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Product Performance

On the analysis of cut resistance in polymer-based climbing ropes: New testing methodology and resulting modes of failure

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ABSTRACT

Rock climbing ropes tend to suffer catastrophic failure when dynamically loaded over a sharp edge. Seeking to gain a better understanding of this phenomenon, a testing methodology based on a pendulum tear tester has been developed to quantify the cut resistance of polymer-based core-sheath climbing ropes in a reliable and reproducible manner. Experimental measurements indicate that the specific energy required to cut a rope is directly proportional to the linear density of the sheath component in the rope, where a high coefficient of determination between the two parameters is observed. Field tests under actual rock climbing conditions involving a granite sharp edge confirm the practical relevance of the developed laboratory methodology. An analysis of failure modes by means of scanning electron microscopy indicates that cut resistance is inversely proportional to the amount of frictional heating introduced at the point of contact between rope and sharp edge.

1. Introduction

Polymer-based rock climbing ropes are composed of thousands of single polyamide 6 filaments which are hierarchically arranged into yarns and ply yarns with various yarn numbers. The rope construction, typically referred to as *kernmantle*, comprises a core of unidirectional strands surrounded by a sheath of braided strands. The core has primarily a load-bearing function, whereas the sheath fulfills multiple functions such as protecting the core from abrasion and dirt, while also contributing to the mechanical performance of the rope. Rock climbing ropes, also known as dynamic ropes, have a strain to failure in the order of 40% which allows stopping a climber's fall in a controlled manner, preventing a shock-related injury [1]. When a rope is stretched during a climber's fall, the filaments are subjected to tensile, bending and torsional deformations due to their helical arrangement [2], where friction between the different rope components plays a major role in energy dissipation [3]. Friction in ropes is the result of relative slip between components, where the slip and the contact pressure define the work done by friction in opposing a structure deformation [4]. Leech has identified various modes of friction in braided polymer fiber ropes, classified as friction between components or within components [4]. The friction between components can take the form of axial slip, twist slip, scissoring (the angle between the two sliding components reduces as tension is increased), or sawing (tangential slip) [4]. In addition, dilation and distortion of cross-sectional area in a rope component represent the types of friction within a component in a tensed rope [4]. The exertion of frictional forces during rope deformation leads to heat generation which in turn causes a temperature rise in the rope [5].

Dynamic climbing ropes typically do not fail in service unless they are dynamically loaded over a sharp object in the form of a cliff edge, a falling rock or a worn metallic carabiner [1]. There has been a significant effort invested in understanding the cut resistance of single filaments, yarns and ropes. Mayo and Wetzel have described that for a single fiber held in tension, transverse compression is likely to introduce local flaws such as cracks and kink bands which lead to progressive local tensile failure [6]. They further describe that, once a blade cuts between halfway to three quarters of the way through the fiber, the increased tension in the remaining fibrils leads to tensile failure [6]. Hudspeth et al. have illustrated the effect of punch geometry on the modes of failure of a clamped single fiber subjected to a transverse load [7]. They observed that a round indenter yields transverse failure strains comparable to the

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expected longitudinal tensile strain to failure, while the tested fiber ends were highly fibrillated, just as in the case of failure due to pure axial tension [7]. In contrast, cutting with a razor blade results in localized failure which is a consequence of the extremely high stress concentration induced at the blade-fiber interface [7]. At the yarn level, the cut resistance of yarns under tension has been studied by Shin et al., who found that higher axial pretensions lead to yarn breakage at lower cutting loads [8]. They observed that most fiber ends in the fractured yarn were bulbous, with a range of bulb sizes within the yarn [8]. Analyses of filaments extracted from partially cut yarns indicated that deformed material at the tip of the advancing blade flows opposite to the direction of cutting, leading to an accumulation of deformed polymer on the front side of the fiber [8].

Various researchers have developed experimental devices to evaluate the effect of different parameters on the dynamic properties of climbing ropes. Pavier used a falling trolley running on a vertical column to dynamically load a rope [9]. In order to perform the test, the rope is threaded through a fixed metal loop (carabiner) while one end of the rope is tied to the trolley, and the opposite end is secured by pneumatic grips. Once the trolley is released, free fall takes place until the rope is fully tensioned (Fig. 1a). Using carabiners with different radii, Pavier showed that, for a 8.7 mm diameter rope and falling mass of 70 kg, a reduction of carabiner radius leads to a decreased number of falls before the rope fails catastrophically (Fig. 1b) [9]. The fact that rope failure occurs at the point in contact with the heavily loaded carabiner during full extension has also been demonstrated by Rüedi et al., who used a 80 kg mass to quantify the effect of carabiner radius on number of falls endured by the rope (Fig. 1b) [10].

The sharp edge resistance of climbing ropes has been a research topic of particular interest for rope manufacturers and sports scientists. Using both laboratory and scale model setups, Blümel et al. have analyzed the sharp edge resistance properties of mountaineering ropes [11,12]. In the laboratory setup, they attached a series of weights to a rope which falls a distance of 0.8 m before contacting a granite sharp edge. Alternatively, the scale model setup makes use of a pendulum impact testing machine adapted with a notched steel blade which represents the sharp edge. Both experimental setups indicate clear linear correlations between the weight of the falling mass (laboratory setup) or cutting energy (scale model setup) and the variables rope diameter, and rope weight per meter [11,12].

Using the pendulum impact testing machine modified by Blümel et al., Bückers [13] evaluated the effect of pre-tensioning force on the cut resistance of a 10.3 mm diameter climbing rope, where an inversely proportional correlation was clearly observed (Fig. 2a). Further, Bückers also measured the energy required to cut cords and ropes of varying diameters, roughly confirming a directly proportional trend between rope diameter and specific cutting energy [13] (Fig. 2b). Bückers observed that the way in which the rope specimens are pre-tensioned during the cutting tests is an extremely critical factor, concluding that the manual pre-tensioning procedure followed by Blümel et al. [11,12] and by Bückers leads to significant uncertainties in the experimental results [13].

Based on all of the above, the purpose of the present work is to describe the development of a testing methodology which quantifies the cut resistance of polymer-based climbing ropes in a reliable and reproducible manner. The capability of the developed testing methodology to produce experimental results which are representative of real life rock climbing scenarios is confirmed by means of field tests. The failure modes of ropes from both laboratory and field test are analyzed and contrasted at the single filament level as a function of their location within the cut specimen.

2. Experimental

2.1. Materials

All dynamic climbing ropes under analysis were produced and supplied by Mammut Sports Group AG. The ropes are made of polyamide 6 filaments, arranged in the form of a core of unidirectional strands engulfed by a sheath of braided strands, where each strand is composed of yarns and ply yarns with various yarn numbers. The ropes were subjected to hydrophobic coatings [14] which are proprietary and not disclosed by the manufacturer. The physical characteristics of relevance for the present study are listed in Table 1. Rope diameters were determined according to DIN EN 892 [15] as follows: rope specimens were clamped in a universal testing machine with a gauge length of 1200 mm and a load of 10 kg. The rope was allowed to relax for 4 min while maintaining the 10 kg force before its diameter was measured at three points 100 mm apart. The reported values represent mean values.

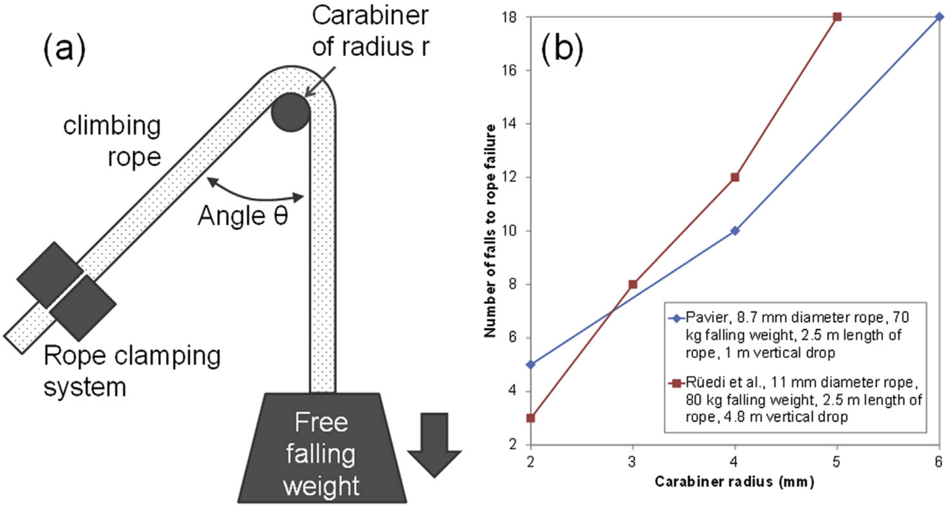

Fig. 1. (a) Schematic illustration (not to scale) of dynamic free-falling weight test to determine the number of falls that a rope withstands before catastrophic failure; (b) number of falls to rope failure as a function of metal loop (carabiner) radius reported by Pavier [9] and by Rüedi et al. [10]. The lines joining the data points in Fig. 1b serve only as a visual aid.