NUMERICAL AND EXPERIMENTAL STUDY OF SAFETY NET SYSTEMS FOR HUMAN AND EQUIPMENT SECURITY (SKI APPLICATION)

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GENERAL INTRODUCTION

Human and material safety systems evolve continuously to become more perfect and face increasing requirements. Indeed, important changes of usage conditions and precautions have been caused by the technological progress of the various domains of life (means of transportation, sporting equipments etc.).

In order to follow this technological expansion and optimize it for the benefit of the human beings, several research projects were carried out. In this framework, the following study is presented, concerning the safety systems by keeping-back nets.

PURPOSE AND CONTEXT OF THE STUDY

The main purpose of this work is to contribute to the elaboration of a methodology of installation of the type “A” safety nets, used in the dangerous edges of the tracks of ski. So far, there is no standard of installation insuring the security and the comfort of skiers, particularly, on competition tracks. Indeed, these can produce, with the evolution of specified sport equipment, very high speeds (e.g. 150 kph).

Some accidents already occurred on competition tracks and fortunately no loss of human life occurred. Nowadays, nets used and their implementation methods are carried out by the field specialists without any standardization. This increases the responsibility of their manufactures and installers in the event of an accident.

In this work we would like to anticipate this aspect of security to bring a contribution in the use of these nets, more precisely in the field of this sport. This study consists of two main parts:

An experimental study: This investigation consists of two subsections. The first will serve for determining the mechanical characteristics of the various materials and elementary components establishing the safety system. The second will be dedicated to the study of the global behavior of nets subjected to dynamic loadings under various boundary conditions.

A numerical study: On the basis of the previous study, this work aims to elaborate a model capable of determining the best configuration of the system studied for a given safety criterion (e.g. HIC). This will allow taking into account the safety standard evolution without needing to repeat expensive experimental studies. Furthermore, once the model is tuned, it can be modified at any time, to change the characteristics and the dimensions of the basic elements of the system.

TERMINOLOGY

In standards:

Safety Net: Net supported by a boltrope, another element of support or a combination of both of them, designed to stop the falling of people or objects from high elevations in the construction field, and to stop people or objects in movement in sport and transport.

Thread: Rope from which the meshes of a net are carried out.

Boltrope: Rope that passes mesh by mesh through the net extremities meshes and which determines the dimensions of the safety net.

In this paper:

Resistance: Minimum break energy.

Static: static or quasi-static as opposed to dynamic impulsive loads.

Elementary components: boltrope, thread, dynamic rope, static rope, involved in the security system.

TYPE OF NET STUDIED

There are various types of nets, generally classified according to the size and shape of their meshes and to their minimum break energy [1]. Indeed, the same terminology is used in different industrial frameworks for different net types. For example, the type A nets in the construction field are less resistant than those of the type B, while in the sport field, the nets of type A are the most resistant. Therefore, some confusion may arise in their nomination.

Nets dealt with in this project are of type A for ski applications. This type is used ***only*** in ***dangerous*** places of ski slopes: in front of cliffs, trees etc. Care must be taken to install type A nets, since they are placed in single layers in places where there is no place for large deflections. They are used in the opposite way as ski nets of type B. Latter are placed one after the other in a sequential way of 3, 4 or 5 nets, each of them being submitted to less loading and installation constraints.

Fundamental characteristics of type A ski nets are summarized in the following table.

	DIAMETER (mm)	MATERIALS	SPECIFIC WEIGHT (g / ml)	TYPE
THREAD	4.5 - 5	Polyethylene or polyamide	6.7-8	Braided thread
STATIC ROPE	12	Polyamide	89	Braided thread
BOLTROPE	12	Polypropylene	70	Mono cabled strand

Table 1 Net components characteristics

SPORT SECURITY NETS

Nets with a defined structure are already used in ski applications. They are composed of a whole series of square or diamond shaped meshes laid out. At the periphery of the net, a boltrope is arranged to reinforce its framing, Figure 1.

The lower side of the net is fixed to a ground cable, under the snow level, by a static rope. This rope is of a variable length in order to regulate the right position of the net regarding snow level.

On its upper side, the net is fixed by a dynamic energy absorption system constituted by pulleys and karabiners fixed to the net and to an overhead cable. Between them slips a dynamic rope, to allow the complete shock damping in case of an accident.

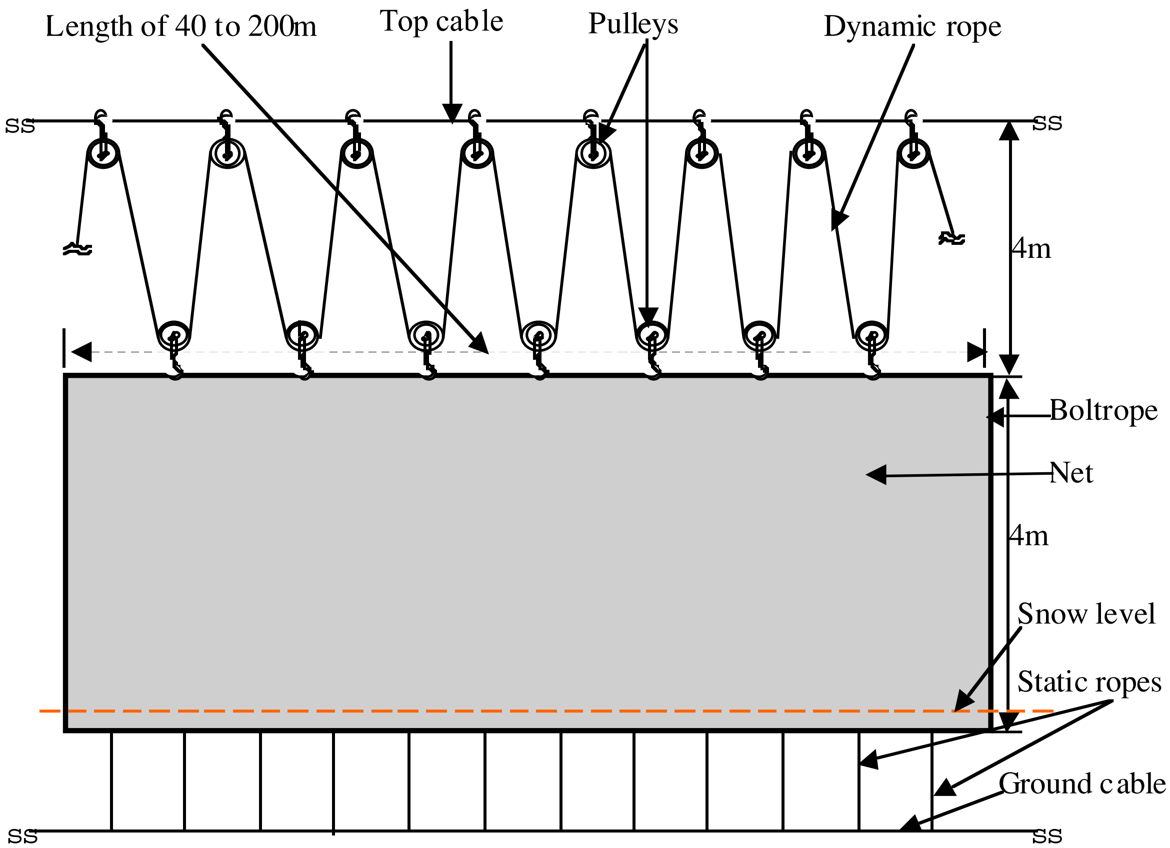


Figure 1 Installation plan of keeping-back ski nets

EXPERIMENTAL STUDY

STATIC MECHANICAL CHARACTERIZATION

Since the mechanical characteristics of all the constitutive elements of the security system are not available, we were brought to realize an experimental characterization study. A part of it is briefly developed below. In this study, only identified basic elements of the protection system are characterized. Namely, the thread, static and dynamic ropes as well as the boltrope were investigated.

Testing configuration

Existing European standards [2], [3], [4], [5] show that the characterization of ropes requires to use a particular device to avoid any slip or rupture on the boundary conditions. A testing configuration was specially designed in order to carry out the tests. The test consists to apply a tensile loading effort, until breakage, at both extremities of each rope: thread, static rope, dynamic rope, boltrope.

Data acquisition

Tests were carried out on a static traction Adamel Lhomargy DY 26 machine, Figure 2.

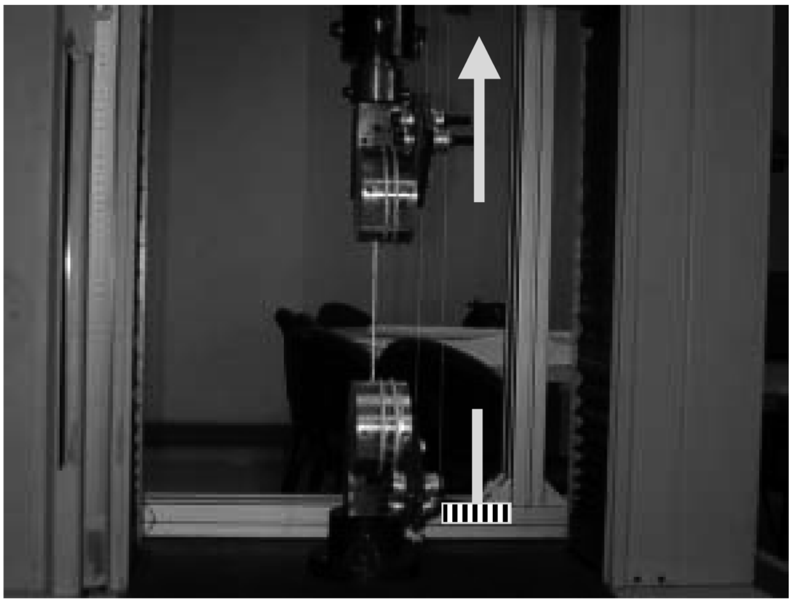


Figure 2 The test assembly on the static tensile machine (Adamel Lhomargy DY 26)

Thread characterization

The global net response is directly related to the thread's chemical and mechanical characteristics as well as to the way it is plaited, Figure 3. Thus, the understanding of its behavior is so fundamental to achieve this study.

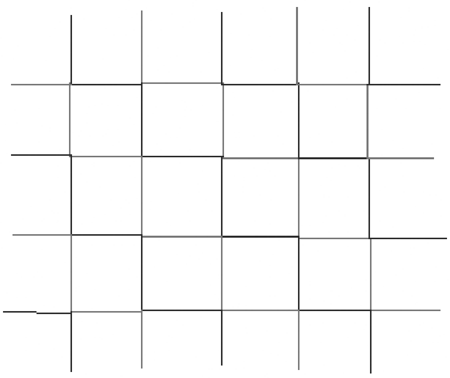


Figure 3 Nets Thread arrangement.

The previous figure shows that plaiting nets create knots which locally introduce a special mechanical behavior. This behavior is important in the understanding of global net response.

Characterization of a two thread strands resulting knot

Standardized knot

Plaited into nets, threads create knots linking different strands. To determine the behavior of these knots, it was necessary to consider this characteristic described in the standard [1], [6], Figure 4.

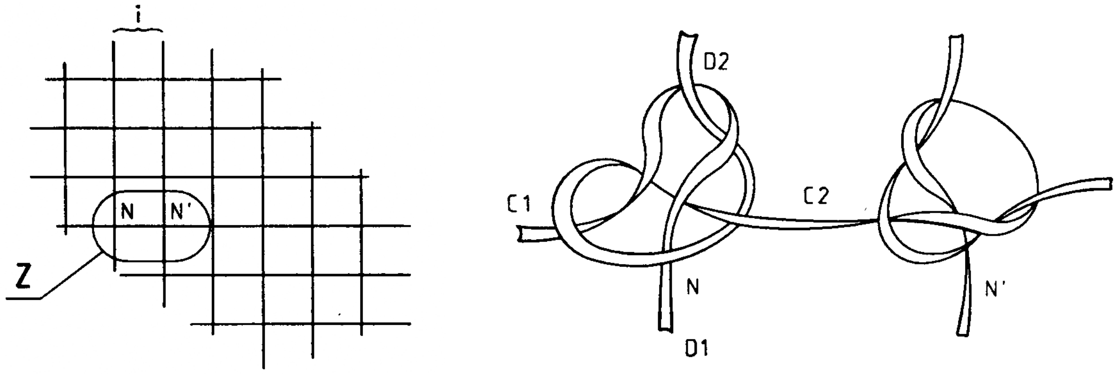


Figure 4 Standardized knot (according to the standard NF IN 1263-1)

Test principle

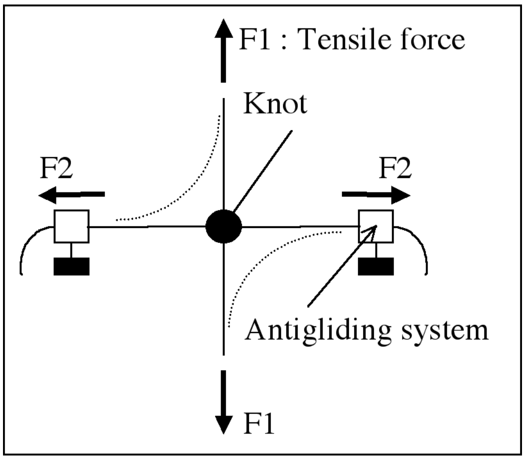
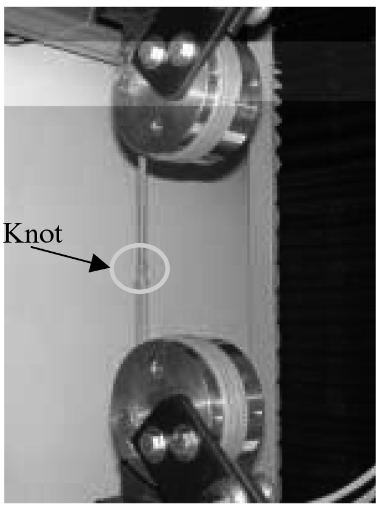


Figure 5 Characterization principle of a standardized knot

A special assembly was conceived with the aim of carrying out the thread characterization test, taking into account the working principle of the used tensile testing machine. Since the tensile test machine is not symmetric, the assembly was designed to insure correct fixation of the 4 strands (C1, D1, C2, D2, Figure 4) and to follow-up the knot during tests, Figure 6 (b).

This test was found equivalent to that represented in the Figure 6 (a). In that case, two strands are fixed on one side of the assembly and the two others on the second side. Thus, the effort is applied on both extremities of the thread (C1, D1) on one side, and on both extremities of the thread (C2, D2) on the other side.



(a)

(b)

Figure 6 Test assembly used for the standardized knot characterization

The main result of these tests is that the presence of the knot decreases the breaking effort by about 40% for one thread or for a thread assembly.

DYNAMIC MECHANICAL CHARACTERIZATION

General interest

In this investigation an intermediate phase insuring the transition between static and dynamic phases is presented. This is planed in two stages : a small-scale elementary study and a large-scale global one.

The first part (small scale) aims to characterize experimentally the dynamic behavior of the protection system elementary components (thread, knot, boltrope, etc.). That will allow the optimization of an elementary numerical model serving as base in a more elaborated modelization.

The second part (large scale) aims to readjust the global numerical model stemming from the elementary study. It consists in impacting several samples of keeping-back net with variable mass, speed and boundary conditions. However, the global numeric models elaborated in this study must be validated quite soon, since the experimental tests have not been carried out yet.

Elementary experimental characterization

This study is realized by a special assembly conceived, realized then calibrated on the static tensile testing machine, Figure 7.

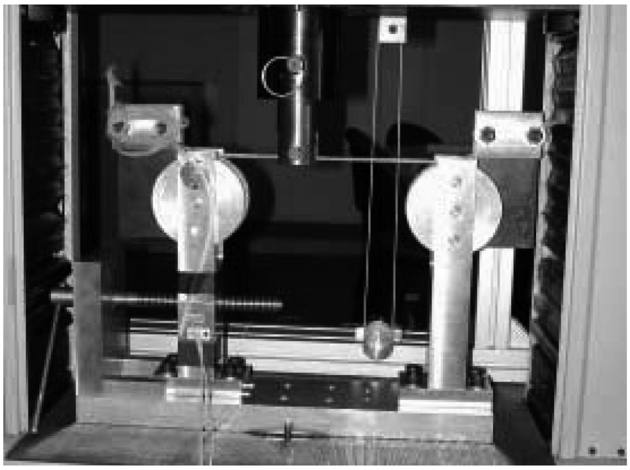


Figure 7 Static calibration of the thread dynamic characterization assembly

A screw nut system is designed within the assembly in order to apply a variable thread pre-tension. This can simulate the tension applied to this structure once the net is assembled in the protection system. The control of the thread pre-tension, with strain gages, gives variable boundary conditions.

Once the thread is fixed on the assembly and the pre-tension applied, the device is centered with regard to the impactor. The center deflection of the impacted thread is measured with a laser sensor acting with 400 Hz, Figure 8.

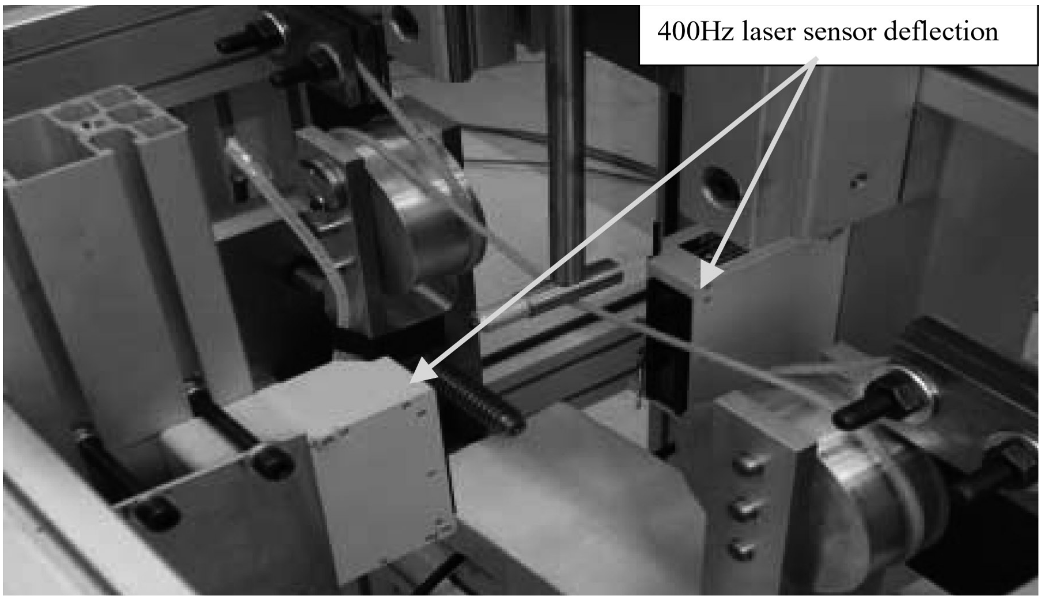


Figure 8 Thread and test assembly locations before the impact

After dropping, the 5 kg mass impactor strikes the thread at a variable speed according to the fall height. This speed is measured with precision with two photodiodes spaced out by a known distance apart (100 mm), Figure 9.

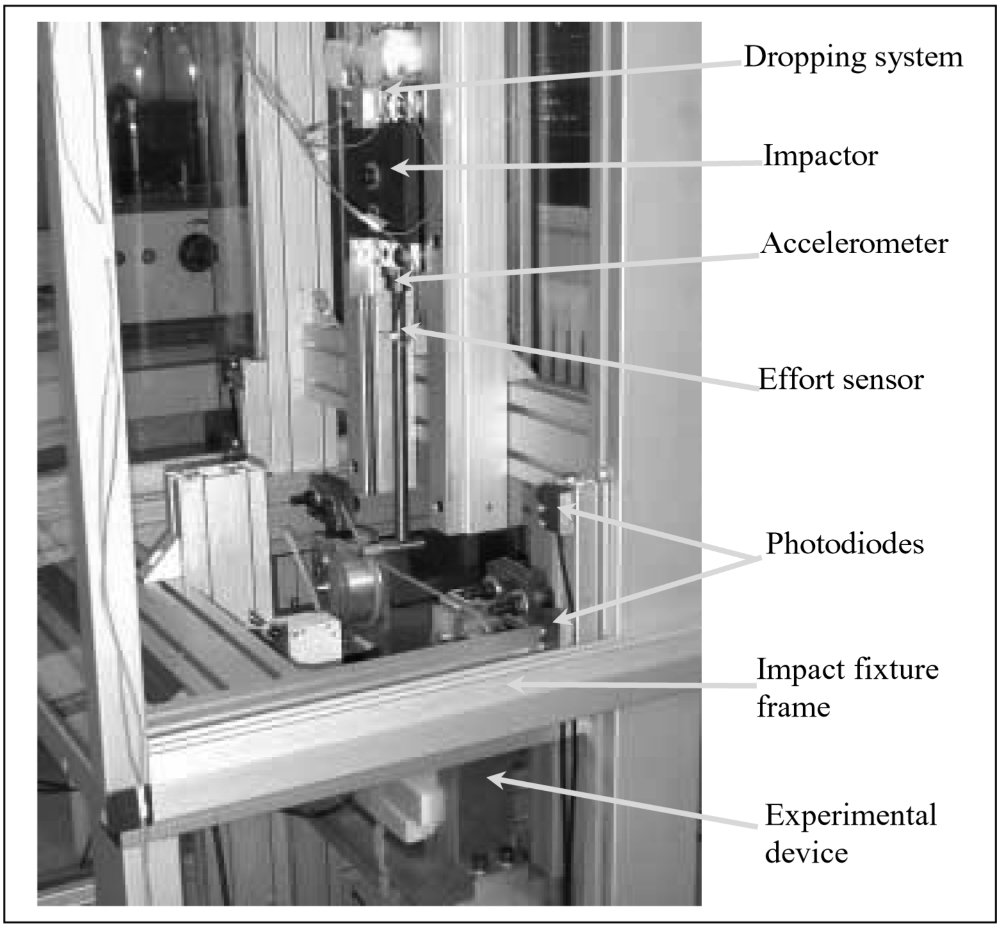


Figure 9 Instrumentation of the dynamic characterization test

An anti-bounce system fixed to the impactor is used to block it on the guide rails just after the shock to avoid a second impact. Sensor signals are insured by a high speed data acquisition system (Nicolet).

A high-speed camera of 1000 images per second is used to visualize phenomena and to understand deformations and the break mechanisms of studied structures, Figure 10. Then, the numerical model calibration is based on the experimental and the numerical images comparison.

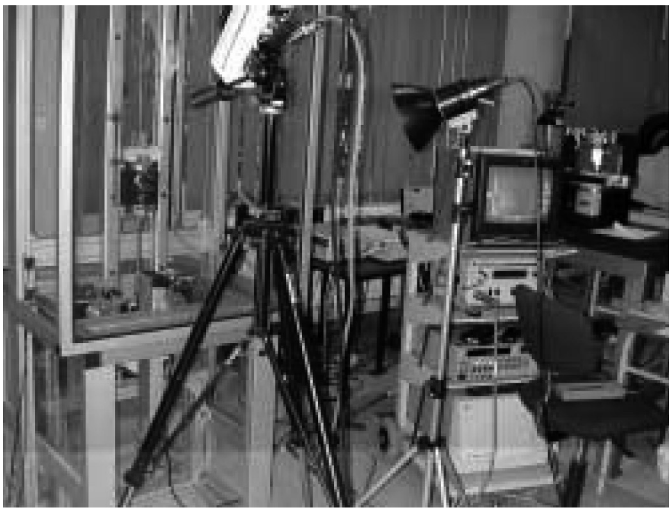


Figure 10 Dynamic characterization test filmed by a high-speed camera (1000 images per second)

Global experimental characterization

In order to carry out this phase and to validate the elaborated numerical models, a special experimental test assembly is designed. Indeed, a 3 meters squared surface net is fixed on a metal frame through Turnbuckles, Figure 11. They apply the desired pre-tensions to the tested samples. A 100 kg spherical mass of 400 mm of diameter is dropped in the center of the net from a height corresponding to a given speed. A high speed data acquisition system records Turnbuckle's applied efforts (pre-calibrated strain gages), the impact point deflection, the sample four corners normal displacements, the impactor center of gravity decelerations and images obtained by two high speed cameras placed on a two perpendicular axes so as to control test symmetry.

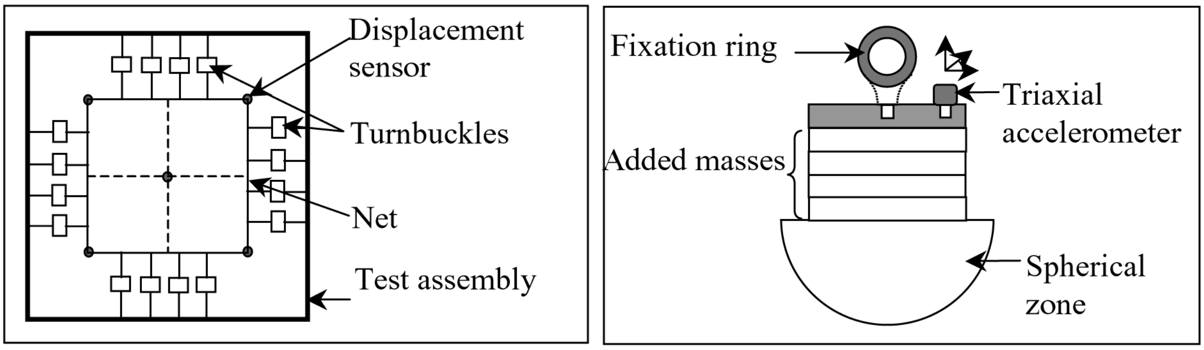


Figure 11 Instrumentation and test assembly scheme

NUMERICAL STUDY

THREAD IMPACT MODELING

The thread, which is the basic element of the keeping-back nets, is the first component exposed to the pulse loadings. Consequently, a fine and successful modeling of its dynamic behavior and its impact response constitutes an essential phase in the elaboration of the complete model. Besides, this phase constitutes a founded stage experimentally validated by the relatively simple characterizations test, inexpensive and very rich in useful information.

Therefore, two elementary numerical models were developed. Boundary conditions were simplified in the first case and represented such as they are in reality in the second one. This study concerns at first the polyethylene threads response modeling.

Simplified modeling

In this model, a 270 mm thread length, embedded in its two extremities, is discretized. Break orientation cylinders are not considered in this case and only iotroduced in the complete model. A 5 kg cylindrical shaped impactor of 14 mm diameter impacts the thread center with a preset initial velocity. The effort, acceleration and the thread center deflection are calculated and compared with the experimental results.

The thread is modeled by elastic-plastic beam elements. Whereas, with cable elements only elastic materials can be modeled, [7], [8], [9]. Otherwise, cable elements would have been very advantageous for this fine modeling because of their null compression forces. The impactor is modeled by solid elements.

Elements choice

Various formulations of beam elements were tested in order to correlate experimental and numerical results with the best calculation efficiency. Hughes-Liu elements have been found not adapted to our calculations. The selected element was of type Belytschko-Schwer. Indeed, although they are a little more expensive than Hughes-Liu elements, they represent better the polyethylene thread's elastic-plastics behavior.

Meshing

The thread was meshed in 10, 20, 40, 60 and 80 elements by LS-INGRID [10]. This mesh generator is very advantages for creating an automatic and a parametric meshing. It is very useful for the global constitutive model of the keeping-back net system. The impactor was meshed enough to represent its cylindrical shape, but not too much because of its rigid material.

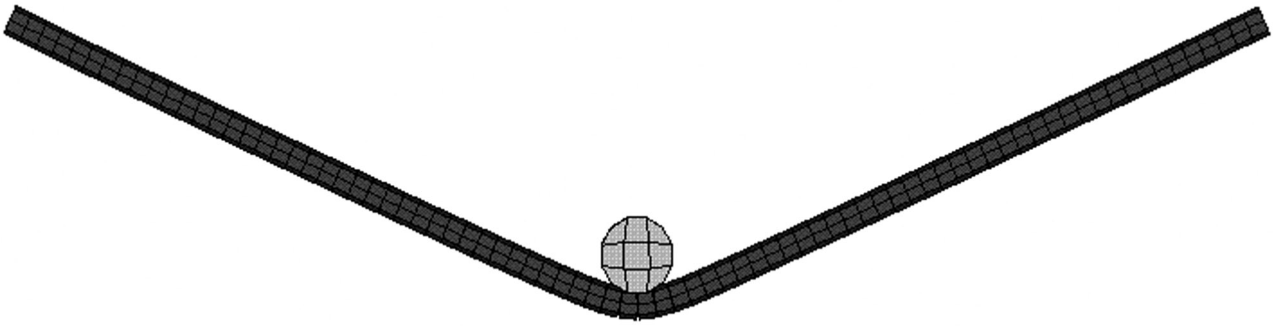


Figure 12 Meshing of the thread's characterization simplified model

Model properties

The impactor is modeled as a 5 Kg rigid body with a fictitious density. The Young's modulus is chosen as that of the thread for a better contact effectiveness. It is moved by a specified z-direction speed, and fixed in the other degrees of freedom.

Calculation units choice

The thread's mass is in the order of few grams (8 g/m). Whereas the order of its deformation is about few millimeters. So, the chosen units should be (g, mm, ms, N, MPa and the mJ).

Contact algorithm choice

Two contact algorithms of were used, T26 and T13. They automatically manage the contact and have the advantage to take into account the beam thickness.

Results and conclusions

This model gives satisfactory results in the representation of the impact force and the thread center deflection whereas the impact acceleration is obtained with less precision. The maximum time-step is limited by a specified curve.

The gravity effect was tested and no remarkable influence was observed. That is why this parameter is neglected in the rest of the project.

Complete model

In this model break orientation cylinders are added to the simplified model in order to be closer to the actual boundary conditions and to exact thread dimensions. The mesh generation is done parametrically by a computer program for the rolling-up of beam elements around the break orientation cylinders.

Meshing

As well as in the simplified model, the thread was discretized finely enough to analyze the meshing effect for this new configuration and the same impactor as the previous model was used. The break orientation cylinders are meshed in 3D cylindrical coordinates system using rigid brick elements T20, Figure 13.

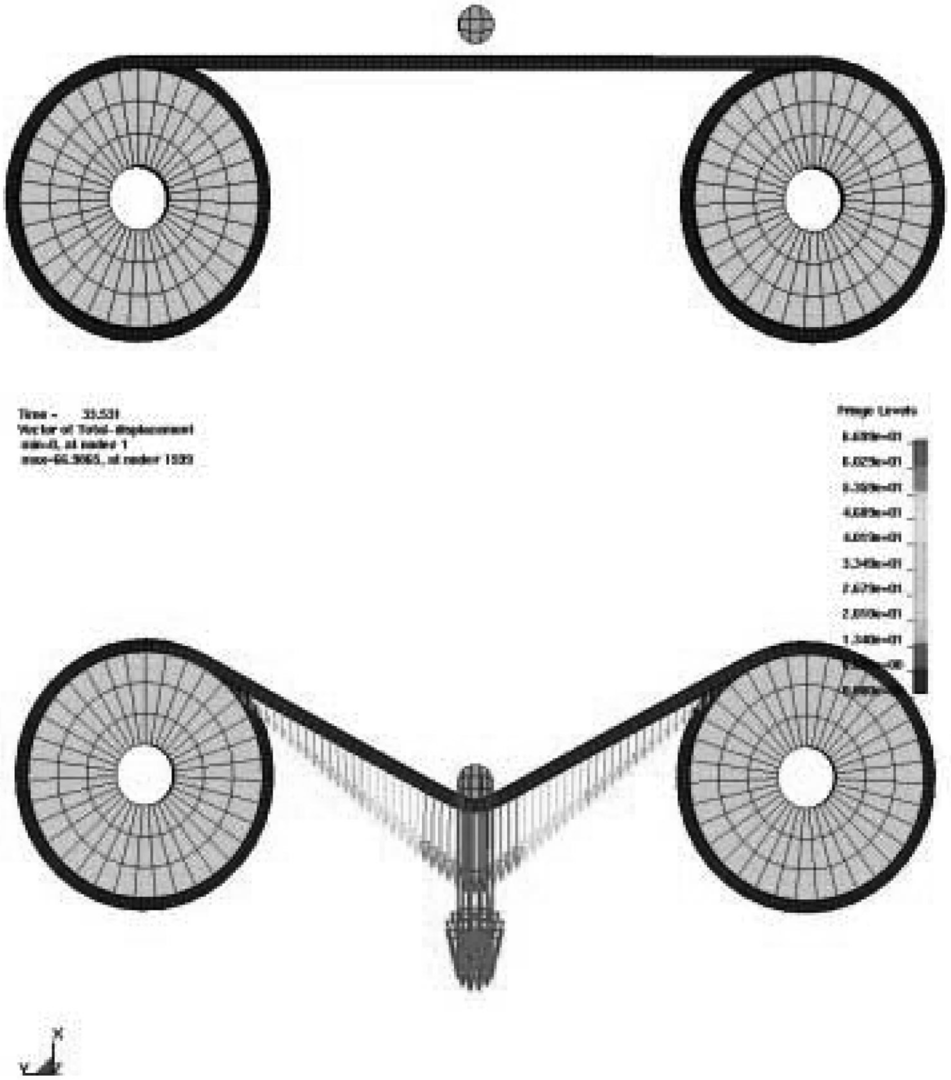


Figure 13 Complete model meshing for dynamic threads characterization

This model increases the accuracy of calculated impact accelerations. Results are comparative to the experimental tests with a 10% diffrence. For example, for a 2.5 m/s impact speed, the impact force is 1175 N, the impactor acceleration is 24 g and the thread center deflection is 61.8 mm respectively compared to 1074 N, 25 g and 57 mm in experience.

Accelerations comparison for 2.5m/s impact speed

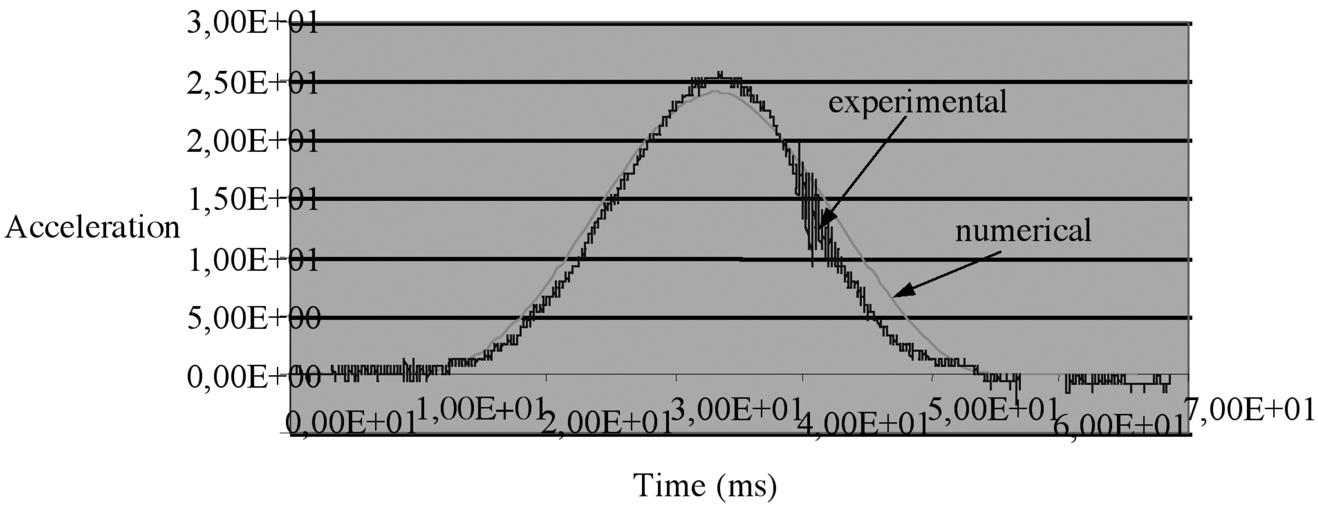


Figure 14 Acceleration comparison of experiments and simulations for 2.5m/s impact speed

KNOT IMPACT REPONSE MODELING

As explained above, the knot reduces thread breaking stress by about 40 %. So, its modeling should take into account this reduction and detect consequently its critical breaking stress.

Therefore, the knot is modeled by discrete beam elements T6, which do not change the thread behavior before breaking. Furthermore, they display beam disconnection when the specified breaking stress is reached.

Once set up, discrete beam defining parameters (stiffness, mass, etc.) are optimized by using knot impact experimental results taken by different test sensors and filmed by the high speed camera. These parameters were chosen to reduce time calculation without decreasing results accuracy.

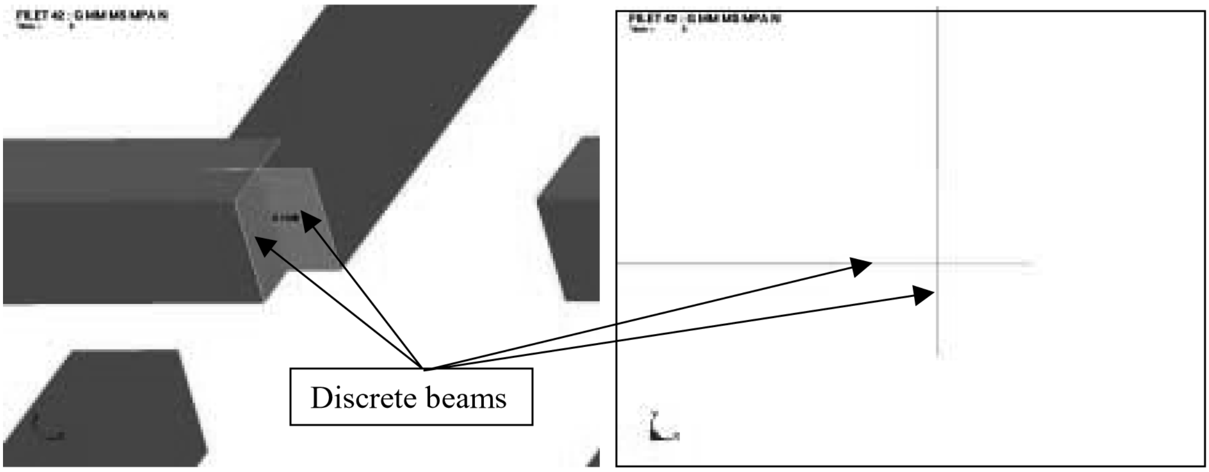


Figure 15 Discrete beam knot modeling.

NET IMPACT RESPONSE MODELING

After the fine modeling validation of the various elements used in the global model elaboration, the net model is composed of Belytschko-Schwer beam elements (threads) and discrete beam elements (knots). A 400 millimeters diameter spherical impactor of 100 kg mass, modeled by rigid material shell elements T20, impacts the center of the net with a specified initial speed. Then the dynamic breaking net behavior is studied.

Breaking stress is shown to be sensitive to boundary conditions, mesh type (squared or diamond-shaped) and net geometrical characteristics (mesh size, …etc.), Figure 16.

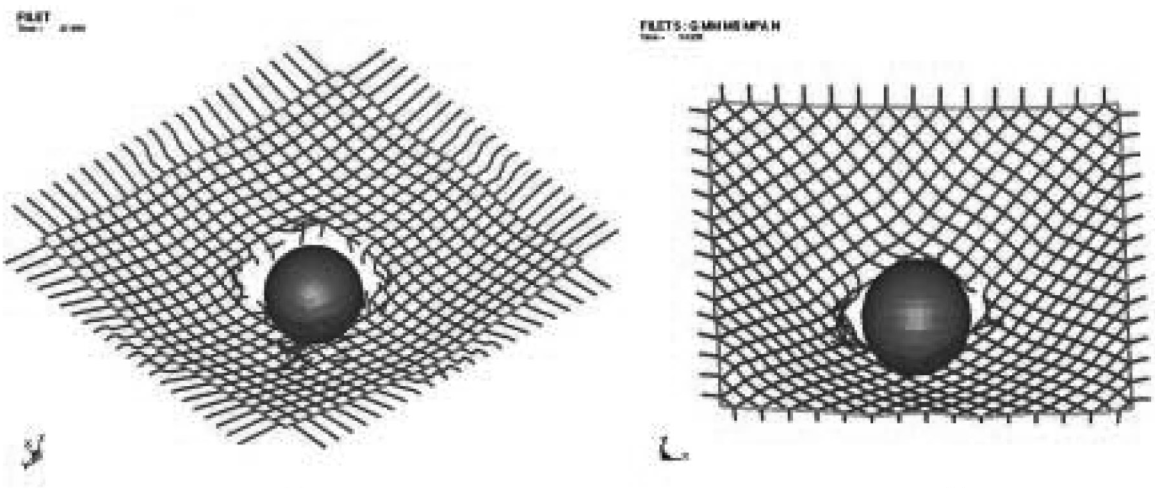


Figure 16 Square (a) and diamond-shaped (b) meshed net breaking display.

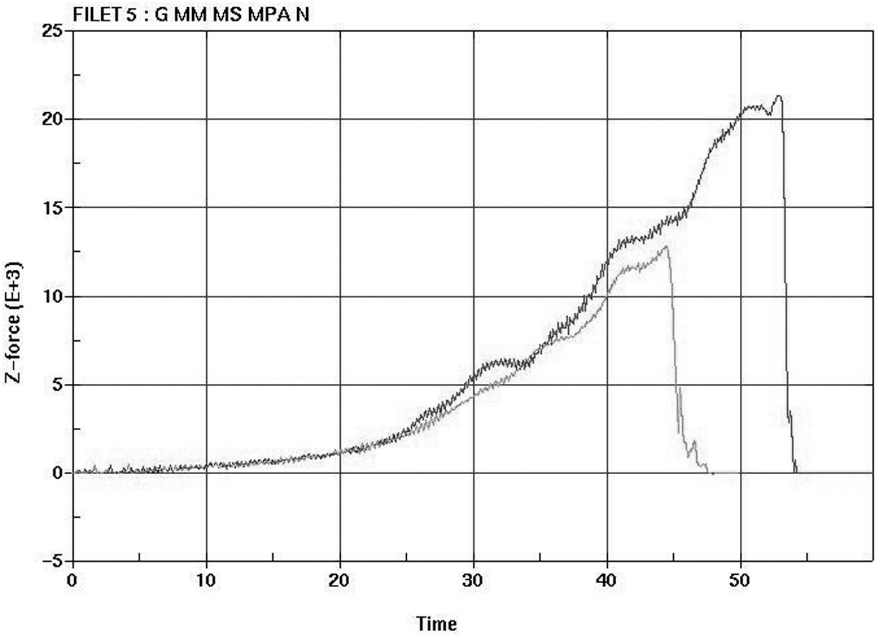


Figure 17 Net breaking force comparison for the two mesh types.

Real safety system configuration used in competitions track edges has also been modeled by introducing dynamic rope net fixation. This rope is passed through pulleys fixed by clevis mounting on a top rigid cable from one side and on the net from the other one, Figure 18.

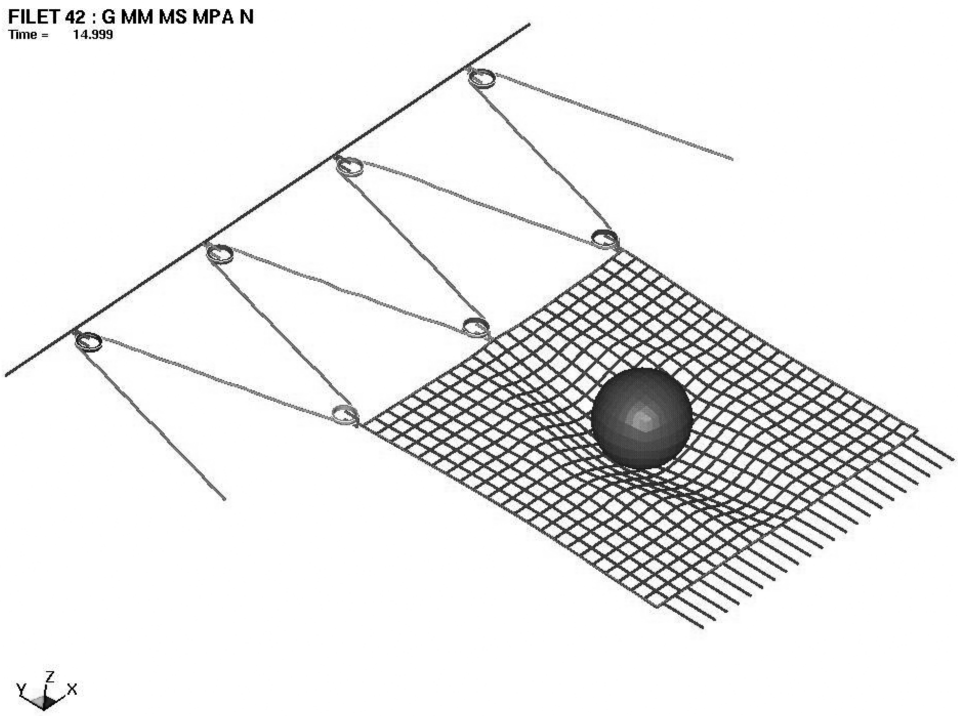


Figure 18 Real configuration modeling of ski keeping-back net safety system

Modeled by rigid beam elements the top cable and clevis mountings are connected by cylindrical joints. In the net side, clevis mountings are fixed to the boltrope. They are connected to rigid shell modeled pulleys by revolute joints. The general automatic contact T26 is used between pulleys and the dynamic rope.

CONCLUSION

In this project, a progressive methodology with different steps of validation was applied to solve a difficult global scale problem. Thus, encouraging results have been found and important recommendations for keeping-back safety nets installation are being developed.

The large-scale experimental validations are being performed and suggestions are being performed in order to standardize net safety system testing using the developed numerical model. However, other investigations should take place in order to study diverse net types (without knot, different materials, …etc.) and unusual net installation systems.

BIBLIOGRAPHY

[1] European standard French version NF EN 1263-1 « Filets de sécurité, Partie 1: Exigences de sécurité, méthodes d'essai », Association Française de Normalisation (AFNOR), December 1997.

[2] European standard French version NF EN 892, « Cordes dynamiques, Exigences de sécurité et méthodes d'essai », Association Française de Normalisation (AFNOR), January 1997.

[3] European standard French version NF EN 564, « Cordelette, Exigences de sécurité et méthodes d'essai », Association Française de Normalisation (AFNOR), April 1997.

[4] European standard French version NF EN 1891, « Cordes tressées gainées à faible coefficient d'allongement », Association Française de Normalisation (AFNOR), August 1998.

[5] European standard French version NF EN 919, « Cordage en fibres pour usages divers, Détermination de certaines caractéristiques physiques et mécaniques », Association Française de Normalisation (AFNOR), December 1995.

[6] European standard French version NF EN 1263-2 « Filets de sécurité, Partie 1: Exigences de sécurité, pour le montage de filets de sécurité », Association Française de Normalisation (AFNOR), October 1998.

[7] Livermore Software Technology Corporation, « Nonlinear Dynamic Analysis of Structures, LS-DYNA keyword user's manual » Version 950, May

[8] John O. Hallquist, « LS-DYNA, Theoretical Manual », Rev. 2 Livermore Software Technology Corporation, 1993.

[9] Susanne Eriksson, Design of a realistic numerical model for simulations in LS-DYNA of a plastic safety net, ENSICA 1999.

[10] Douglas W. Stillman & John O. Hallquist, « LS-INGRID: A Pre-Processor And Three Dimensional Mesh Generator For The Programs LS-DYNA, LS-NIKE3D And TOPAZ3D" Version 3.3 Livermore Software Technology Corporation,1993.