# Snapping of ropes under stress

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**Abstract** - This phenomenon occurs in certain conditions, in steel ropes or textile (e.g. mountaineering) ropes, in the latter in ways which are linked to the characteristics of the synthetic fibres in question.
Tests have been performed on ropes stressed according to U.I.A.A. standards, simulating a locked-end fall-factor 2.
In these conditions, a notch applied suddenly and to a sufficient depth, causes the rope to break instantly. The tests, however, show that if the notch is applied slowly the rope gradually cut down to the last fibre, and that the phenomenon does not occur if the notch is present before the application of the force even if it is applied dynamically.
Special tools used in the experimental tests are described and the results of both experimental tests and numerical model analysis are provided.

## 1. Description of the phenomenon, conditions for its occurrence

A mountaineering rope, stressed up to 1/2 - 1/3 of its breaking force, snaps when a cutting blade notches it slightly but suddenly. The stresses involved are lower than the force of 12 kN, that is the maximum value taken into consideration in the U.I.A.A. standard, in the case of first fall-factor 2 (vertical fall, with a locked end, of the first climber from a height equal to double the length of the rope).
Regarding the conditions in which the phenomenon occurs, the sudden application of a notch to a stressed cord is required to avoid redistribution of the stress in the residual section, according to the static stress equilibrium.
Acting gradually, a cord stressed with a winch, can be cut down to the last fibre (obviously, if the stress is applied with the suspension of a weight, cutting will stop when the stress in the residual section reaches breaking value). The phenomenon does not occur if the notch is applied to an unstressed cord and the stress is applied successively, slowly or even dynamically, as can be easily verified with the Dodero (applying the notch far from the driving gear zone). It has also been verified that a granite splinter can cause a rope to snap in a way similar to the blade used in laboratory.
The depth of the notch depends on the stress applied.
The first step in the mechanical analysis of the phenomenon was to consider the impulsive transmission of the stress from the cut fibres to the adjacent ones by friction, with a fast propagation of the snap. This effect was verified in parallel tests on steel ropes and in a numerical model simulating their behaviour. However, textile ropes differ from steel in both material characteristics and structure (they are made of a bundle of parallel strands within a textile sheath).

The only action of this effect contrasted with an examination of the snapped ropes. There were more cut fibres than had actually been incised by the blame, and in the broken ropes a residual flection could be seen near the notch.

The results of experimental tests performed with specific tools confirm the complexity of the phenomenon, which is disguised by its rapidity. In a transversally blocked cord the process of self-cutting requires a much deeper notch than is necessary in a free cord. It must also be deeper than that corresponding to the alignment of the centroid of the resistant area after the notch and the force axis.

## 2. Description of the tools used to study the phenomenon in the laboratory

The load was applied statically by a winch and measured using an off-centre load cell. This experimental arrangement was more versatile and easy to perform than applying a great static load or the dynamic impulse given by the fall of an 80 kg mass.

The pieces of cord used in the tests had a useful length of 2 meters and the notch was applied to the central section.

The principal element of the test apparatus is a sharp, straight edged steel blade which is threw to the rope at a speed of about 4 m/s. The depth of penetration, related to the initial position of the rope, can be fixed with a precision of one tenth of a millimetre using the micrometer screw (‘A’ in fig. 1). An adjustable support was applied to the rope, on the side opposite to the blade (B, in fig. 1), to verify the depth of the notch. However, it was never utilised, since the tests were carried out with highly stressed ropes and very sharp blades.

To evaluate the displacement of the rope in the direction of the blade, which was blocked after the cut, a further support was placed on its side (C, in fig. 1). The distance of this support from the cord can be regulated with a precision of one tenth of a millimetre. This support controls the displacement of the rope towards the blade. In different tests it can be placed gradually farther and farther from the initial position of the cord until there is no longer contact when the rope snaps (free rope). Once the position of the cord is fixed, the same equipment can also be used to apply a notch of prefixed and unchangeable depth, regarding displacement or deformation effects, (fig. 1c).

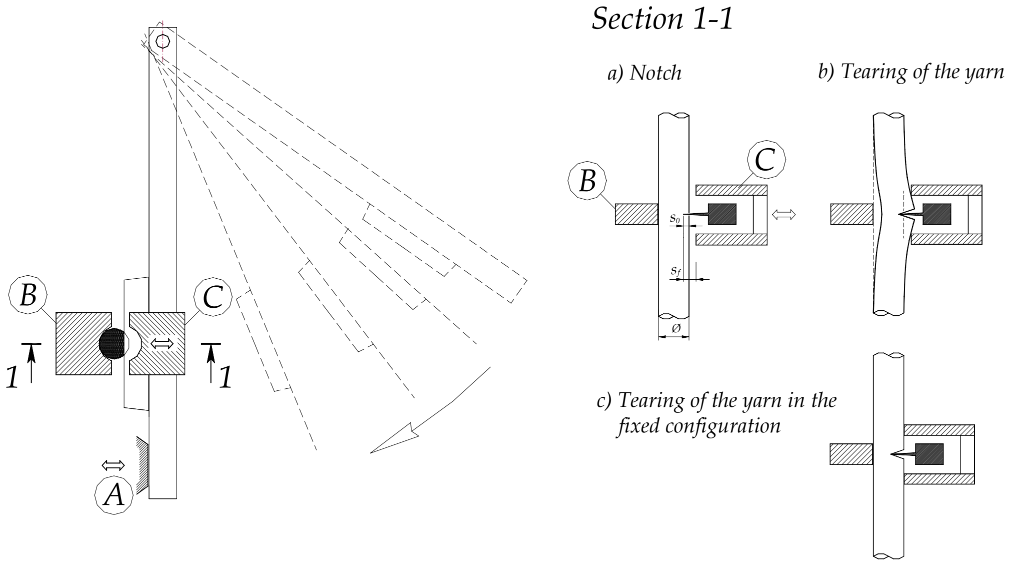

*Fig. 1. Ways of operating the tool used in the laboratory*

## 3. Results of the experimental research

The stresses released at the surface of the notch cause a misalignment between the axis of the load, corresponding to the rope axis, and the resultant of the stress in the notched section. They therefore cause a bending effect in the rope, as indicated in fig. 1b. As a consequence the cord moves onto the blocked blade and the initial cut deepens, given also the action of inertial forces connected with the speed of displacement. In mountaineering the phenomenon occurs until an opening of 30° of the dihedral of the cutting edge, as experimentally tested. The above-described tools make it possible to easily measure the value of the displacement of the rope towards the blade, sufficient to cause the tear propagation described above.

The results of several tests carried out on the same type of 11 mm diameter cord are briefly reported.

Applying an axial force of 8 kN to the cord, a sudden 2.5 mm deep notch applied to the section (now reduced to 8.9 mm diameter by transversal contraction), caused displacement towards the blade of 1.7 mm and started the snap. The same result was obtained by directly applying a 2.5+1.7=4.2 mm notch with the support apparatus connected to the blade, regulated to prevent the cord from moving closer to the blade. In a cord, which was previously cut to a depth of 4.2 mm, a gradually increasing applied load led to failure at a value of 11.6 kN instead of 8 kN.

## 4. Building a numerical model of mountaineering cord to study the phenomenon

In the past several authors [1,2,3] have studied the mechanical behaviour of yarns. In most cases the formulations have been based on experimental parameters concerning stress and strain distributions and failure. Pan [3,4] calculates the stress in a loaded yarn as a function of the distance from the centre and the yarn twist. In the description of the failure phenomenon the internal friction between subsystems is a recurring aspect of fundamental importance [5]. Thanks to it, a broken fibre (fragmentation) can still bear stress and contribute to the overall resistance of the yarn [6,7]. Another aspect studied in the mechanical behaviour of rope and connected to the friction, is the load sharing process. The breaking strands transfer, completely or partially, the loads borne before the failure to the strands remaining whole. Phoenix [8] has studied this phenomenon extensively. Various aspects (e.g. material characteristics dependent on temperature, humidity, etc., Pan [3]), together with the inner non linearity of the constitutive model of the single strand and the discontinuity between the different subsystems (strands, ply yarn, etc.), make the mechanical behaviour strongly non linear and very difficult to simulate numerically.

To obtain an accurate description of the phenomenon it is also necessary to consider the dynamic effects in the representation. These, even if of short length, are fundamentally important. As far as this aspect of the problem is concerned, explicit bibliographic references have not been found nor are analytical and numerical formulations available which permit simulation.

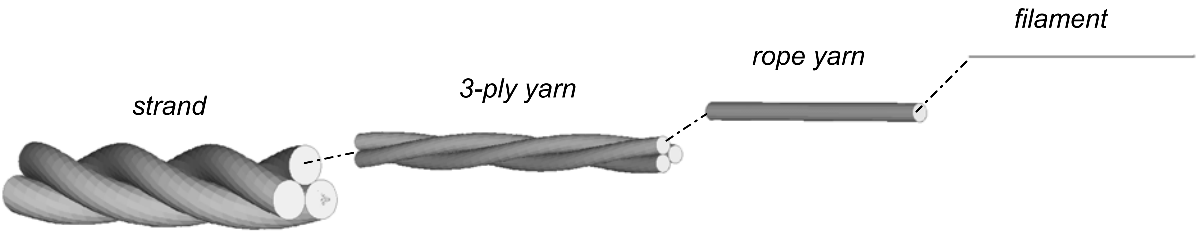

*Fig. 2. A rope structure*

The cord analysed comprises thousands of nylon strands combined in successive levels in textile yarn, rope yarn, 3-ply yarn, strand (fig. 2). Three single yarns helicoidally twisted around an axis form the 3-ply yarn. Unlike other ropes (for instance for sailing) which usually have all the elementary yarns twisted clockwise or anticlockwise, in the ropes analysed the 12 inner yarns are parallel and contained in an external sheath which keeps them compressed (depending on the load applied to the rope). The sheath is composed of strands laid at 90° as in fig. 3. The constitutive model of the single filament is non-linear of the hardening type as in fig. 4.

The inner strands are formed by rope yarn helicoidally twisted with a step of about 8 mm in the unloaded rope. As can be clearly seen in the graph in fig. 4[1], the twisting effect makes the strand less stiffer than straight strands.

The numerical model is based on the strands, modelled with beam type finite elements, to which a constitutive non-linear elastic link is assigned. This material allows for a non-linear relationship between axial force and displacement, but no plastic flow. The behaviour is not path dependent and on unloading, all applied strains will be recovered. Different paths in tension/compression are used. More complex models, i.e. with plasticity and appropriate hardening rule, do not contribute further information towards understanding the mechanical behaviour of rope in the dynamic process of failure. Numerical modelling has been performed only with mono-dimensional finite elements, which seem to be the best to represent rope geometry and the contact problem in its natural discrete form. The core strands are modelled with beam elements with 6 d.o.f./node. The alternative use of truss elements (3 d.o.f./node) would strongly reduce the d.o.f., but, at the same time, would increase the number of iterations for the solution at each time step.

The first solution has been preferred, assuming bending stiffness characteristics for beam elements, which are reduced with respect to those of homogeneous material with diameter equal to that of the strand. Transversal contact between the core strands, sheath strands and between the core and sheath strands is simulated with friction elements whose axial stiffness is non-zero only if compressed (contact friction). The assigned value of stiffness is different from element to element, since it is dependent on the contact area between the connected strands.

The unitary stiffness has been assumed from experimental tests that supply the value of lateral contraction for different values of the applied load. The results of the analysis show how the value of the stress in the strands of the sheath, increases more than proportionally to the deformation measured along the rope axis as a consequence of the variation to the form of the mesh of the sheath.

The contact elements lie on parallel planes perpendicular to the longitudinal axis of the rope. These planes are positioned along the rope where the nodes of the sheath are.

The sheath is formed by 44 strands, 22 twisted in one direction and 22 in the opposite direction, creating a square mesh with directrixes forming a 45° angle with the rope axis. At the contact points the strands are placed one on top of the other. In the same way, in the numerical model, the single strands of the sheath are discontinuous and connected with radial friction elements, as in figure 3.

The numerical model leads to a 20000 equations system.

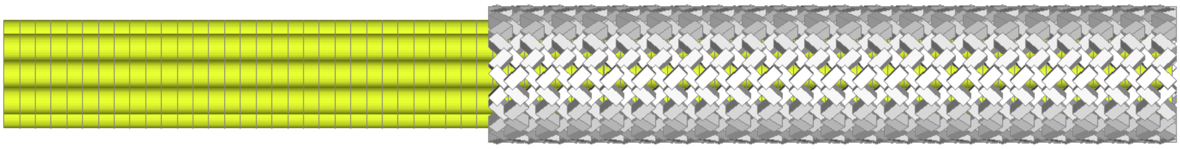

*Fig. 3. Axonometric view of the numerical model*

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[1] By courtesy of Luigi Signoretti, Montefibre SPA, Mestre

The core strands are modelled with straight beam elements, transversally connected by contact-friction elements.

Some *cut-off* elements are placed in the middle section to simulate the failure of the strands when the stress resistant value is reached. Multi-point constraints are used to maintain equal the transversal displacements at the ends of each cut-off element.

The initial conditions of the dynamic analysis have been assumed in relation to the static analysis results carried out on the same model. The simulation of the initial notch is introduced by removing the multi-point constraints and setting equal to zero the maximum traction value of the *cut-off* elements in the zone cut by the blade.

The dynamic analysis considers both geometric and material non-linearity. The transient state, following the initial notch of the wires, is characterised by the displacement of the whole strands towards the virtual cutting blade, thought fixed in its initial position. By means of an automatic routine, the analysis is interrupted when the centroid of a strand (beam) reaches the edge of the blade. The mpcs of the corresponding *cut-off* elements are removed and the maximum traction value is set to zero. The analysis goes on setting as initial condition the configuration of the last step analysed.

The final phase of snapping begins when the remaining strands exceed, in rapid sequence, the resistant strength.

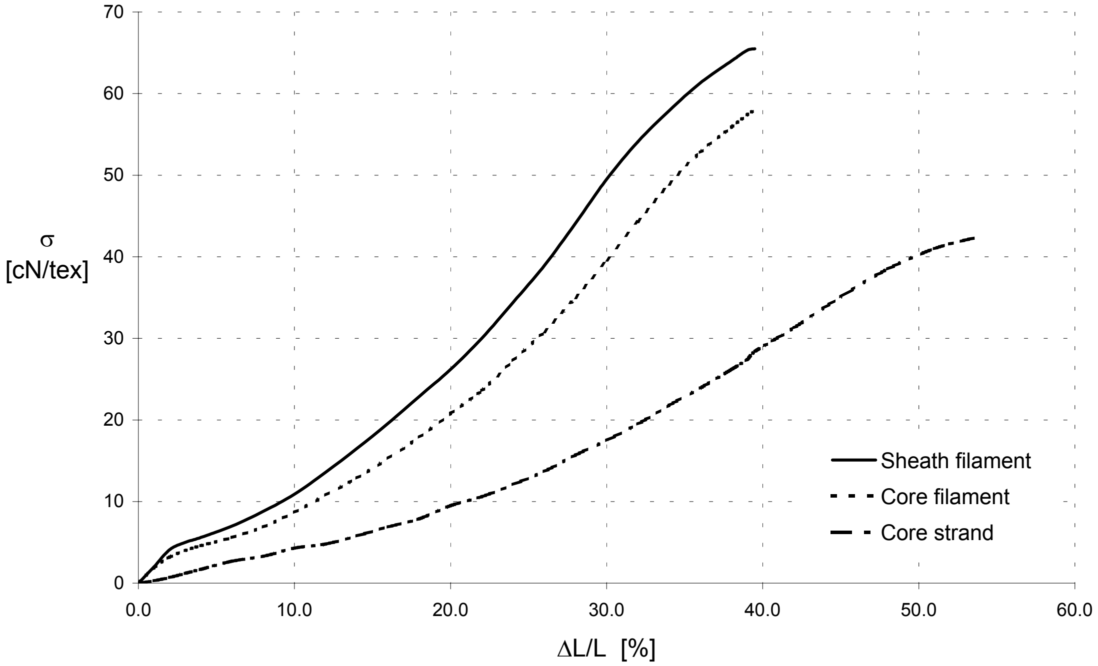

*Fig. 4. Axonometric view of the numerical model*

## 4.1 Numerical results

The results refer to a load of 10 kN and a friction coefficient of 0.3. In figure 3 the contour of normal stress is reported for different time points. Initially, the blade cuts 3 of the 12 core strands and 7 sheath strands (fig. 5a). At 0.0005 seconds after the initial notch, as a result of the displacement of the rope towards the blade, other 3 strands are cut, two completely and one partially. Soon later the remaining strands break in rapid sequence, starting from the inner ones, for reaching their ultimate limit strength (fig. 5b,c,d).

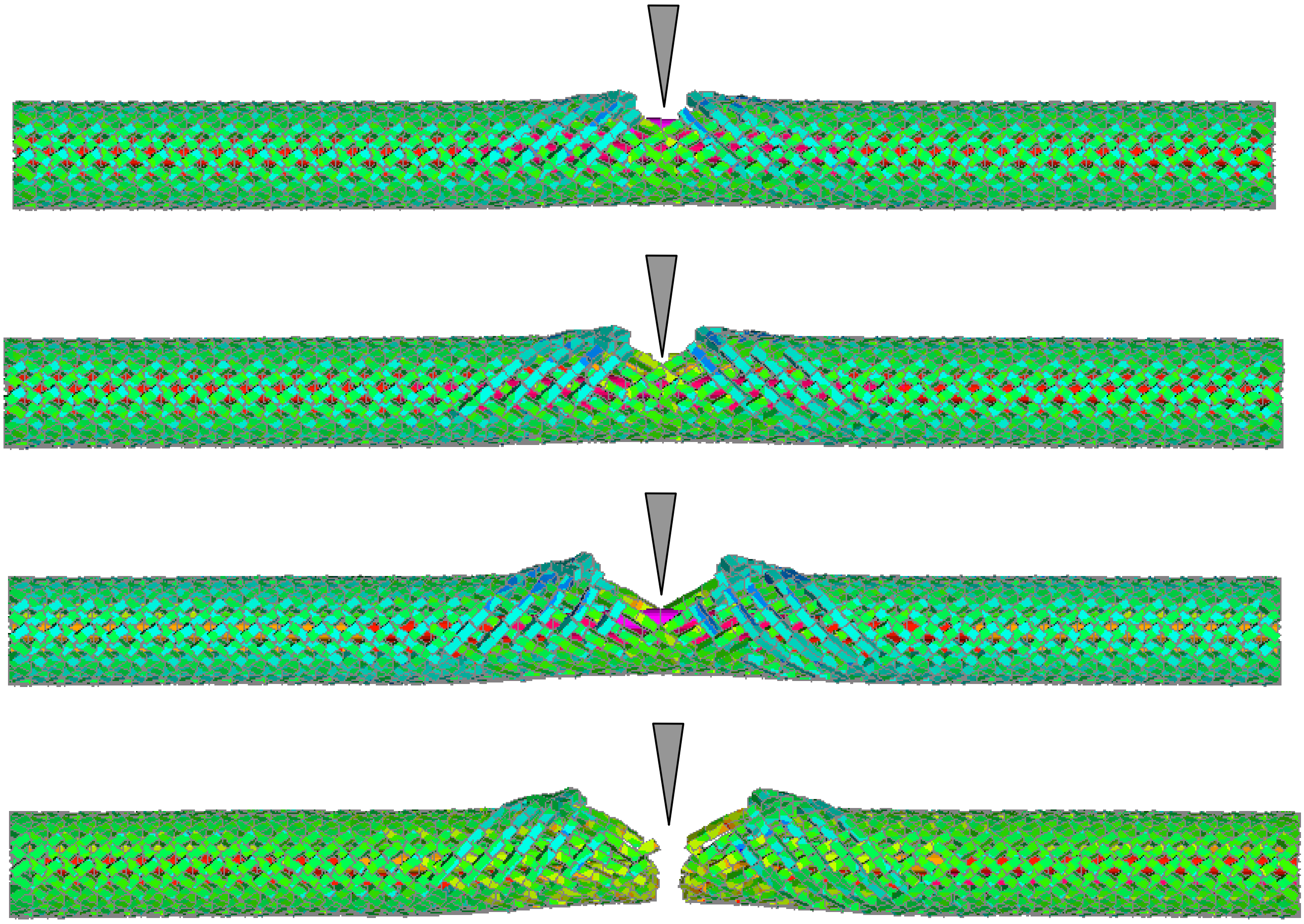

*Fig. 5. Deformed rope configuration for different time steps after the application of the notch*

In fig. 6 the displacement in the direction of the blade is graphed in time. The displacements of the core yarns are calculated in the notched section. From the results of the analyses it emerges that the transverse displacement diminishes with an increase of the friction coefficient.

The graph in fig. 7 represents the time history of the axial force in the core strands. As consequence of the *load sharing*, the strands in direct contact with the cut ones are subjected to an increase of stress grater than that obtained for static redistribution. This effect, different from the previous case, increases with an increased friction coefficient.

The numerical model used allows the phenomenon to be reproduced and the effects of each parameter to be analysed separately.

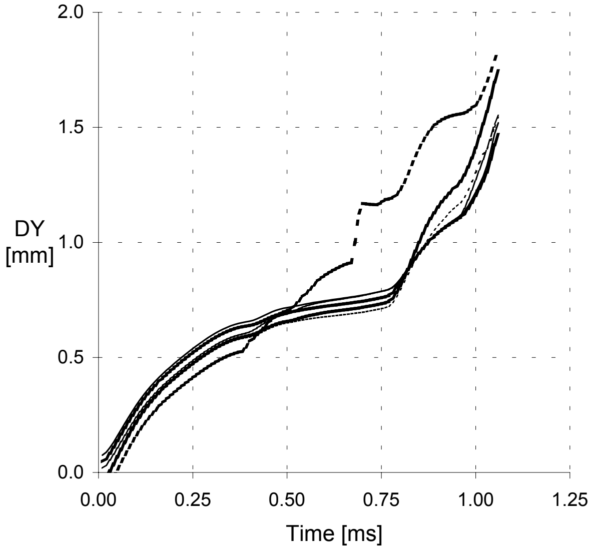

*Fig. 6. Time history of the displacement of the yarn towards the blade*

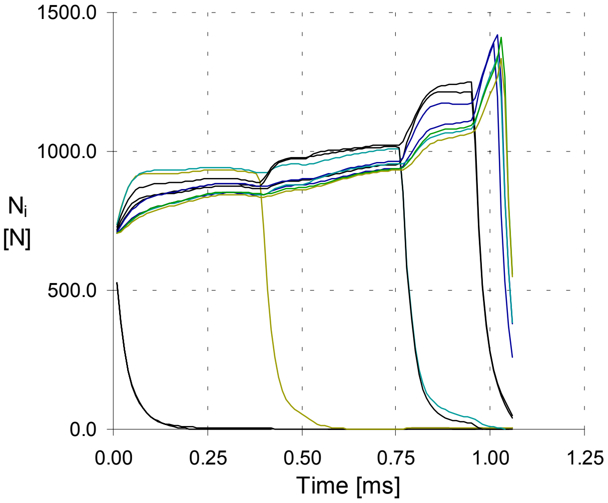

*Fig. 7. Time history of the axial force in the core yarns*

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