International Journal of Impact Engineering 38 (2011) 900–909

Contents lists available at ScienceDirect

International Journal of Impact Engineering

journal homepage: www.elsevier.com/locate/ijimpeng

Influence of moisture on functional properties of climbing ropes

A. Nikonov, I. Saprunov, B. Zupančič, I. Emri*

Center for Experimental Mechanics, University of Ljubljana, Ljubljana, Slovenia, and Institute for Sustainable Innovative Technologies, Ljubljana, Slovenia

ARTICLE INFO

Article history:
Received 8 July 2010
Received in revised form
31 May 2011
Accepted 8 June 2011
Available online 24 June 2011

Keywords:
Wet ropes
Impact
Viscoelasticity
Jolt
Energy dissipation

ABSTRACT

Recently developed experimental-numerical-analytical (ENA) methodology presented in Ref. [13] by Emri et al. based on a simple non-standard falling weight experiment, was used for mechanical characterization of "dry" and "wet" climbing ropes. Analysis of the maximum impact force; the visco-plastic component of rope deformation; the amount of stored, retrieved and dissipated energy; the stiffness of the rope; and the maximum value of the first derivative of the de-acceleration (jolt) showed that moisture significantly affects the functionality and durability of ropes. "Wet" ropes create larger maximum force, dissipate less energy, and generate larger retrieved energy that propels climbers in the opposite vertical direction. Properties of "wet" ropes are also more sensitive to number of repeated drops. Major changes of all physical quantities are, as a rule, observed during the first three to four drops. It has been shown that for the safety of climbers the most indicative properties are dissipated energy and jolt (first derivative of climber de-acceleration). The ratio of dissipated and retrieved energy, $\psi = W_{\mathrm{dys}}/W_{\mathrm{ret}}$, could be used as a criterion for evaluation of the quality of climbing ropes.

1. Introduction

The quality of climbing ropes is determined by two parameters, i.e., climber safety and durability of the rope [1]. Durability in this case does not mean just failure of the rope, but rather deterioration of its time-dependent response when exposed to an impact force. Both parameters are governed by time-dependent properties of the material from which ropes are manufactured.

The UIAA (Union Internationale des Associations d'Alpinisme) has established standard testing procedures to measure how ropes react to severe drops [2]. The standard says little about the durability of ropes, which is more difficult to define or assess with a simplified procedures. The experiments prescribed by the UIAA standard are not geared to analyze the time-dependent deformation process of the rope, which causes structural changes in the material and consequently affects the functionality and durability of the rope itself. This is particularly important when ropes are exposed to extreme weather conditions.

It is well known that humidity notably affects the characteristics of ropes, in particular those that are fabricated from polyamide (PA) fibers. "Wet" ropes become difficult to manage, check fewer drops, and have less strength [3].

Baszczynski in Ref. [4] studied fiber ropes and webbing, made from polyamide fibers, used in energy absorbers and guided type fall arresters. Laboratory tests proved that the changes in temperature and humidity especially influence dynamic elongation of this equipment and the force acting on anchor point during fall arresting. Particularly he recognized that conditioning of energy absorbers to "wet" (simulation of rain) can, in some cases, cause an important increase of the dynamic elongation and arrest force by comparison with conditioning to temperature of +20 °C and relative humidity of 65%. Conditioning of some energy absorbers at temperatures lower than 0 °C, after they were preconditioned at "wet" environment, causes such significant increase of the tearing force that during fall arresting the arrest force can exceed its limit.

The effect of moisture on the dynamic properties of synthetic mountaineering ropes was investigated by Spierings in Ref. [5]. They have proposed a new method for the moistening of mountaineering ropes, called Rope Working Stimulator (RWS). The method allows moistening of mountaineering ropes in a more practical way than other methods do. With this equipment, the rope is sprayed with water, moved and bent around artificial carabiners to simulate effects of practical usage. After the treatment in the RWS, the ropes were tested dynamically according to EN 892 (2004) [6] in order to quantitatively investigate their behavior in the moist state. For a rope humidity greater than about 4%, the number of drops sustained decreases significantly and for a humidity greater than about 25%, the number of drops sustained

---

* Corresponding author. Center for Experimental Mechanics, University of Ljubljana, Pot za Brdom 104, SI-1125 Ljubljana, Slovenia. Tel.: +386 1 6207 100.
E-mail address: igor.emri@fs.uni-lj.si (I. Emri).

0734-743X/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijimpeng.2011.06.003

can fall below the threshold value given by the standard, i.e., 5 drops. For the “wet” ropes, they also observed a significant increase of the impact force.

Cotugno et al. in Ref. [7] reviewed the processes involved in the absorption of water by polymeric yarns. The plasticization effect of water causes reductions in elastic modulus and yield strength. This occurs by changing the mechanisms of yield and deformation, as well as the cutting of polymer chains by hydrolysis. The authors show that the equilibrium water content of a specific polymer is not so sensitive to temperature, whereas the rate of absorption is controlled by diffusion, and is therefore strongly temperature-dependent. Nylon-6 absorbs large quantities of water which causes significant changes in mechanical properties and a reduction in the polymer’s glass transition temperature.

The presence of water also notably affects the number of drops. Signoretti in Refs. [8,9] studied the effect of wetting of ropes on the results of DODERO drop testing. He reports that the number of drops withstood is reduced to 30% of the value for the original “dry” rope! This is true for both new and used ropes. He states that even brief immersion, equivalent to a short rain shower, may result in reduction of number of drops. He states that the absorption of water has an effect equivalent to an increase in temperature. This was also described by Kohan in Ref. [10], and even earlier by Emri and Pavšek in Ref. [11]. The latter showed that the effect of moisture on material time-dependent properties may be modeled analogously as the effect of temperature by so-called time-moisture superposition principle. The effect of temperature and pressure on mechanical properties of polymers is reviewed in Ref. [12].

Signoretti also reports that the impact force on the first drop on the DODERO drop test is larger for about 5–10% after wetting, as if the rope had become “more rigid” than the “dry” one. He proposes that this may be due to increased friction force caused by fibers swelling due to water absorption. Based on the findings presented here we believe that some of the above conclusions need further re-examination.

Knowledge on the viscoelastic nature of the material is one of the main understandings required for determining new criteria for safer climbing ropes, i.e., smaller impact force, bigger dissipation energy, less stiffness, less elongation, smaller jolt, etc. However, there is relatively little known about the influence of time-dependent properties of polymeric materials on the mechanical behavior of ropes. Therefore, more detailed experimental and analytical analysis of the influence of time-dependency of the material from which the ropes are made on their behavior under impact loading is needed.

Recently we have developed a new Experimental–Numerical–Analytical (ENA) methodology, presented in Ref. [13], that allows prediction of thirteen physical parameters, which describe time-dependent properties of tested ropes, and consequently safety of climbers. All these parameters can be determined from a measured time-dependent (dynamic) response of ropes exposed to a falling-weight impulse loading.

In the work presented here we have used the new ENA methodology to analyze the effect of moisture on durability and functionality of ropes.

Water acts like a plasticizer, and it strongly modifies the mobility of the amorphous part of macromolecules and shifts, similar as temperature (see Ref. [11]), mechanical response functions and corresponding spectrum along the logarithmic time scale to the “shorter” times. Thus moisture may drastically change the time-dependent properties of PA, and consequently hamper the safety of climbers.

We analyze the effect of moisture on the time-dependent behavior of climbing ropes exposed to ten consecutive falling-weight impact loadings. For each of the ten consecutive drops we analyze the maximum impact force, $F_{\max}$; the visco-plastic component of rope deformation, s_{vp}; the amount of dissipated energy, W_{dis}; the stiffness of the rope, k_{ini}, at $F(t) = mg$; and the maximum value of the first derivative of the de-acceleration, $j_{\max}$, commonly called as jolt. The latter is considered to be the most important safety indicator in car crash analyses. These physical quantities inherently depend on time-dependency of polymeric material and define the functionality and durability of ropes. Their determination using the ENA methodology is presented in the following section.

2. Theoretical background

Details of ENA methodology are described elsewhere [13], therefore, we present here just a brief summary of the developed analytical procedure.

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

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

In phase A, the weight (mass) is dropped at $t = 0$, and it falls freely until $t = t_0 = \sqrt{2h/g}$, where the rope becomes straight, which is indicated in the Fig. 1b 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 motion of the moving mass between points T_0 and T_7 may be written as $m\ddot{s}(\tau) = mg - F(\tau)$. Here m is the mass of the weight, g is the gravitational acceleration, $\ddot{s}(\tau)$ denotes the second derivative of the weight displacement that corresponds to the evolution of the rope deformation, $s(\tau)$, measured from the point T_0. Taking into account the initial conditions at point T_0, i.e., $s(\tau = 0) = 0$, and $\dot{s}(\tau = 0) = v_0 = \sqrt{2gh}$, the solution of the equation of motion gives the displacement of the weight as function of time, which represents the elasto-visco-plastic deformation of the rope as function of time,

$$s(\tau) = \frac{g\tau^2}{2} - \frac{1}{m}\int_0^{\tau} I(\lambda)\mathrm{d}\,\lambda + v_0\tau. \tag{1}$$

In the formula (1) the function $I(\lambda) = \int_0^{\lambda} F(v)\mathrm{d}\,v$ represents the impulse of force generated in the rope.

The deformation energy of the rope at any stage of deformation may be expressed then as (for details see Ref. [13]):

$$\begin{aligned} W(\tau) &= \int_0^{s(\tau)} F(x)\mathrm{d}\,x = \int_0^{\tau} F(\lambda)\frac{\partial s(\lambda)}{\partial \lambda}\mathrm{d}\,\lambda \\ &= \int_0^{\tau} F(\lambda)\left[g\lambda - \frac{I(\lambda)}{m} + v_0\right]\mathrm{d}\,\lambda. \end{aligned} \tag{2}$$

At point T_1, where $\tau = \tau_1$, force acting on the rope becomes equal to the weight of the mass. At T_2, jolt will reach its negative extreme value. The force acting on the rope and the weight has its maximum at T_3. If properties of the rope would be elastic, the location of the

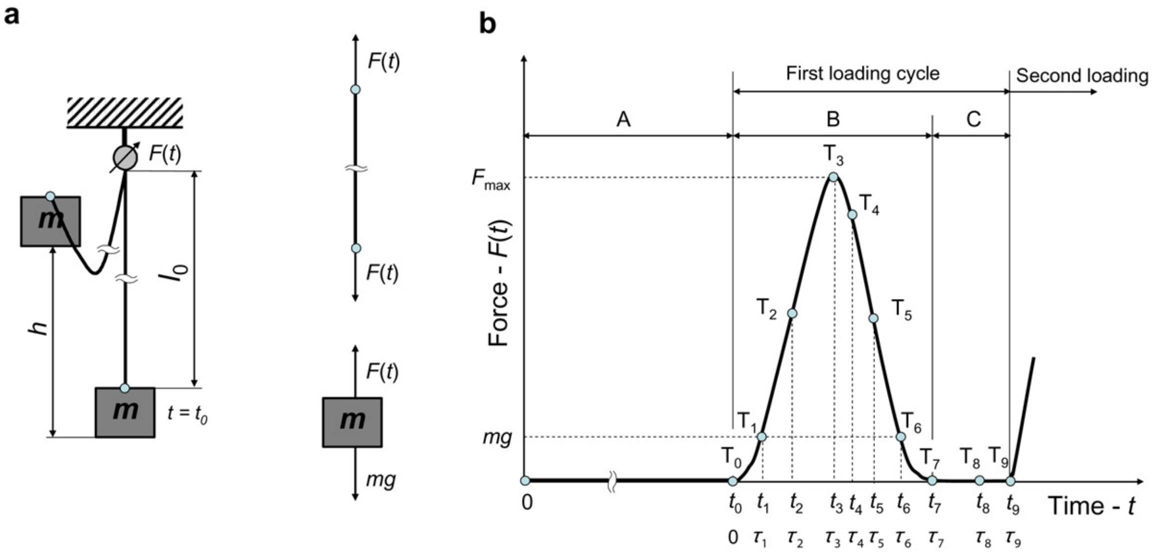

Fig. 1. Schematics of (a) the rope exposed to the falling mass, and (b) the force measured during the falling mass experiment.

maximum force should coincide with the location of the maximum deformation; however, because of the viscoelastic nature of the rope, its maximum deformation, will be delayed and will 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, jolt (derivative of de-acceleration) will reach its positive extreme value. At T_6, where $\tau = \tau_6$, force acting on the rope again becomes equal to the weight of deadweight. Finally, at point T_7, where force acting on the rope becomes equal to zero, the weight will start its free fly in the upward (vertical) direction.

Considering two characteristic times, τ_4 and τ_7, one may derive equations for maximum deformation, $s_{\max} = s(\tau_4)$, elastic component, $s_{\mathrm{el}} = s(\tau_4) - s(\tau_7)$, and visco-plastic component, $s_{\mathrm{vp}} = s(\tau_7)$, of rope deformation. Similarly we can calculate stored energy, W_{stor}, dissipated energy W_{dis}, and retrieved energy, W_{ret}, of the rope deformation process. Using the measured force and utilizing the Eqs. (1) and (2) one can readily calculate all above mentioned physical quantities that determine climber safety and durability of the rope. In addition we may want to know the stiffness of the rope, $k_{\mathrm{ini}}(F = mg)$, and maximum change of (de-) acceleration, $j_{\max}$, commonly called as jolt. The governing equations for these physical quantities are (for further details and explanations see Ref. [13]):

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

$$s_{\max} = s(\tau_4) = \frac{g\tau_4^2}{2} - \frac{1}{m}\int_0^{\tau_4} I(\lambda)\mathrm{d}\,\lambda + v_0\tau_4, \tag{4}$$

$$s_{\mathrm{el}} = s(\tau_4) - s(\tau_7) = \frac{1}{m}\int_{\tau_4}^{\tau_7} I(\lambda)\mathrm{d}\,\lambda - \frac{g(\tau_7^2 - \tau_4^2)}{2} - v_0(\tau_7 - \tau_4) \tag{5}$$

$$s_{\mathrm{vp}} = s(\tau_7) = \frac{g\tau_7^2}{2} - \frac{1}{m}\int_0^{\tau_7} I(\lambda)\mathrm{d}\,\lambda + v_0\tau_7 \tag{6}$$

$$W_{\mathrm{stor}} = \int_0^{s_{\max}} F(x)\mathrm{d}x = \int_0^{\tau_4} F(\lambda)\frac{\partial s(\lambda)}{\partial \lambda}\mathrm{d}\lambda = \int_0^{\tau_4} F(\lambda)\left[g\lambda - \frac{I(\lambda)}{m} + v_0\right]\mathrm{d}\lambda \tag{7}$$

$$W_{\mathrm{dis}} = \int_0^{\tau_4} F(t)\left[gt - \frac{I(t)}{m} + v_0\right]\mathrm{d}\,t - \int_{\tau_4}^{\tau_7} F(t)\left[gt - \frac{I(t)}{m} + v_0\right]\mathrm{d}\,t \tag{8}$$

$$\begin{aligned} W_{\mathrm{ret}} &= \int_{s_{vp}}^{s_{\max}} F(x)\mathrm{d}\,x = -\int_{\tau_4}^{\tau_7} F(\lambda)\frac{\partial s(\lambda)}{\partial \lambda}\mathrm{d}\,\lambda \\ &= -\int_{\tau_4}^{\tau_7} F(\lambda)\left[g\lambda - \frac{I(\lambda)}{m} + v_0\right]\mathrm{d}\,\lambda \end{aligned} \tag{9}$$

$$j_{max} = \mathrm{MAX}\left[\frac{1}{m}\frac{\mathrm{d}\,F(t)}{\mathrm{d}\,t}\right], \text{ and} \tag{10}$$

$$k_{\mathrm{ini}} = \left.\frac{\mathrm{d}\,F(s)}{\mathrm{d}\,s}\right|_{F=mg}, \tag{11}$$

where $F(s)$ represents the force as a function of deformation of the rope. The force as a function of the rope deformation allows construction of the loading-unloading hysteresis diagram, which vividly demonstrates the amount of energy that is dissipated by the rope during one loading and unloading cycle. These parameters are summarized in Table 1.

Table 1
Physical quantities used to analyze the effect of moisture on functionality and durability of ropes.

N	Physical quantity	Symbol	Corresponding equation
1	Maximum force	$F_{\max}$	(3)
2	Maximum deformation	$s_{\max}$	(4)
3	Elastic part of rope deformation	s_{el}	(5)
4	Viscoplastic part of rope deformation	s_{vp}	(6)
5	Stored energy	W_{stor}	(7)
6	Dissipated energy	W_{dis}	(8)
7	Retrieved energy	W_{ret}	(9)
8	Maximum jolt	$j_{\max}$	(10)
9	Stiffness of the rope at $F = mg$	k_{ini}	(11)

3. Experimental setup and measuring procedure

Experimental setup is quite simple and is essentially similar to that for standardized experiments. It consists of a force sensor with an amplifier, data acquisition system with a build-in A/D converter, and appropriate software for data storing and analysis according to the ENA methodology. Thus, the essential part of the measuring setup is the software DAR (Dynamic Analysis of Ropes). The input information for DAR is a set of discrete values of measured force as function of time, $F(t)$, which is essentially the same information that is measured during the standardized experiment. Thus, DAR could be with minor adjustments directly used in all standard experiments (see Ref. [6])! Using the set of equations, Eqs. (3)–(11), we may then calculate all physical quantities listed in Table 1, which are important for the evaluation of rope functionality (i.e., climber safety) and its durability. Detail description of the experimental setup and newly developed DAR software is presented elsewhere [14].

In this study we have used DAR measuring system for analyzing the effect of moisture on functionality and durability of dynamic climbing ropes. We have tested four "dry" and four "wet" specimens prepared from the same commercial rope. Tested rope was single rope made out of polyamide fibers. Diameter of the rope was 9.7 mm, and weight per meter was 63 g. Core of the rope consisted of nine 3-ply yarns.

First, all ropes were cut to the same length and both ends were sawn, as shown in Fig. 2a, to obtain two sets of 8 samples with length $l_0 = 3.5 \pm 0.04$ m. The procedure of length measurements is shown on Fig. 2b.

Before measuring its length each sample was placed onto the flat surface and loaded with the weight $m = 916g$, as shown in Fig. 2b to keep it in a straight position. The set of "dry" ropes were then kept at room condition, whereas the "wet" samples were immersed in water at $26 \pm 2^{\circ}$C for 96 h. Each rope was then exposed to 10 consecutive impact loadings (drops of deadweight) with the time interval of 5 min between each drop. Timing between two consecutive drops was kept very accurate, i.e., within few seconds. The length of tested ropes was measured and recorded at the beginning and at the end of each drop. During the experiment rope was connected to the force sensor with one end and to the deadweight with the other in such way that both ends of the rope were practically on the same level, i.e., $h = l_0 - \Delta l$, where $\Delta l = 5.5$ cm corresponds to the length of release element. The release element is placed between the upper fixture of the rope and the deadweight, and is used to set the mass free to fall. In all experiments the mass of the deadweight was $m = 43.85 \pm 0.02$ kg. The deadweight was dropped from the height, h, and the force was recorded as a function of time, $F(t)$.

Force as function of time was measured with the force sensor type Z6FC3, manufactured by HBM company with the range 0–10 kN. The sensitivity of the sensor was 2 mV/V with sensitivity tolerance of ±0.05%. We have used 12 bit A/D conversion with 40 kHz sampling rate. Measurements and evaluations were performed with self-developed software written in LabView.

Following this experimental procedure for each tested "dry" and "wet" rope we have obtained 10 sets of experimental data $F(t)$, i.e., one for each consecutive impact loading. Two examples of the measured force for a "dry" and a "wet" rope are shown in Fig. 3; Fig. 3a shows measured force as function of time during the first, and Fig. 3b during the tenth impact loading, respectively. On the same figure are also shown locations of the characteristic points from T_1 through T_7.

We clearly see that "dry" and "wet" ropes behave significantly different. Also, we may observe that properties of both, "dry" and "wet", ropes significantly change after ten consecutive impact loadings. These effects become even more vivid when we investigate characteristic physical quantities responsible for climber safety and ropes durability that are listed in Table 1.

4. Results and discussion

From each measured force signal, $F(t)$, we can immediately calculate, using Eq. (1), the corresponding deformation of the rope as function of time, $s(t)$. For the measured force signals shown in Fig. 3 the results of these computations are shown in Fig. 4.

For the "dry" rope are also indicated characteristic points T_0, T_4, and T_7. We may notice again large difference between the deformation process of "dry" and "wet" ropes, as well as the effect of repeated impact loadings.

The two sets of data, $F(t)$, and s(t), may be isochronously combined to obtain $F(s)$, which represents the relation between the force acting on the rope (and climber) and deformation of the rope during the complete loading and unloading cycle. The obtained set of data may be shown as a "hysteresis diagram". In Fig. 5 are shown such diagrams for the "dry" and "wet" rope during the first, Fig. 5a, and the tenth, Fig. 5b, loading cycle. The results shown correspond to the data displayed in Figs. 3 and 4.

The hysteresis diagrams vividly show the maximum force, $F_{\max}$, and maximum deformation, $s_{\max}$, of the rope, as well as the amount of energy that is retrieved, W_{ret}, dissipated, W_{dis}, and stored, $W_{\mathrm{stor}} = W_{\mathrm{dis}} + W_{\mathrm{ret}}$, by the rope in this process. In Fig. 5a we show these quantities for the "dry" rope, along with the characteristic points from T_1 through T_7. The difference between the "dry" and the "wet" rope, as well as the effect of the number of loading cycles is obvious and significant! In general we may say that "wet" ropes create larger maximum force that acts on a climber, dissipate less

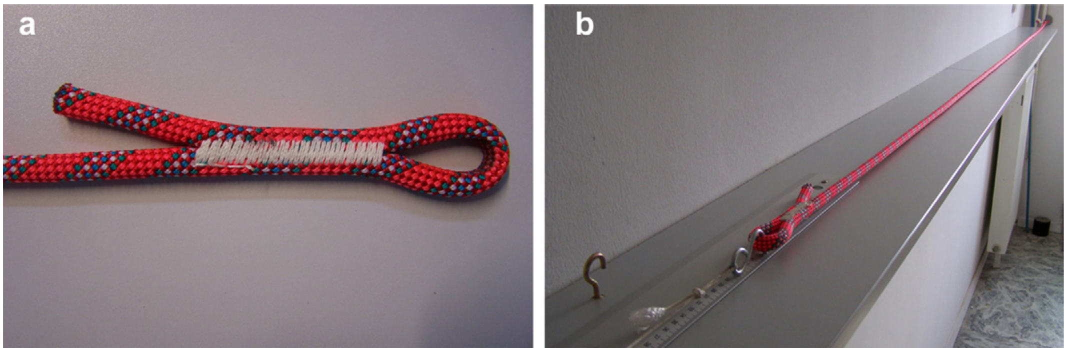

Fig. 2. Preparation of ends of tested ropes (a), and measurement of their length (b).

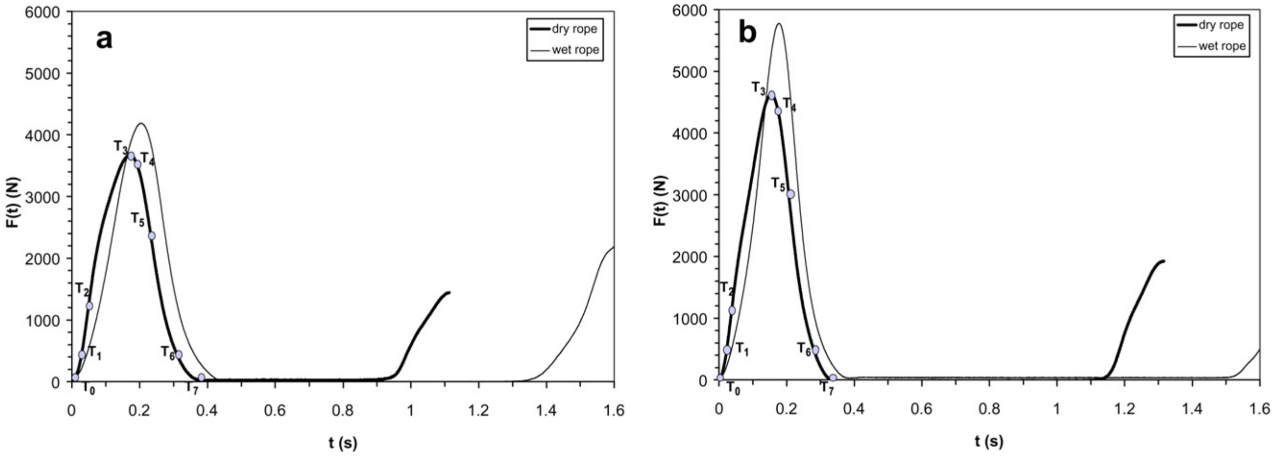

Fig. 3. An example of measured force as function of time for a “dry” and a “wet” rope during the first (a), and tenth (b) impact loading.

energy, and generate larger retrieved energy that propels climbers in the opposite vertical direction. Such rebounds may be extremely dangerous for the climber. As expected, properties of both, “dry” and “wet”, ropes are significantly changing with the number of loading cycles.

Using Eq. (2) one may also analyze the process how the rope absorbs part of climber's kinetic energy during the complete cycle of impact loading. Neglecting the air resistance, the sum of the deformational energy of rope, $W(\tau)$, and potential, $W_{\mathrm{pot}}(\tau)$, and kinetic, $W_{\mathrm{kin}}(\tau)$, energy of climber should be constant at all times, $W(\tau) + W_{\mathrm{pot}}(\tau) + W_{\mathrm{kin}}(\tau) = \mathrm{const}$. For a “dry” and a “wet” rope during the first and the tenth loading cycle the evolution of deformational energy of the rope is shown in Fig. 6. Results correspond to data in Figs. 3–5.

From Fig. 6 we may observe that stored energy of “wet” ropes is larger than of the “dry” ropes. This might come as a surprise at the first glance, because both ropes absorb exactly the same kinetic energy of deadweight, W_{kin}, which is determined with the initial velocity of the falling weight at time $t = 0$, from which the deadweight was dropped. The observed difference results from the fact that deformation of “wet” ropes is larger then that of “dry” ropes. Since the stored energy is equal to $W_{\mathrm{stor}} = W_{\mathrm{kin}} + m \cdot g \cdot s_{\max}$, it becomes obvious that stored energy of “wet” ropes must be larger than that of “dry” ropes.

Energy storing process is completed at point T_4 where deformation of the rope reaches its extreme value. At this point climber (deadweight) starts to travel in opposite upwards direction. The part of the deformation energy stored as elastic potential energy, W_{ret}, is then retrieved between the points T_4 and T_7. The remaining part of the stored energy, W_{stor}, is dissipated by the rope during the loading and unloading cycle, $W_{\mathrm{dis}} = W_{\mathrm{stor}} - W_{\mathrm{ret}}$. The retrieved energy at point T_7 starts to propel the climber in opposite upwards direction. Thus, W_{ret} may not be considered as a desirable property of climbing ropes. We may clearly see that “wet” ropes dissipate much smaller amount of energy and mostly store the kinetic energy of a climber in a form of elastic potential energy, which is completely retrieved upon unloading the rope. The dissipated part of the energy is partially converted into heat and partially into structural changes of the rope on macroscopic as well as on molecular level. The ratio between the two could be used as a criterion for evaluating the importance of the material time-dependent properties, from which the individual fibers are made, versus the macroscopic structure of the rope. We will address this question in one of our upcoming papers. It is important to note that after ten loading cycles the dissipated energy, W_{dis}, of the “dry” rope did not change much, whereas the “wet” rope substantially lost its capability to dissipate impact energy. Since dissipation of impact energy is one of the most desirable properties of climbing

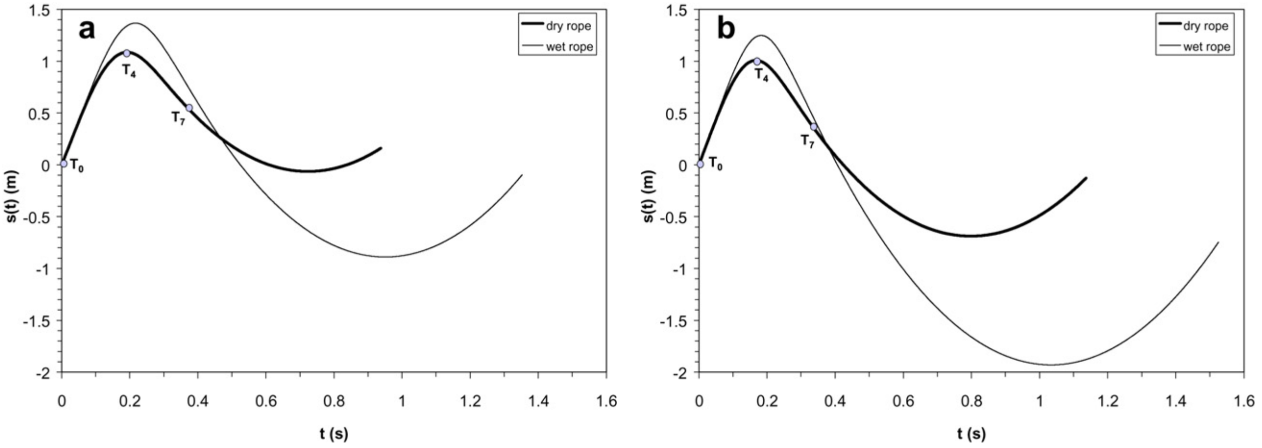

Fig. 4. An example of the calculated deformation of the “dry” and “wet” rope as function of time during the first (a), and tenth (b) impact loading (results correspond to the measured forces shown in Fig. 3).

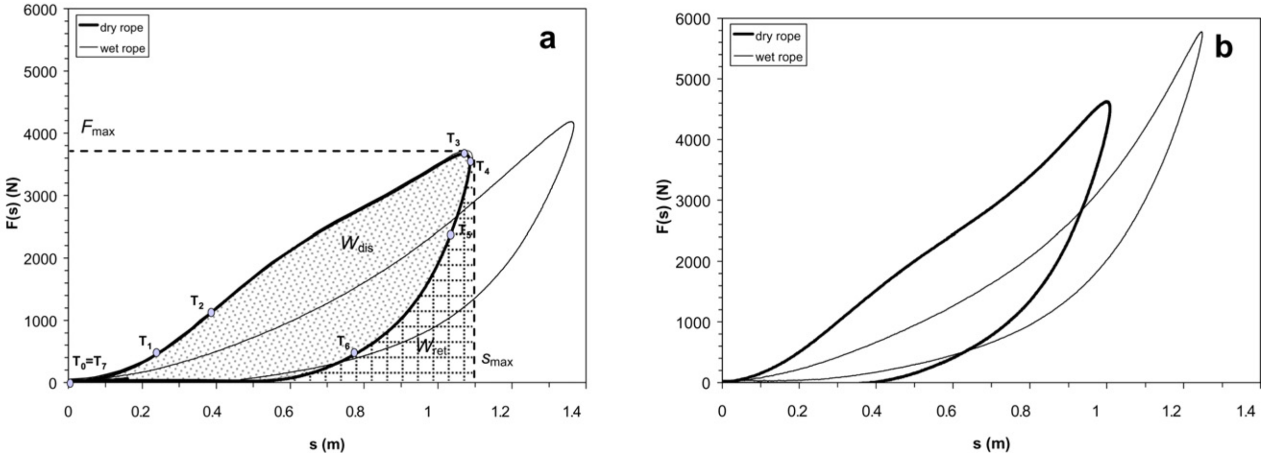

Fig. 5. Hysteresis diagram for the “dry” and “wet” rope during the first (a), and tenth (b) impact loading (results correspond to data on Figs. 3 and 4).

ropes we may conclude that moisture strongly deteriorates the functionality of climbing ropes!

Another very important parameter that determines the quality of climbing ropes is a derivative of climber acceleration or de-acceleration, commonly called as *jolt*, $j(t) = d\,\ddot{s}(t)/d\,t$. From the experience in human space explorations and from car crash experiments it is known that for human beings the change of acceleration or de-acceleration, i.e., magnitude of jolt, is more dangerous than the magnitude of acceleration (inertial force) to which a body is exposed.

The Russian Space Agency has defined that maximum jolt for non-professional cosmonauts (space tourists) should not exceed $j = 120$ g/s, (see Ref. [15])! In Fig. 7 we show comparison of the time-evolution of jolt for “dry” and “wet” ropes during the first and the tenth impact loading. We clearly see that “dry” ropes reach the critical value of $j = 120$ g/s only after ten consecutive drops. Whereas, for the “wet” ropes this critical value is superseded for more than 30 g/s, which could be fatal for the climber. This is particularly important for non-experienced beginners that are learning climbing techniques and are inclined to fall more often.

Hence, we again see significant difference between the “dry” and the “wet” ropes and tremendous effect of the number of loading cycles. Therefore we will systematically analyze the effect of the number of loading cycles on each of the nine physical parameters that are important for climber safety, and are listed in Table 1.

4.1. The effect of the number of loading cycles

All presented results are average values of measurements performed on four “dry” ropes and four “wet” ropes. On all figures are indicated standard deviations which show in all cases good repeatability of experimental results. As expected, standard deviations for experiments on “wet” ropes are slightly larger than those for experiments on “dry” ropes. Nevertheless, the repeatability of measurements is still very good.

4.1.1. Maximum force, F_{max}

The first important quantity is the maximum force F_{max} that is acting upon the climber during the loading cycle. This quantity is measured directly and is also prescribed by the standard EN 892:2004 (see Ref. [6]). Fig. 8 shows comparison of F_{max} as function of number of drops for “dry” and “wet” ropes.

From the shown results we may observe that “dry” and “wet” ropes behave significantly different. The difference at the first drop is not so large, however, with the increased number of drops the maximum force for “wet” ropes increases much faster than that of “dry” ropes. In fact, already at the second impact loading the

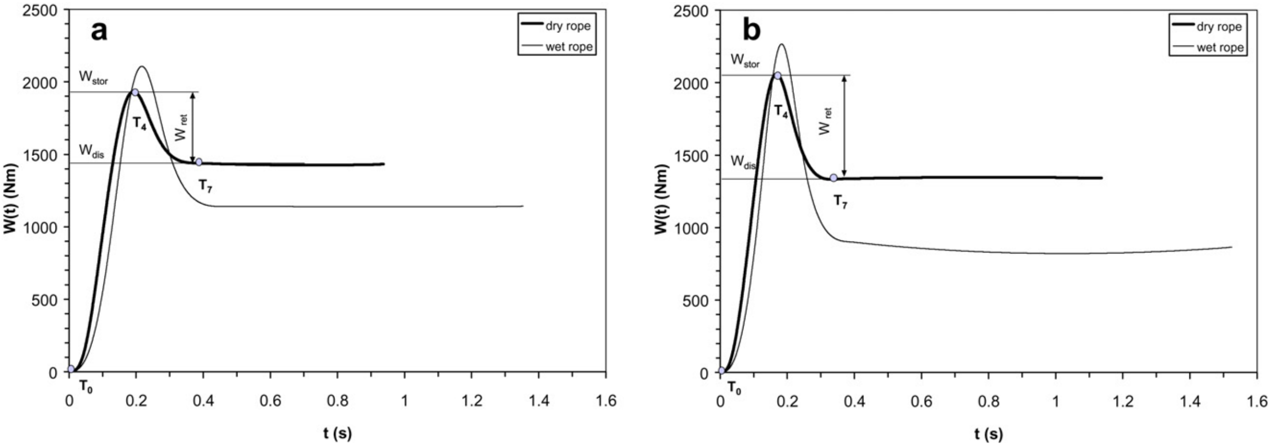

Fig. 6. Transformation of climber’s kinetic energy into rope’s potential-(retrieved) and dissipated energy, for the “dry” and “wet” rope, during the first (a), and tenth (b) impact loading.

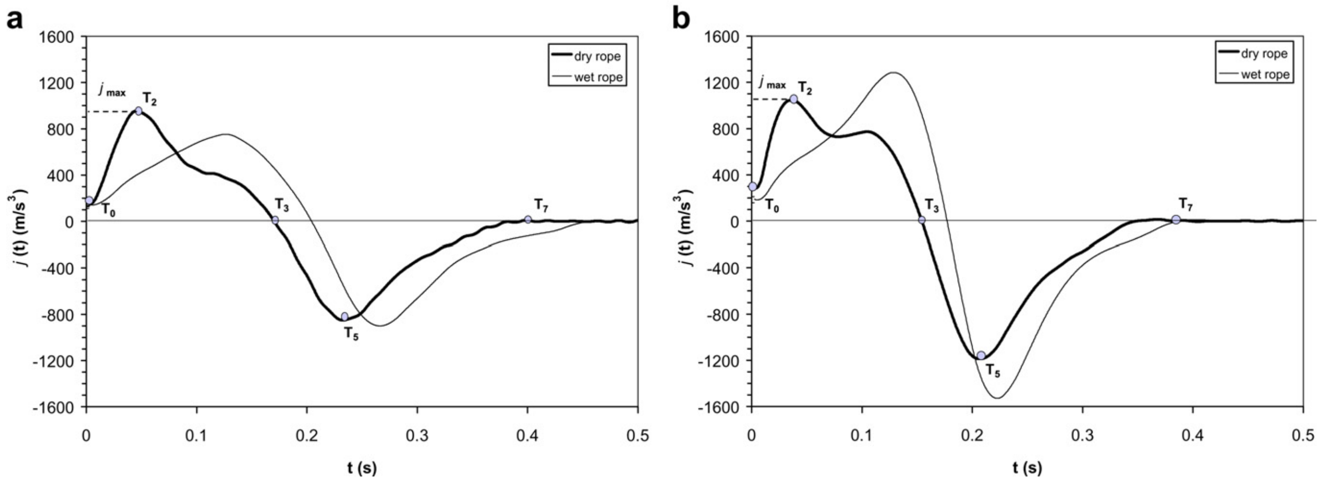

Fig. 7. Jolt as function of time for the "dry" and "wet" rope during the first (a), and tenth (b) impact loading (results correspond to data on Figs. 3 and 4).

maximum force of "wet" ropes exceeds the maximum force that is reached with "dry" ropes after ten consecutive drops. Thus, one could as well say that the *life-time* of "wet" ropes is ten times shorter then that of "dry" ropes! For climbers this is definitely information that should be considered very seriously.

4.1.2. Maximum deformation, s_{max}

Comparison of maximum deformation, s_{max}, of "dry" and "wet" ropes as function of number of drops is displayed in Fig. 9. One observes that "wet" ropes, in addition to generating larger forces that act upon the climber, deform much more than if they are "dry". For both groups of ropes s_{max} slowly decreases with the increased number of drops, which means that both groups of ropes become stiffer from one drop to another.

With the dashed straight lines we have indicated general trends of how s_{max} changes with number of drops. For both groups of ropes major change is observed during the first three drops. From then on changing of s_{max} with number of drops becomes steadier. It is also interesting to note that difference in s_{max} between the two groups of ropes essentially does not change with number of drops, namely, the second two straight lines are in parallel.

4.1.3. Elastic part of deformation, s_{el}

Maximum deformation may be subdivided into the elastic part, s_{el}, and visco-plastic part, s_{vp}, of deformation, $s_{\mathrm{max}} = s_{\mathrm{el}} + s_{\mathrm{vp}}$. Upon unloading the elastic part of deformation is instantaneous and is responsible for the force that propels the climber in opposite vertical direction. Comparison of the results on elastic deformation, s_{el}, of "dry" and "wet" ropes is presented in Fig. 10.

Again, we observe severe effect of moisture on behavior of ropes. The elastic deformation of "wet" ropes is practically twice as large as that of "dry" ropes. In this case the effect of number of loading cycles on both groups of ropes is slightly different. s_{el} of "dry" ropes more or less linearly increases with number of loading cycles, whereas s_{el} of "wet" ropes changes more rapidly during first three drops and then remains practically unchanged throughout the remaining seven drops. All together we may conclude that elastic deformation of "dry" and "wet" ropes is not drastically affected by the number of repeated loading cycles. This indicates that material properties of fibers from which ropes are made are not drastically affected by number of loading cycles.

4.1.4. Visco-plastic part of deformation, s_{vp}

The visco-plastic part of rope deformation, s_{vp}, represents process during which the rope dissipates the kinetic energy of a climber. The visco-plastic deformation essentially consist of two parts, $s_{\mathrm{vp}} = s_{\mathrm{ve}} + s_{\mathrm{pl}}$, i.e., the viscoelastic part, s_{ve}, and the plastic part, s_{pl}. The first time-dependent part, s_{ve}, will be retrieved after certain (delayed) time, whereas the second part, s_{pl}, represents permanent deformation of a rope. Thus, s_{pl} essentially represents

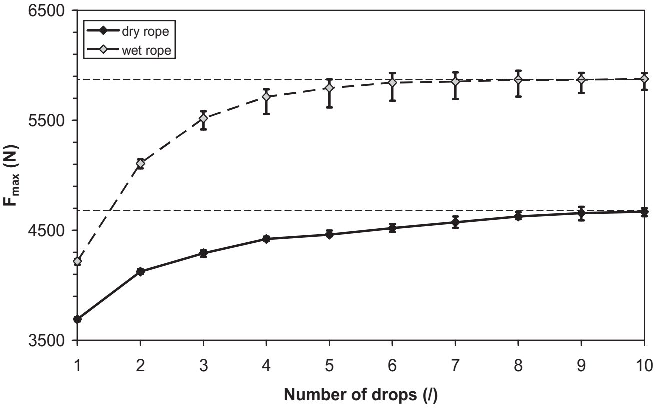

Fig. 8. Maximum force acting on "dry" and "wet" ropes (force acting on climbers) as function of number of drops.

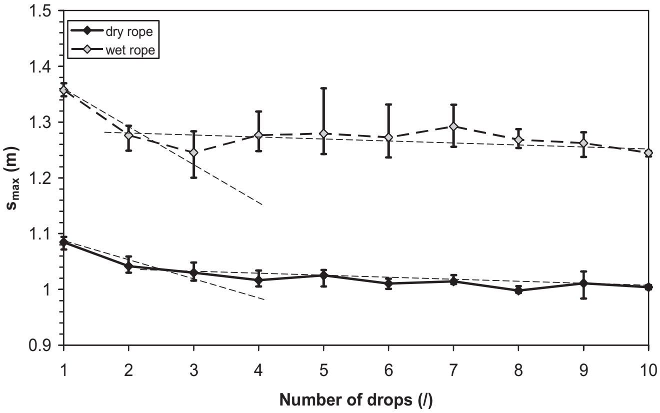

Fig. 9. Maximum deformation of "dry" and "wet" ropes as function of number of drops.

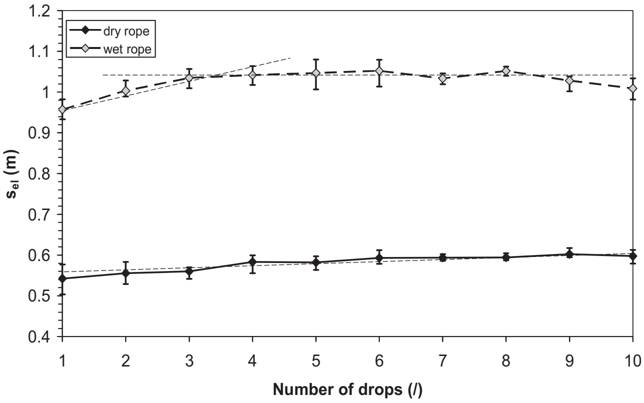

Fig. 10. Elastic part of deformation of “dry” and “wet” ropes as function of number of drops.

permanent damage of a rope caused by the impact loading. Both deformations together, $s_{vp} = s_{ve} + s_{pl}$, represent a process that is responsible for absorbing and dissipating kinetic energy of a falling climber. Comparison of visco-plastic deformation of “dry” and “wet” ropes as function of number of drops is shown in Fig. 11. As expected “dry” ropes exhibit larger visco-plastic deformation than the corresponding “wet” ones. This difference is increasing with number of loading cycles. Thus, “wet” ropes are more sensitive on repeated impact loadings. For both groups of ropes main changes of s_{vp} happen during the first three to four drops. From then on s_{vp} remains for both ropes practically independent of number of drops, as this is shown with two parallel horizontal dashed lines.

4.1.5. *Stored energy, W_{stor}*

The sum of the kinetic, $W_{kin}(\tau)$, and the potential, $W_{pot}(\tau)$, energy of the falling mass (climber), and the deformation energy of the rope, $W(\tau)$, should be constant at all times (neglecting the dissipation due to the air resistance), $W(\tau) + W_{pot}(\tau) + W_{kin}(\tau) = \text{const.}$ At point T_4 where the deformation of a rope reaches its maximum climber starts to move in opposite vertical direction. At this point his velocity is equal to zero and the sum of kinetic and potential energy is converted into rope’s deformation energy which we also call “stored” energy, W_{stor}. Since deformation of “wet” ropes is larger then that of “dry” ropes the stored energy, W_{stor}, of “wet” ropes will be larger. This is clearly demonstrated in Fig. 12, which shows W_{stor} of the “dry” and “wet” ropes as function of number of drops. We may again note that W_{stor} changes with number of drops most significantly during the first two to three drops. From then on W_{stor} starts to increase very slowly. We may also observe that for “dry” and “wet” ropes changing of W_{stor} with number of loading cycles follows roughly the same path, i.e., both dashed lines in Fig. 12 are drawn in parallel.

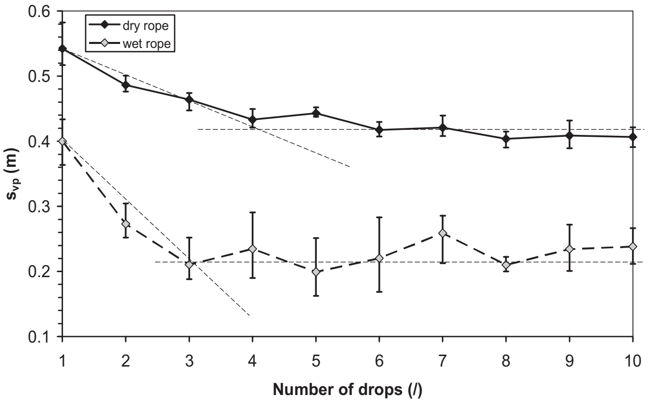

Fig. 11. Visco-plastic deformation of “dry” and “wet” ropes as function of number of drops.

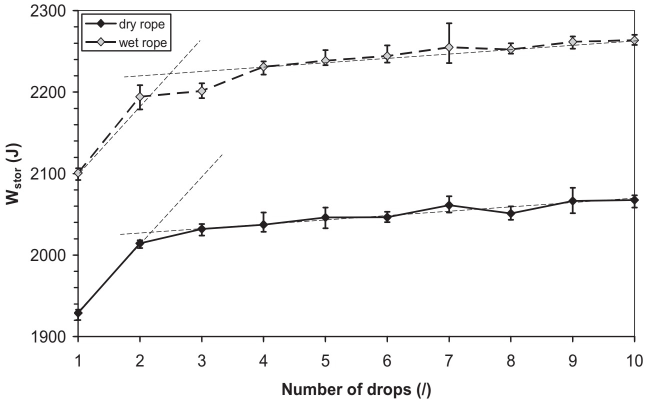

Fig. 12. Stored energy of the “dry” and “wet” rope as function of number of drops.

4.1.6. *Dissipated energy, W_{dis}*

Dissipated energy, W_{dis}, is one of the most important and most desirable characteristics of climbing ropes. This is the energy that is “absorbed” by the rope during the loading cycle. There are two major mechanisms of energy dissipation. The first is Coulomb friction between the individual fibers, whereas the second is dissipation of energy due to the time-dependent (visco-elasto-plastic) behavior of polymeric material (in our case polyamide) from which individual fibers are made. During rope deformation both mechanisms happen simultaneously. For designing the ultimate climbing rope it would be important to understand both mechanisms in more detail. The proposed ENA testing methodology allows studying these phenomena more closely and might be used as an approach for further improvement of climbing ropes. Comparison of “dry” and “wet” ropes as function of number of drops is shown in Fig. 13.

From Fig. 13, we may clearly observe huge difference between the “dry” and “wet” ropes. While W_{dis} of “dry” ropes does not change much with number of loading cycles, the “wet” ropes after four drops literary lose potential of dissipating kinetic energy of a falling climber. Already at the fourth drop W_{dis} of “wet” ropes is almost half smaller than that of the corresponding “dry” ropes.

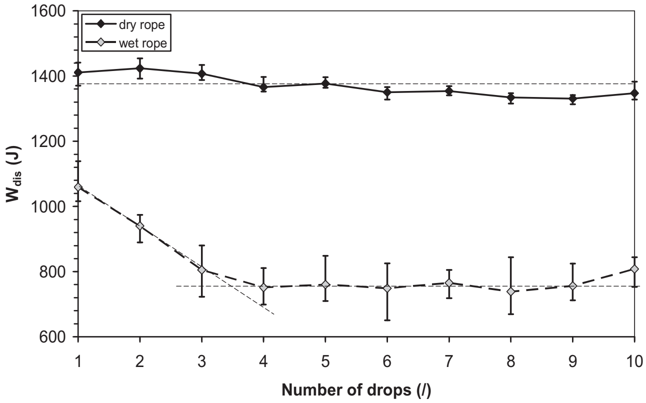

Fig. 13. Dissipated energy of the “dry” and “wet” ropes as function of number of drops.

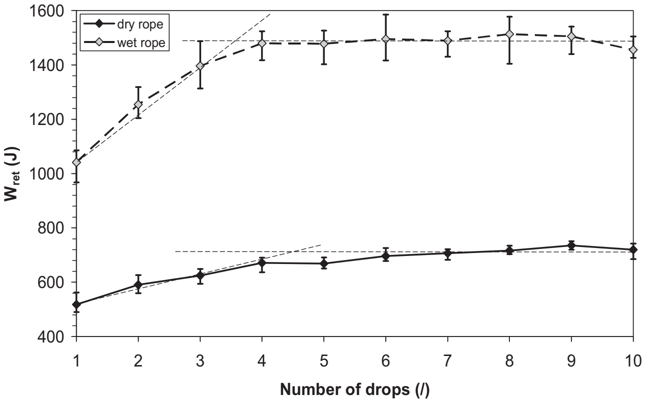

Fig. 14. Retrieved energy of the “dry” and “wet” rope as function of number of drops.

Hence, moisture has indeed tremendous effect on performance of climbing ropes. Thus, climbers must be especially cautious when climbing in “wet” conditions.

4.1.7. Retrieved energy, W_{ret}

Retrieved energy, W_{ret}, is a part of kinetic energy that is stored as an elastic deformation and is completely retrieved during the unloading of the rope. W_{ret} is responsible for bouncing climbers in opposite vertical direction. Such vertical free flies are uncontrollable and can be for climbers very dangerous. W_{ret} is therefore non-desirable property of climbing ropes. Comparison of W_{ret} for “dry” and “wet” ropes as function of number of drops is shown in Fig. 14.

We clearly see that W_{ret} for “wet” ropes is more that two times larger than that for “dry” ropes; this difference noticeable increases with number of loading cycles. Thus, climbers should expect significantly increased bouncing when they use “wet” ropes. Again, it is interesting to observe that for both groups of ropes, “wet” and “dry”, main changes of properties happen within first three to four drops! Within first three drops W_{ret} of “wet” ropes changes for about 50% percent, and then after it remains practically constant throughout the remaining seven loading cycles.

Since W_{dis} is a desirable rope characteristic and W_{ret} is not, one could introduce the ratio $\psi = W_{\text{dis}}/W_{\text{ret}}$ as a criterion for evaluation of the quality of climbing ropes. High quality ropes would have large values of ψ, and vice versa. To compare “wet” and “dry” ropes according to this criterion we show ψ as function of number of drops in Fig. 15. We indeed see that ψ very vividly shows the difference between the two groups of ropes. For “wet” ropes we find that $\psi < 1$, which means that retrieved energy is larger then the dissipated one, whereas we see that for “dry” ropes $\psi > 2$. We believe that it should be possible to determine a critical value of ψ below which rope should be considered as unsafe. Determination of this criterion will be one of our subjects for future research.

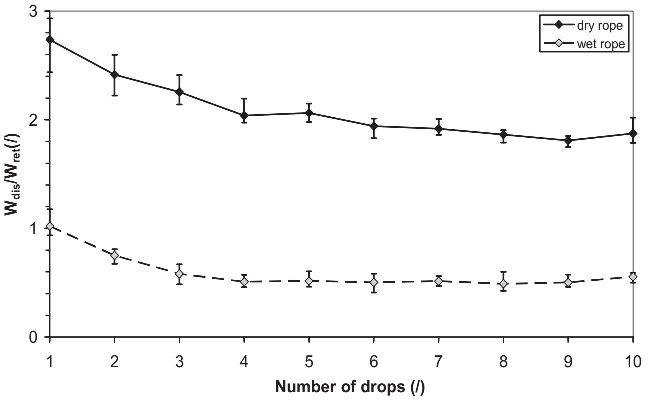

Fig. 15. $\psi = W_{\text{dis}}/W_{\text{ret}}$ for “dry” and “wet” ropes as function of number of drops.

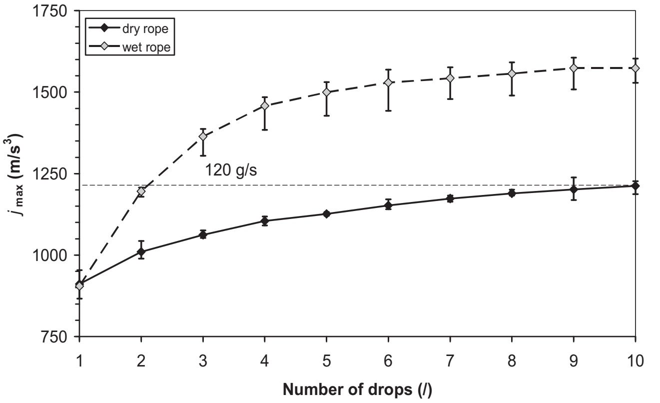

Fig. 16. Maximum jolt generated during the impact loading of “dry” and “wet” rope as function of number of drops.

4.1.8. Jolt, j

From the car crash accidents it has been well established that human body may resist quite large accelerations and de-accelerations (large forces), however, at the same time it is very sensitive to changes of the (de-)acceleration, known as jolt, defined in Refs. [16,17].

The Russian Space Agency has defined that maximum jolt for non-professional cosmonauts should not exceed $j = 12$ g/s, see Ref. [15]. This value could be low for professional well trained cosmonauts who are expected to survive at $j = 300$ g/s. However, at present there are no unique tolerance limits for fall arrest (de-)acceleration.

Fig. 16 shows how jolt is changing with number of drops. We may see that “dry” ropes reach the critical value of $j_{\max} = 120$ g/s only after 10 consecutive drops.

On the other hand “wet” ropes reach the critical value of $j_{\max} = 120$ g/s already during the second drop. For climbers, particularly beginners, this is a very alarming finding, which requires further systematic analysis of this problem.

4.1.9. Stiffness, $k_{ini}(F = mg)$

Stiffness k_{ini} was calculated at k_{ini}, i.e., $k_{\text{ini}}(F = mg)$. Comparison of “wet” and “dry” ropes stiffness as function of number of drops is shown in Fig. 17. As one would expect “dry” ropes are almost twice

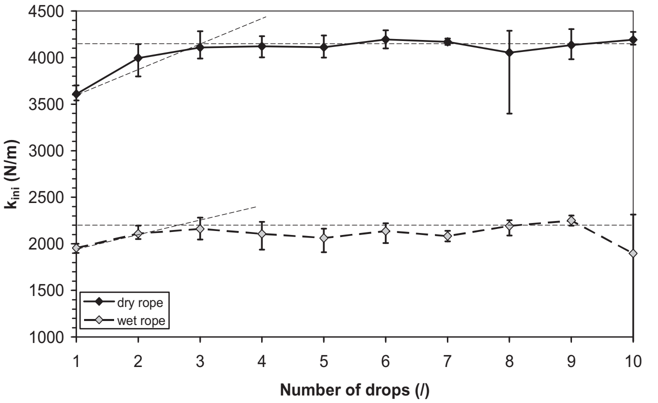

Fig. 17. Stiffness of the “dry” and “wet” rope at the beginning of each impact loading at $F = mg$ as function of number of drops.

as stiff as “wet” ropes. For both ropes we again observe that main changes of the stiffness happen during the first three loading cycles, and from then on it remains practically unchanged.

5. Conclusions

Experimental analysis of “dry” and “wet” ropes exposed to the impact loading showed that moisture has a significant effect on the functionality and durability of ropes. In brief, “wet” ropes create larger maximum force, dissipate less energy, and generate larger retrieved energy that propels climbers in the opposite vertical direction. Major changes are, as a rule, observed during first three to four loading cycles.

More particular findings may be summarized as follows:

(i) With the increased number of loading cycles the maximum force for “wet” ropes increases much faster than that of “dry” ropes. Already at the second loading the maximum force of “wet” ropes exceeds the maximum force that is reached with “dry” ropes after ten drops.

(ii) “Wet” ropes deform much more than “dry” ones. For both ropes $s_{\max}$ slowly decreases with the increased number of loading cycless, which means that both ropes become stiffer from one loading cycle to another.

(iii) The elastic deformation of “wet” ropes, s_{el}, is practically twice as large as that of “dry” ropes. The elastic deformation for both ropes is not drastically affected by the number of loading cycless.

(iv) “Dry” ropes exhibit larger visco-plastic deformation than the corresponding “wet” ones. s_{vp} of “wet” ropes drastically changes within first three drops and then remains more or less unchanged, and quite small. Similar is true for the “dry” ropes, however, change of s_{vp} with number of loading cycles is much smaller.

(v) W_{stor} is much larger for the “wet” ropes. Changing of W_{stor} with number of loading cycles is most significant during the first two to three drops.

(vi) W_{dis} of “dry” ropes does not change much with the number of loading cycles, whereas the “wet” ropes after four drops literary loose their potential of dissipating energy of a falling climber.

(vii) W_{ret} for “wet” ropes is more that two times larger than that for “dry” ropes. These difference noticeable increases with number of drops.

(viii) Since W_{dis} is a desirable rope characteristic and W_{ret} is not, one could introduce the ratio $\psi = W_{dis}/W_{ret}$ as a criterion for evaluation of the quality of climbing ropes. High quality ropes would have large values of ψ, and vice versa.

(ix) Examined “dry” ropes reach the critical jolt value of $j_{\max} = 120\ g/s$ only after 10 consecutive drops, whereas “wet” ropes reach the critical value already during the second loading cycle.

(x) Investigated “dry” ropes are almost twice as stiff as “wet” ropes. Main changes of stiffness happen during the first three loading cycles.

References

[1] Blackford JR. Materials in mountaineering. In: Jenkins M, editor. Materials in sports equipment. Cambridge, UK: Woodhead Publishing; 2003. p. 279–325.

[2] Mountaineering and climbing equipment ‘Dynamic ropes’. Available: http://www.theuiaa.org/upload_area/cert_files/UIAA_101_ropes_2009.pdf; January 2009.

[3] Cox SM, Fulsaas K. Mountaineering: the freedom of the hills. 7th ed. Seattle: The Mountaineers; 2003.

[4] Baszczynski K. Influence of weather conditions on the performance of energy absorbers and guided type fall arresters on a flexible anchorage line during fall arresting. Safety Science 2004;42(6):519–36.

[5] Spierings AB, Henkel O, Schmid M. Water absorption and the effect of moisture on the dynamic properties of synthetic mountaineering ropes. Int J Impact Eng 2007;34(2):205–15.

[6] EN 892:2004. Mountaineering equipment – dynamic mountaineering ropes – safety requirements and test methods. European Standard; 2004

[7] Cotugno S, Mensitieri G, Musto P, Nicolais L. Water sorption and transport in polymers. In: Nylon and ropes for mountaineering and caving. Turin: Italian Alpine Club Technical Committee; 8–9 March 2002.

[8] Signoretti G. Wet and icy ropes may be dangerous. J UIAA 2001;2:25–8.

[9] Signoretti G. The influence of water, ice and sunlight on the dynamic performance of mountaineering ropes. In: Nylon and ropes for mountaineering and caving. Turin: Italian Alpine Club Technical Committee; 8–9 March 2002.

[10] Kohan MI, editor. Nylon plastics handbook. Cincinnati, OH: Hanser Gardner; 1995.

[11] Emri I, Pavšek V. On the influence of moisture on the mechanical properties of polymers. Mater Forum 1992;16(2):123–31. Rushcutters Bay.

[12] Tschoegl NW, Knauss WG, Emri I. Poisson’s ratio in linear viscoelasticity – a critical review. Mech Time-Depend Mater 2002;6(1):3–51.

[13] Emri I, Nikonov A, Zupančič B, Florjančič U. Time-dependent behavior of ropes under impact loading – a dynamic analysis. Sports Technol 2008;1(4–5): 208–19.

[14] Nikonov A, Burnik S, Emri I. Examination of the time-dependent behaviour of climbing ropes under impact loading. Kinesiol Slov 2010;16(3):7–13.

[15] Simonyants RP, University of Bauman, Moscow (private communication); 2010.

[16] Riches D. Analysis and evaluation of different types of test surrogate employed in the dynamic performance testing of fall-arrest equipment. Prepared by Safety Squared for the Health and Safety Executive. Contract Research report 411/2002.

[17] Crawford H. Survivable impact forces on human body constrained by full body harness; 2003. Crown Copyright.