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EXAMINATION OF THE TIME-DEPENDENT BEHAVIOUR OF CLIMBING ROPES UNDER IMPACT LOADING

PREISKAVA ČASOVNO ODVISNEGA VEDENJA PLEZALNIH VRVI PRI IMPULZNIH OBREMENITVAH

ABSTRACT

A recently developed experimental-numerical-analytical methodology, based on a simple non-standard falling weight experiment, allows the calculation of several physical quantities that are important for the safety of a climber, such as: the maximum force acting on the rope; jolt, i.e., the derivative of the (de)acceleration; the maximum deformation of the rope; and modification of the stiffness of the rope within each loading cycle. This methodology was used in the mechanical characterisation of three commercial climbing ropes. The results indicate that ropes which according to the existing UIAA standard belong to the same quality class actually exhibit significantly different behaviour when exposed to the same loading conditions. One of the tested ropes exceeded the critical jolt value (120g/s) already during the second fall. Thus, although it satisfies the requirements of the EN 892 standard, this rope may not be considered safe. The results prove that the existing safety standards need to be reconsidered.

Keywords: climbing ropes, maximum force, jolt, viscoelasticity

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IZVLEČEK

Novo razvita eksperimentalno-numerično-analitično metoda, zasnovana na analizi mehanskega odziva vrvi na obremenitev generirano s prostim padom uteži, omogoča določitev večih fizikalnih veličin, ki opredeljujejo varnost plezalca: ujemno silo, spremembo pospeška (pojemka), maksimalno deformacijo vrvi, ter spremembo togosti vrvi v enem ciklu obremenitve. Izračuni mehanskih lastnosti treh tipov vrvi so primerjani med seboj z uporabo novo razvite metode. Predstavljeni rezultati kažejo, da se časovno odvisne lastnosti vrvi, ki v skladu s standardom UIAA sodijo v isti kakovostno-varnostni razred, dejansko med seboj močno razlikujejo. Pri eni izmed preizkušenih vrvi je sprememba pojemka presegla kritično vrednost 120g/s že pri drugi obremenitvi. To vrv, kljub temu, da izpolnjuje zahteve standarda EN 892, ne moremo označiti kot varno. Predstavljeni rezultati potrjujejo potrebo po spremembi obstoječih standardov za zagotavljanje varnosti plezalcev.

Ključne besede: plezalne vrvi, ujemna sila, sprememba pospeška, viskoelastičnost

INTRODUCTION

Climbing ropes are designed to secure a climber. They are designed to stretch under a high load so as to absorb the shock force. This protects a climber by reducing the fall forces. Ropes should have good mechanical properties such as high breaking strength, large elongation at rupture and good elastic recovery (Jenkins, 2003; McLaren, 2006; Soles, 1995).

The UIAA *(Union Internationale des Associations d'Alpinisme)* has established standard testing procedures to measure, among other things, how a rope reacts to serious falls (Burnik, Simonič, & Jereb, 2004; Simonič, 2003). Ropes are drop tested with a standardised weight and procedure simulating a climber's fall (EN 892:2004). This reveals how many of these hypothetical falls the rope can withstand before it ruptures. Currently all ropes on the market fulfil the requirements of the standard to withstand the required minimal number of falls, and some are even rated to a much higher number. The standard also prescribes the maximum force which is transmitted to a climber during a fall.

The standard says little about the durability of ropes, which is more difficult to define and assess with simple procedures. Ropes are commonly produced from polyamide fibres that exhibit viscoelastic behaviour. Thus, in this case durability does not just mean the failure of a rope, but rather the deterioration of its time-dependent response when exposed to an impact force. The experiments prescribed by the UIAA standard are not geared to analyse the time-dependent deformation process of ropes, which causes material structural changes and consequently affects the durability of ropes. The time-dependency of ropes also governs the evolution of all physical quantities that are responsible for climbers' safety, e.g., the first derivative of climber (de)acceleration.

In this paper we utilise a recently developed experimental-numerical-analytical methodology based on a simple non-standard falling weight experiment (Emri, Nikonov, Zupančič, & Florjančič, 2008) to analyse the viscoelastic properties and safety of three commercial climbing ropes.

MATERIALS AND METHODS

Theoretical treatment

The time-dependent response of a rope under the dynamic loading generated by a falling mass (deadweight) may be identified from an analysis of force measured at the upper fixture of the rope (Emri, Nikonov, Zupančič, & Florjančič, 2008). This force is transmitted through the rope and acts on the falling weight (mass), as schematically shown in Figure 1(a). In such experiments a mass, m, is dropped from an arbitrary height, $h \le 2l_0$, where l_0 is the length of the tested rope.

Force measured as a function of time, $F(t)$, may be expressed as a set of N discrete data pairs, $F(t) = \{F_i, t_i;\ i = 1,2,3, \cdots, N\}$. An example of such measured force is schematically shown in Figure 1(b). The diagram is subdivided into three distinct phases A, B and C.

In phase A, the weight (mass) is dropped at $t = 0$, and falls freely until $t = t_0 = \sqrt{2h/g}$ where the rope becomes straight, which is indicated in Figure 1(a) as point T_0, and represents the end of the free-falling phase of the mass, and the beginning of phase B. At point T_0 in phase B, where $\tau = t - t_0 = 0$, the falling mass starts to deform the rope. Neglecting the air resistance, and the wave propagation in the rope, the equation of the motion of the moving mass between points T_0 and T_7 may be written as $m\ddot{x}(\tau) = mg - F(\tau)$. Here m is the mass of the weight, g is the gravitational

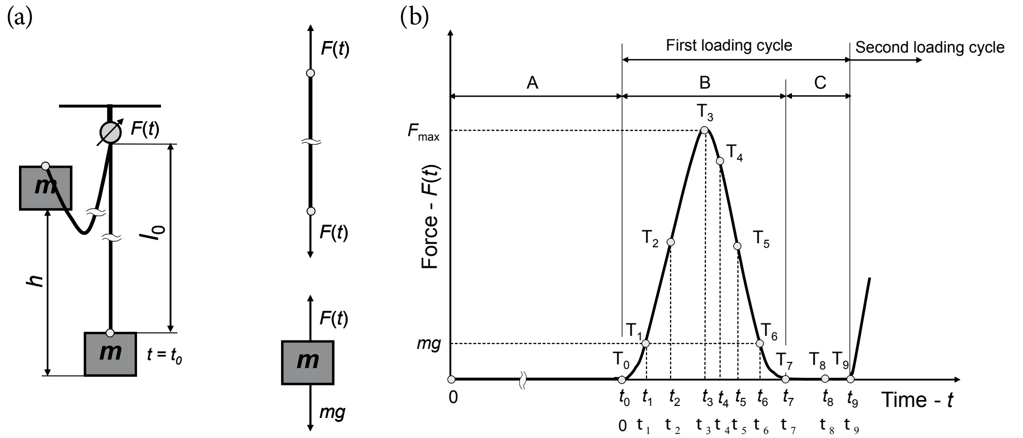


Figure 1: Schematics of a rope exposed to a falling weight (a) and force measured during the falling weight experiment (b)

acceleration, $\ddot{x}(\tau)$ denotes the second derivative of the weight displacement, $x(\tau)$, measured from point T_0. Thus, $x(\tau)$ represents the time-dependent deformation of the rope. Taking the initial conditions at point T_0 into account, i.e. $x(\tau = 0) = 0$, and $\dot{x}(\tau = 0) = v_0 = \sqrt{2gh}$, the solution of the equation of motion gives the displacement of the weight as a function of time, which represents the elastoviscoplastic deformation of the rope as a function of time (Emri, Nikonov, Zupančič, & Florjančič, 2008)

$$x(\tau) = \frac{g\tau^2}{2} - \frac{1}{m}\int_0^{\tau}\left[\int_0^{\lambda} F(\upsilon)d\upsilon\right]d\lambda + v_0\,\tau \quad . \tag{1}$$

At point T_1, where $\tau = \tau_1$, the force acting on the rope becomes equal to the weight of the mass. At T_2, jolt (a derivative of de-acceleration) will reach its negative extreme value. The force acting on the rope and on the weight has its maximum at T3. If the rope's properties were elastic, the location of the maximum force should coincide with the location of the maximal deformation; however, because of the viscoelastic nature of the rope, its maximal deformation will be delayed and take place at $\tau = \tau_4$, that is, at point T_4, where the velocity of deadweight is equal to zero. At $\tau = \tau_5$, indicated as point T_5, the jolt will reach its positive extreme value. At T_6, where $\tau = \tau_6$, the force acting on the rope again becomes equal to the weight of deadweight. Finally, at point T_7, where the force acting on the rope becomes equal to zero, the weight will start its free fly in an upward (vertical) direction.

Considering two characteristic times, τ_4 and τ_7, one may derive equations for the maximal deformation, $s_{max} = x(\tau_4)$, elastic component, $s_{el} = x(\tau_4) - x(\tau_7)$, and viscoplastic component, $s_{vp} = x(\tau_7)$, of the rope deformation.

In addition, we may want to know the stiffness of the rope, $k(F = mg)$, and maximal change of (de-)acceleration, M, commonly called jolt. The governing equations for these physical quantities are (Emri, Nikonov, Zupančič, & Florjančič, 2008):

$$F_{max} = \mathrm{MAX}\{F_i, t_i;\ i = 1,2,3,\cdots,N\} \tag{2}$$

$$s_{\max} = x(\tau_4) = \frac{g\tau_4^2}{2} - \frac{1}{m}\int_0^{\tau_4}\left[\int_0^{\lambda} F(\upsilon)d\upsilon\right] d\lambda + v_0\ \tau_4, \tag{3}$$

$$s_{el} = x(\tau_4) - x(\tau_7) = \frac{1}{m}\int_{\tau_4}^{\tau_7}\left[\int_0^{\lambda} F(\upsilon)d\upsilon\right] d\lambda - \frac{g(\tau_7^2 - \tau_4^2)}{2} - v_0(\tau_7 - \tau_4) \tag{4}$$

$$s_{vp} = x(\tau_7) = \frac{g\tau_7^2}{2} - \frac{1}{m}\int_0^{\tau_7}\left[\int_0^{\lambda} F(\upsilon)d\upsilon\right] d\lambda + v_0\tau_7 \tag{5}$$

$$M_{\max} = \mathrm{MAX}\left[\frac{1}{m}\frac{dF(t)}{dt}\right], \text{ and} \tag{6}$$

$$k = \left.\frac{dF(s)}{ds}\right|_{F=mg}, \text{ where} \tag{7}$$

$$F(s) = \left\{F_i = F(t_i),\ s_i = s(t_i) = \frac{gt_i^2}{2} - \frac{1}{m}\int_0^{t_i}\left[\int_0^{\theta} F(\tau)d\tau\right] d\theta + v_0 t_i;\ 0 \le t_i \le t_7,\ i = 1,2,3,\cdots,N\right\}. \tag{8}$$

These parameters are summarised in Table 1.

Table 1: Physical quantities used to analyse the safety of climbers and durability of ropes

Physical quantity	**Symbol**	**Unit**
Maximum force	$F_{\max}$	N
Maximum deformation	$s_{\max}$	m
Elastic part of rope deformation	s_{el}	m
Viscoplastic part of rope deformation	s_{vp}	m
Maximum jolt	M_{max}	m/s^3
Stiffness of the rope at $F = mg$	k	N/m

Experimental setup

The experimental setup is schematically presented in Figure 2. A force sensor is fixed to the console around 6 m above the floor. The rope being tested is connected to the force sensor at one end and to the weight at the other in such a way that both ends of the rope are on the same level. The weight is then dropped so as to expose the rope to an impact force, which is measured with the force sensor. The measured signal is amplified, converted into digital form (using at least a 12 bit A/D converter) and processed with a specially developed LabView program. In all experiments the mass of the weight was 43.85±0.02 kg.

Free fall tests were conducted on three different commercial ropes. The diameter of each rope was roughly the same, i.e., 9.8 mm. The ropes were first cut into four pieces of equal length, i.e., 3.38±0.04 m. Both ends of each specimen were then sewn to form a noose, as schematically shown in Figure 3. The length of each specimen was measured and recorded before and after the testing.

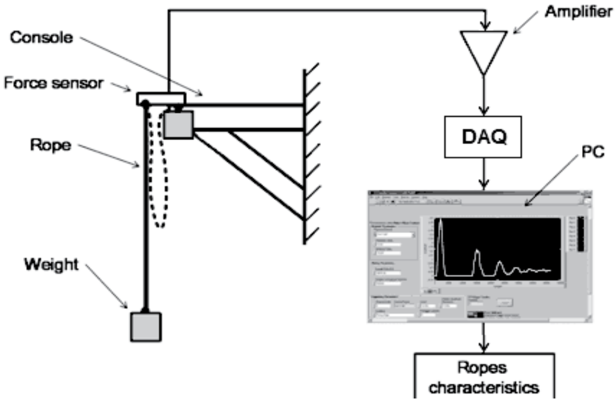


Figure 2: Schematic apparatus layout

All experiments were performed with the same room temperature (26±2oC) and moisture conditions.

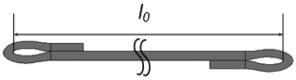


Figure 3: Specimen with nooses

Each specimen was exposed to 10 consequent falls, with 5 minutes' waiting time between two falls. The measured signals were stored and later analysed with self-developed software named DAR. We performed four such series of experiments for each rope.

RESULTS

From the measured force, *F(t)*, we calculated the following physical quantities: maximum force, F_{max}, maximum deformation of the rope, S_{max}, maximum derivative of (de)acceleration, M_{max}, and stiffness of the rope, *k*. By using these physical quantities we compared the performance of three commercial ropes, identified as R1, R2 and R3. According to the existing UIAA standard, these ropes belong to the same quality class.

Two examples of the force response measured on rope R1 during the first and tenth impact loadings are shown in Figure 4.

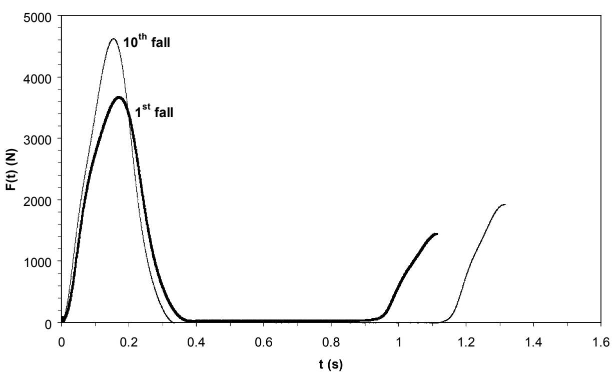
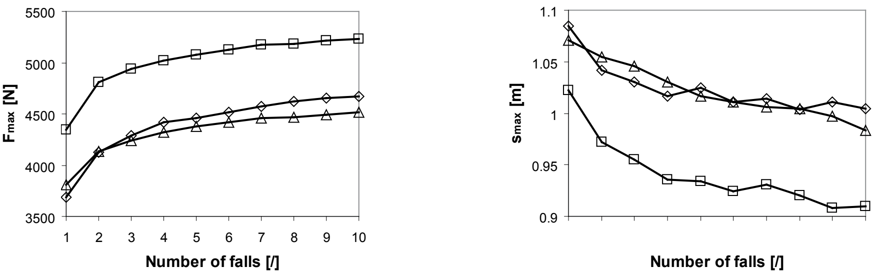


Figure 4: Force response of rope R1 during the first and tenth impact loadings

A comparison of the time-dependent behaviour of the three different ropes exposed to impact loading is presented in Figures 5 and 6. In diagrams the calculated characteristics of the ropes are presented as functions of the number of falls. Figure 5 shows the average values of maximum force, F_{max}, and the maximum deformation of the rope, S_{max}. The average values of maximum jolt, M_{max}, and the stiffness of the rope at the beginning of rope deformation, k, are presented in Figure 6. The maximum absolute deviations from the average values for each physical quantity are presented in Table 2.

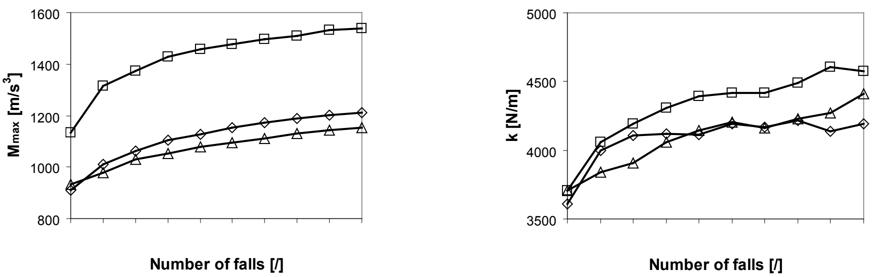
(a) (b)



Legend: ◇ - rope R1, □ - rope R2, △ - rope R3

Figure 5: The maximum force (a) and the maximum deformation of the rope (b) as functions of the number of falls

(a) (b)



Legend: ◇ - rope R1, □ - rope R2, △ - rope R3

Figure 6: The maximum jolt (a) and the stiffness of the rope at the beginning of rope deformation (b) as functions of the number of falls

Table 2: Maximum absolute deviations of physical quantities

Physical quantity	**Max. deviation**
Maximum force	66 N
Maximum deformation	0.03 m
Maximum jolt	252 m/s3
Stiffness of the rope at $F = mg$	63 N/m

DISCUSSION AND CONCLUSIONS

From the diagrams presented above we may recognise that ropes designated equal according to the existing standard exhibit significantly different behaviour when they are exposed to the same impact loading conditions.

After the tenth fall rope R2 generated 15% bigger maximum force, 10% smaller maximum deformation and 35% bigger maximum jolt than ropes R1 and R3. Therefore, rope R2 may be considered more dangerous for climbers than the other two ropes. The stiffness at the beginning of the rope deformation is a little bigger for rope R2 in comparison to that of ropes R1 and R3.

Jolt, i.e., a derivative of climber acceleration or de-acceleration, is a very important parameter for the safety of climbers and may be used to evaluate the quality of climbing ropes. From experience of human space explorations and from car crash experiments we know that a change in acceleration or de-acceleration, i.e., the magnitude of jolt, is more dangerous for human beings than the magnitude of acceleration (inertial force) to which a body is exposed. According to these investigations, the maximal jolt should not exceed $M_{max} = 120\ g/s$, which approximately corresponds to the value $M_{max} = 1200\ m/s^3$.

The obtained results clearly demonstrate that ropes R1 and R3 reach this critical value only after ten consecutive loadings. However, for rope R2 this critical value is already exceeded after the second fall, which could be fatal for a climber. This is particularly important for inexperienced beginners who are learning climbing techniques and are likely to fall more often.

The results indicate that ropes which according to the existing UIAA standard belong to the same quality class and are declared to have the same UIAA standard characteristics actually exhibit significantly different behaviour when they are compared according to the new

experimental-analytical methodology which takes new physical quantities such as jolt into account.

We may therefore conclude that the testing of ropes according to the UIAA standard is not sufficient to guarantee climber safety!

REFERENCES

Burnik S., Simonič E., & Jereb B. (2004). Odpornost plašča plezalnih vrvi [Resistance of climbing rope's sheath]. *Šport, 52(2), 62-66.*

Emri I., Nikonov A., Zupančič B., & Florjančič U. (2008). Time-dependent behaviour of ropes under impact loading: a dynamic analysis. *Sports Technology, 1*(4-5), 208-219.

EN 892:2004 (E): Mountaineering equipment. Dynamic mountaineering ropes. Safety requirements and test methods. The European Committee for Standardization, November 2004.

Jenkins, M. (2003). (ed.), *Materials in Sports Equipment,* Woodhead Publ. Ltd., Cambridge.

McLaren A.J. (2006). Design and performance of ropes for climbing and sailing, *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications, 220*(1), 1-12.

Simonič, E. (2003). *Standardi in obraba vrvi [Standards and wear of ropes].* Unpublished bachelor's thesis, Ljubljana: Univerza v Ljubljani, Fakulteta za šport.

Soles C. (1995). Single-rope buyer's guide. *Rock & Ice, 68,* 117-134.