible to use the computer program for analysing HFALs equipped with intermediate structural anchor points. Nevertheless the solution of this problem demands changes in Equations 2-6 describing the forces and the displacement of the mass.

REFERENCES

Baszczyński, K., & Zrobek, Z. (1998). Stalowe poziome liny zaczepowe [Horizontal flexible anchorage lines made from wire ropes]. ***Bezpieczeństwo*** *Pracy, 6,* 18-22.

Dolecki, M. (1990). Obciążenia dynamiczne działające na człowieka podczas powstrzymywania spadania z wysokości [Dynamic loads acting on human body during fall arrest]. *Prace CIOP, 145,* 83-105.

European Committee for Standardization (CEN). (1996). *Protection against falls from a height—Anchor devices—Requirements and testing* (Standard No. EN 795:1996). Brussels, Belgium: Author.

Miura, N., & Sulowski, A.C. (1991). Introduction to horizontal lifelines. In A.C. Sulowski (Ed.), *Fundamentals of fall protection* (pp. 217-283). Toronto, Ont, Canada: International Society for Fall Protection.

Noel, G. (1991). Study of pendular motion and its importance for vertical and horizontal clearances. In A.C. Sulowski (Ed.), *Fundamentals of fall protection* (pp. 345-356). Toronto, Ont, Canada: International Society for Fall Protection.

Paureau, J. (1998). *Falls from height—Simplified modelling* ***of man/protective*** *device systems.* Unpublished manuscript.

Paureau, J., & Jacqmin, M. (1998). Life lines. Specifications. Testing. *Cahier de Notes Documentaires, 173,* 413-428.

Riches, D., & Feathers, L. (1998). Research, development and testing of multiple span multiple use horizontal lifelines from the designer's perspective. In *International Fall Protection Symposium & Exhibition, Wuppertal, Germany* [Abstract] (pp. 104-105). Wupperlal, Germany: Bau-Berufsgcnosscnschaft Rheinland und Westfalen, Zcntrum **für** Sichcrhcitstechnik.

Sulowski, A.C. (1991a). Fall protection systems—Classification. In A.C. Sulowski (Ed.), *Fundamentals of fall protection* (pp. 285-301). Toronto, Ont, Canada: International Society for Fall Protection.

Sulowski, A.C. (1991b). Residual risk in fall arresting systems. In A.C. Sulowski (Ed.), *Fundamentals of fall protection* (pp. 321-344). Toronto, Ont, Canada: International Society for Fall Protection.

Timmcrmans, F. (1998). Design of horizontal lifelines to protect several persons from falling. In *International Fall Protection Symposium & Exhibition, Wuppertal, Germany* [Abstract] (pp. 103-104). Wuppertal, Germany: Bau-Berufsgenosscnschaft Rheinland und Westfalen, Zcntrum für Sicherheitstcchnik.