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Nonlinear finite element analysis applied to the development of alpine ski safety net

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Abstract

New technologies applied to the manufacturing of sport equipment allow skiers to reach velocities higher than in the past and, as a consequence, the number of serious accidents is increasing. Safety nets installed in the critical areas of the ski tracks can help to prevent the most severe consequences of an accident. In this paper, experimental tests and numerical simulations are introduced which were performed to characterise the behaviour of a safety net under static and dynamic loads and to support the development of a numerical tool to design high-performance safety net systems. As an application of the tool, the impact of a skier onto a high containment net was simulated and the risk level associated with the impact evaluated by means of injury criteria typical of crash analyses.

Introduction

The technological advance in ski equipment allows professional and non-professional skiers to reach remarkable velocities and, with the velocity, also the number of accidents is increasing. Although most of the accidents are due to risk-taking behaviour in skiing, where the threat comes from the environment around the ski track, safety net may help avoiding severe accidents [10].

In the current European Norms for the manufacturing and the installation of the safety net [5,6], there is no specific prescription in terms of containment level or energy absorption capability of the net. Nonetheless, it is straightforward to understand the importance of keeping into count these parameters especially in the design of safety net system for ski race tracks where accidents are characterised by high velocity and hence the risk of fatal accidents is higher.

Although news and statistics show that the number of severe and sometime fatal accidents is growing, only a limited number of papers on this topic are available in the scientific literature. Giorla and Berutti [7] in their research work on air mattresses to install along the ski tracks used injury criteria such as the head injury criterion (HIC) to assess the severity of the impact. Injury criteria and energy absorption capability of the safety device were measured in a test performed using a surrogate of human beings. Gourinat et al. [8,11] showed with tests and analyses the importance of type ‘A’ nets for skiers’ safety. Type ‘A’ nets are usually installed in the critical areas of ski tracks and are meant

to prevent the skiers from ending up off the track. They are usually large in size and fixed to the ground.
Questions about skiers' safety remain open and the need of numerical tool to assess severity of the accidents and to design and develop the safety net is still an open research field.
At the Laboratory for the Safety in Transport of the Politecnico di Milano, a research work on safety net systems was recently undertaken, which focused on Type 'A' safety nets. The research comprised experimental and numerical activities and had as a scope to demonstrate that numerical simulations can be used to support the design of safety net systems, reduce the number of tests to perform for the certification, and, hence, reduce time and cost associated to the development of high standard safety nets. As a result, it was eventually shown that numerical simulations can be used to assess the performance of ski nets and associated safety level.

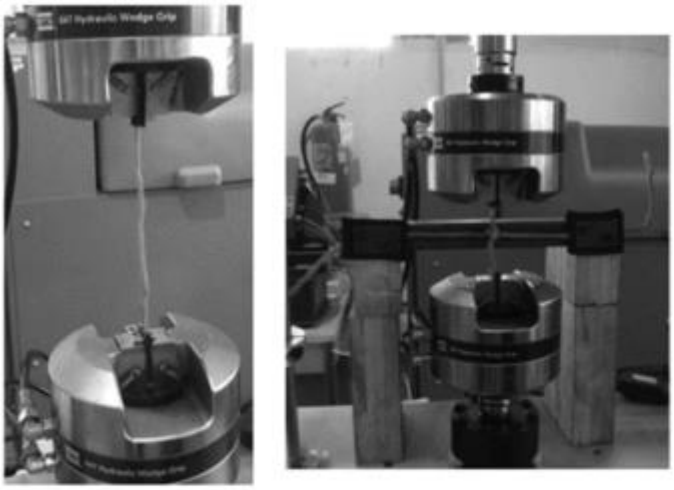
Method

The research work introduced here is divided into two parts. In the first part, tensile tests and drop tests were performed on net components to characterise the materials used to manufacture the net.
A numerical model was developed and validated by comparing numerical results and test data. Nonlinear simulations were performed using an explicite finite element code, LS-DYNA 971 [9].
Data collected in test on the single and knotted braid were used to calibrate the material model of the net. Data collected in static and dynamic tests on a net were used to validate the simulation set-up with regard to control parameters and contact definitions.
In the second part of the research, as an application, the numerical model developed in the first part of the research was used to simulate the impact of a skier against a safety net.
The skier was modelled using a validated numerical model of an anthropomorphic test device (ATD) [3]. The performance of the safety system was then evaluated referring to injury criteria typical of crash analyses: Head injury criterion (HIC), Thoracic Trauma Index (TTI) and Thoracic Compression Criterion (TCC) [1,2,4].

Experimental tests

Static and dynamic tests on single and knotted braids and on net specimens were performed.

Single and knotted braid testing
Ski safety nets are made of high-density polyethylene, a material characterised by a high resistance and tenacity. Initial attempts of using nonlinear finite element (FE) code to study safety net behaviour [9] showed that an accurate characterisation of this material is necessary to assess the net performance with a degree of accuracy. In view of this, static tensile tests were performed both on single braids and knotted braids (Figure1).



(a) (b)

Figure 1. Tensile tests on single braid (a) and knotted braid (b).

Single braid samples (Figure 1(a)) were created in a length range of 120–240 mm. The distance between the two clamped ends was in the range of 55–175 mm. The results of the single braid tests were repeatable: the mean force at failure was 1.69 kN and the mean elongation at failure was of 39% (Table 1).

	S1	S2	S3	S4	S5	S6
Force at failure (kN)	1.67	1.64	1.72	1.78	1.68	1.67
Elongation at failure (%)	39	41	40	39	37	37

Table 1. Single braid test results.

Tests were also performed to characterise the nonlinear behaviour of knotted braids under uniaxial and biaxial loads. To perform tests under biaxial loads, an iron frame was built and braids were clamped on both the test device and the iron frame. The distance between the grips was in the range of 70–100 mm (Figure 1(b)). Results of tests (Table 2) showed that due to the necking at the knot the mean elongation at failure, 74%, was larger than that of the single braid while the mean force at failure was smaller, 1.0 kN.

	K1	K2	K3	K4
Force at failure (kN)	0.95	0.99	1.03	1.06
Elongation at failure (%)	75	72	74	76

Table 2. Knotted braid test results.

Net testing

Tests on nets were performed using a portion of the safety net according to the test specifications contained in the current European Norms [5]. The test apparatus used for the tests is shown in Figure 2.

Figure 2. Test facility used for the tests on the net.

Tensile test

A net sample of 3 × 3 m was used for the static tensile test. The net was constrained to a rigid structure with metal hooks. A 100 kg sphere was placed under the net at its centre and lifted up with a crane at a constant velocity of 1 m/min until the net was broken (Figure 3).

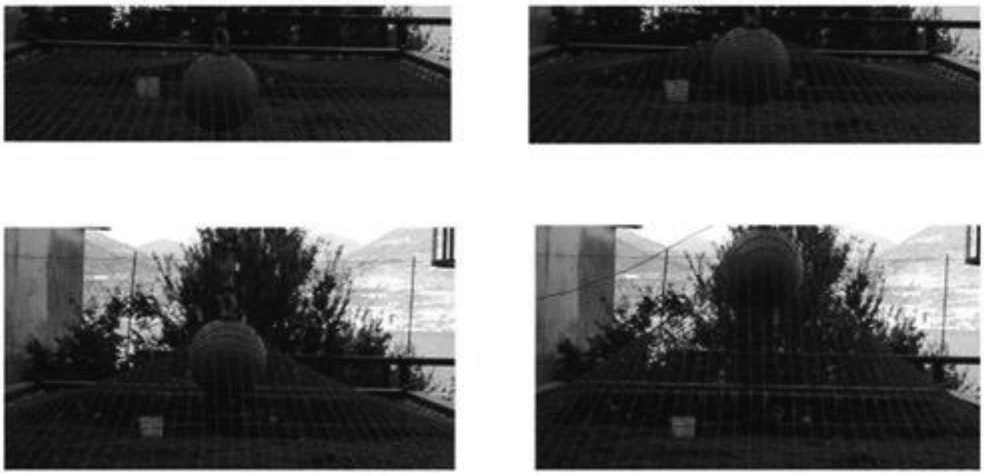


Figure 3. A sequence of frames from the video of the tensile test on the net.

An experimental test was performed. Force and displacements were measured. The mean force–displacement curves created is shown together with the results of the simulation in Figure 8. The force at failure was 19.3 kN. The maximum displacement was 1.29 m.

Drop test

A dynamic test on the full net was also performed. A metal ball, 100 kg in weight and 500 mm in diameter, was dropped on a net sample of 5 × 7 m. The net sample was pre-tensioned at 500 N. Test specifications prescribed for this type of tests impact energy of 7 kJ and maximum deflection to be less than 75% of the shortest dimension of the net. Impact energy of 7 kJ was obtained dropping the 100 kg ball from a 4 m height. Being the shortest dimension of the net, 5 m, the maximum allowable deflection was fixed at 3.75 m.

The net deflection was evaluated using the frames of the video of the test captured with a high speed camera (Figure 4). The maximum net deflection obtained in the tests, about 2 m, was in the range allowed by the test specifications. The time history of the ball displacement obtained from it is shown together with the result of the numerical simulation in Figure 9.

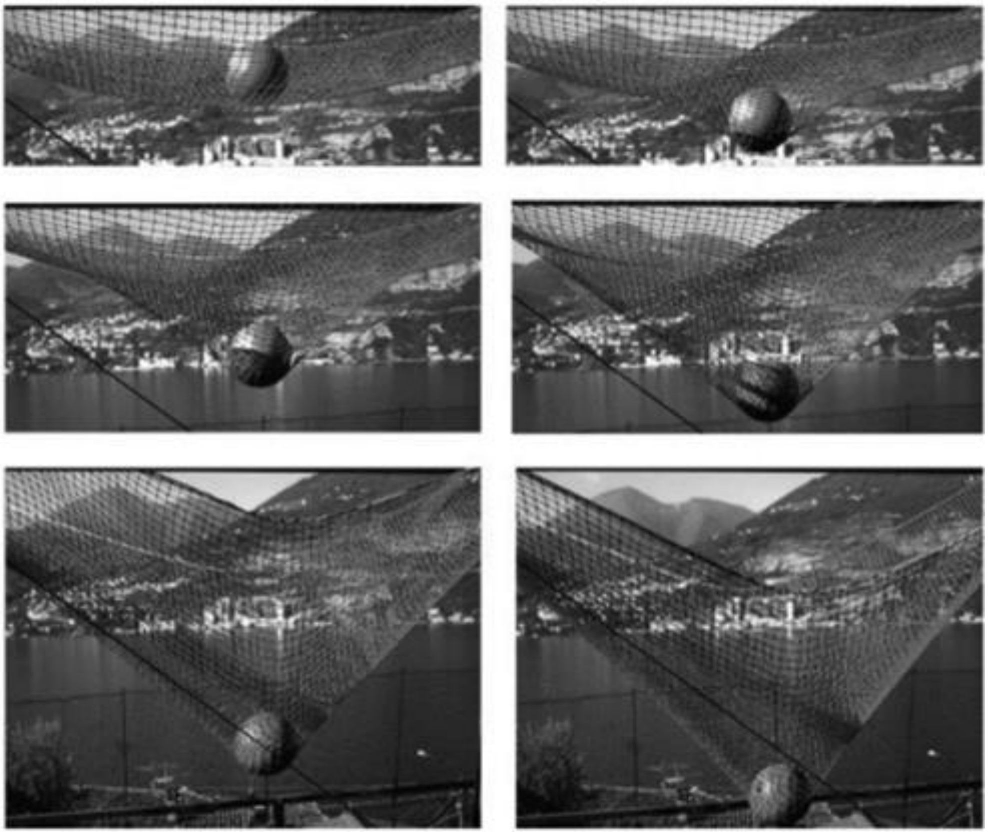


Figure 4. A sequence of frames from the high speed video of the drop test.

Numerical simulation

Simulations reproducing the tests described in the previous paragraph were performed using LS-DYNA 971 [9].

Single and knotted braid modelling

With regard to the tensile tests, the finite element model of the single braid consisted of tubular beams, constant section, Belytschko–Schwer formulation [9], and an isotropic material model kinematic hardening plasticity was created. The knotted braid (Figure 5) was modelled with zero length beam element and an elastic–plastic material model for spring with damping.

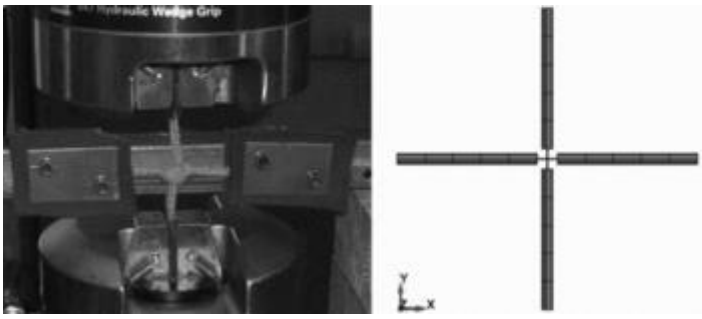


Figure 5. Experimental test and numerical model of the knotted braid.

Geometry and boundary conditions of both of the types of sample tests were the same as in the actual tests. The results of the static tensile test of the knotted braid in terms of maximum force and displacement are listed together with the data collected during the tests in Table 3.

Net modelling

The finite element model of the net sample (Figure 6 and 7) was created by the union of single braids and knotted braids. Beam elements were also used to model the frame that restrained the net in the test. Boundary conditions reproducing the test constraints were imposed: all the translational degrees of freedom of the nodes along the edges of the net were restrained.

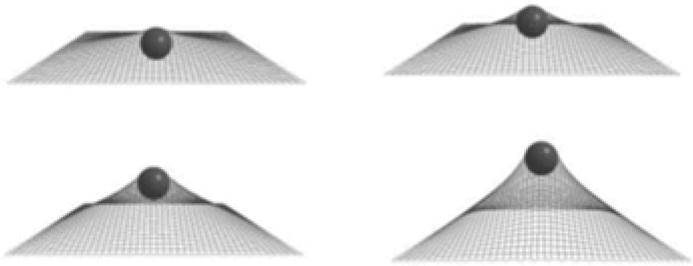


Figure 6. A sequence of frames from the simulation of the net tensile test.

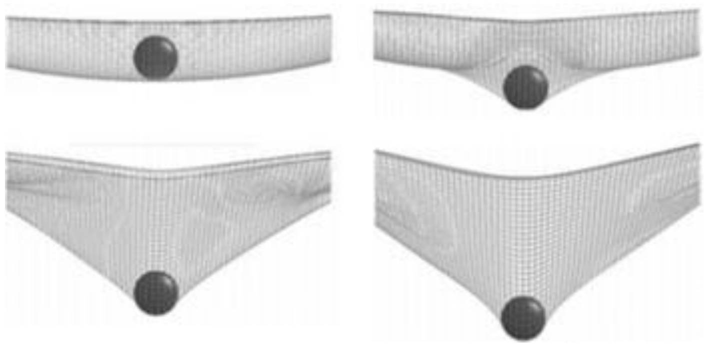


Figure 7. A sequence of frames from the simulation of the drop test.

The net was pre-loaded using gravity load both in static and dynamic models and the sphere was modelled as a rigid body with a mass of 100 kg. The contact between the net and the sphere was enforced using the soft constraint method.

Tensile test

With regard to the tensile test simulation, the finite element model of the 3 × 3 m net consisted of 37,840 beam elements with a reference length of 7 mm. The finite element model of the sphere, defined as a rigid body, consisted of 1176 shell elements. The reference length of these elements (28 mm) was decided to guarantee a degree of accuracy to the net-to-sphere contact interface. A displacement was imposed to the sphere as in the test.

A sequence of frames from the tensile test simulation is shown in Figure 6. The results of the static tensile test of the net system in terms of maximum force and elongation are listed together with the data collected during the tests in Table 4. The force–displacement curve is shown together with the test curve in Figure 8.

Drop test

With regard to the drop test simulation, the finite element model of the 7 × 4 m safety net used in the drop test consisted of 119,006 beam element. The finite element model of the sphere consisted of

1944 shell elements. An initial velocity of 8.7 m/s was imposed to the rigid sphere as in the experimental test. The boundary conditions were the same as in the test.
A sequence of frames from the drop test simulation is shown in Figure 7. The results of the simulation in terms of maximum force and displacement are listed together with the data collected during the tests in Table 5. The force–displacement curve is shown together with the test curve in Figure 9.

Numerical–experimental correlation

Single and knotted braid testing

With regard to the braid, a good correlation between experimental tests and numerical simulation was obtained (Table 3).

	Tests	Simulation	Relative error
Force at failure (kN)	1.01	1.07	6%
Elongation at failure (%)	75	78	4%

Table 3. Knotted braid test: comparison between test data and numerical results.

Net testing

A good numerical–experimental correlation was also obtained for both the static and dynamic net tests.

Tensile tests

With regard to the net tensile tests, main force and displacement at the centre of the net were very close (Table 4). A direct comparison between test and simulation in terms of force–displacement curve is shown in Figure 8.

	Test	Simulation	Relative error
Force at failure (kN)	19.27	18.61	3%
Net displacement (m)	1.29	1.28	<1%
Absorbed energy (kJ)	6.68	7.15	5%

Table 4. Tensile test: comparison between test data and numerical results.

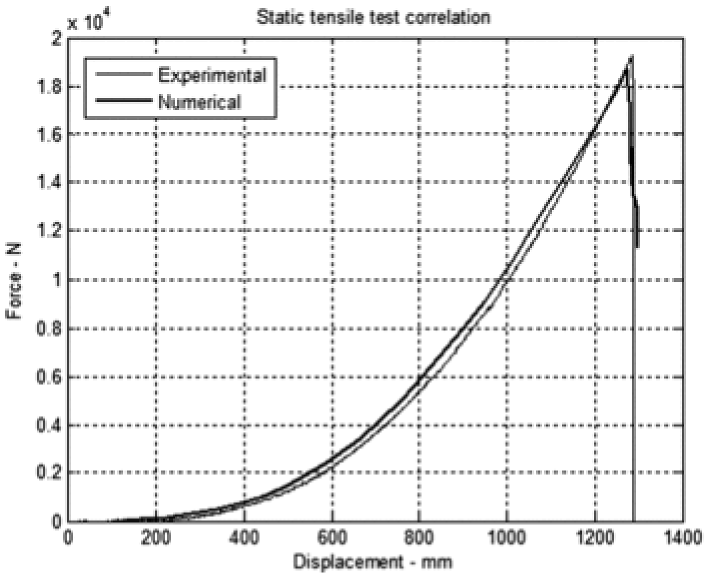


Figure 8. Static tensile test on the single braid: numerical–experimental correlation.

Drop tests

A good correlation was obtained also for the full net drop impact test: details are reported in Table 5. A direct comparison between test and simulation in terms of ball displacement time history is shown in Figure 9.

	Test	Simulation	Relative error
Max. sphere acceleration (g)	9.2	9.1	<1%
Absorbed energy (kJ)	5.7	5.0	4%
Max. net displacement (m)	2.0	1.8	11%

Table 5. Drop test: experimental test and numerical simulation.

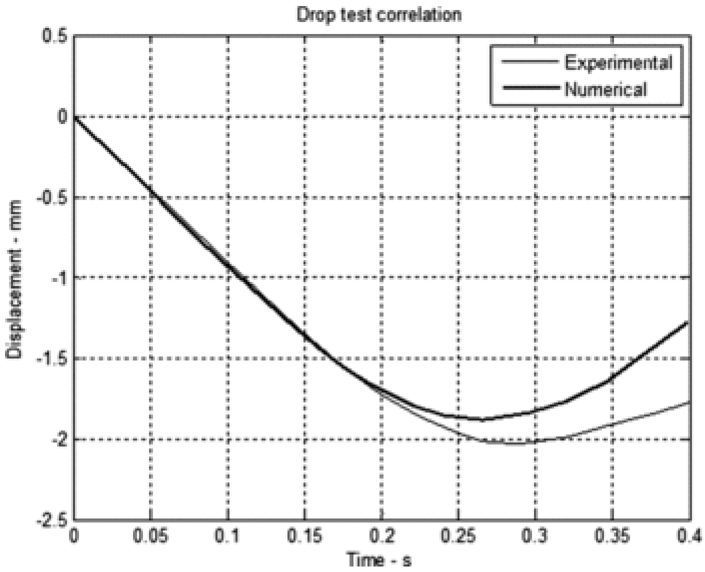


Figure 9. Drop test: numerical–experimental correlation.

Discussion

From the comparison of the test data and numerical results, it emerges that the numerical model captures the overall behaviour of the net system within acceptable levels of accuracy with small relative errors before the braid failure. As predictable, the relative errors in terms of maximum force and displacement are greater in the dynamic test than in the static test.

In particular, with regard to the time history of displacement of the metal ball in the dynamic test (Figure 9), it can be observed that, in the drop phase, there is a close correlation between numerical results and test data up to 85% of the maximum displacement. Afterward, the displacement obtained in the simulation is smaller than that observed in the test and that was due to the anchorage of the net. As a general remark, it has to be mentioned that the anchorage system of the net has in fact a great importance in terms of dynamic behaviour and performance of the net in terms of absorbed energy capability.

A full characterisation of the anchorage system could have improved the numerical–experimental correlation. However, the anchorage system modelling was not in the scope of the research and it was decided to leave it for future investigations. The good correlation obtained up to 85% of the maximum net displacement was deemed more than adequate for the scopes of the research.

Applications: impact of a skier against a Type 'A' safety net

The model validated against the tests was used to assess the performance of the safety nets installed along a competition ski track throughout the simulation of the impact of a skier against the safety net. Two impact scenarios were considered: free fall onto the net and later impact at various velocities and impact angles. The first scenario is representative of the fall of a skier from ski-lifts or chairlifts, while the second scenario is representative of the impacts along the track during a competition.

Skier finite element model and net performance

The skier was modelled using the finite element model of a Hybrid III 50th percentile (H350) ATD. The model was validated within a previous research work [3]. The H350 is one of the most sophisticated ATDs and it is employed in aerospace and automotive industry to assess the severity of crash and to evaluate the performance of safety devices such as airbags and safety belts.

The H350 model used in the simulation allowed evaluating the HIC, the TTI and the TCC.

The severity of the impact was hence assessed in terms of the ratio between the value of injury criteria obtained from the simulations and the maximum allowable values – i.e. HIC_{all} = 1000, TTI_{all} = 60 g, and TCC_{all} = 52 mm.

Free fall simulation

To simulate a skier's free fall, the finite element model of the ATD was dropped on a 7 × 4 m net with an initial velocity of 8.85 m/s (Figure 10). The values of all the injury criteria considered were well under the maximum allowable values: HIC = 14.9, TTI = 9 g, and TCC = 6 mm.

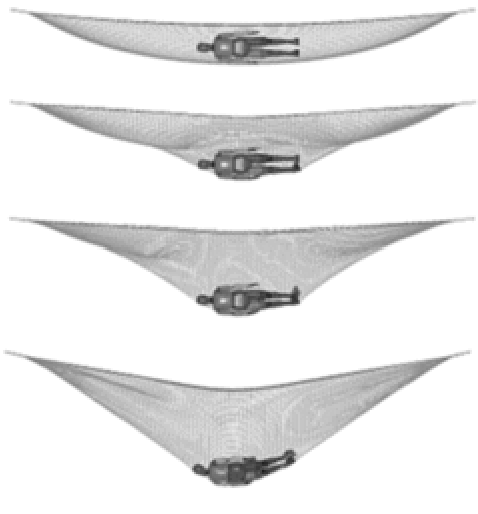


Figure 10. A sequence of frames from the simulation of the skier's free fall.

Oblique impact simulations

Impacts at various velocity and incidence angles were simulated to study the dynamics of actual ski accident. Four impact velocities were considered: (1) 40 km/h (typical of non-professional skiers), (2) 60 km/h (medium velocity for professional skiers), (3) 80 km/h (maximum velocity for type 'A' safety net), and (4) 100 km/h. This last scenario is not prescribed by the European Norm, but it was considered to assess the consequences of the worst possible impact scenario for a professional skier. Three different impact angles were also considered: 30°, 60°, and 90°. The finite element model of the net was the same described in the previous paragraphs, but of larger dimensions: 14 × 4 m. The

actual net restraint system used along the ski pistes was modelled. Triangular braid structures were created both in the upper and lateral part of the net. The nodes of triangular braid structures at the bottom and the two extremities of the net system were fully restrained to simulate the actual constraint system.
A sequence of frame from the simulation of the impact at 80 km/h at an angle of 90° is shown in Figure 11. The results for the simulation in terms of energy balance and net displacement are summarised in Table 6. The injury criteria are listed in Table 7 together with the ratio between results of the simulation and allowable values (in parenthesis).

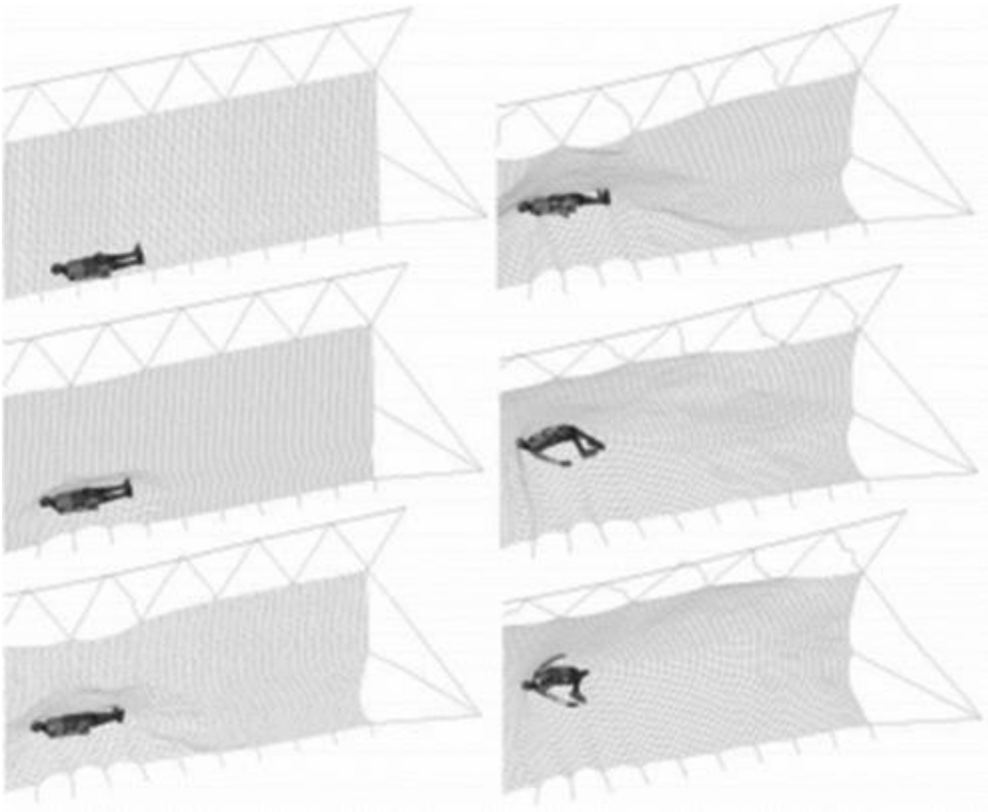


Figure 11. Frame from the simulation of the lateral impact at 80 km/h and 90° incidence.

	Impact angle	Kinetic energy	Absorbed energy[a]	Net displacement
	(°)	(kJ)	(kJ)	(m)
Scenario (1) impact at 40 km/h	90	4.8	4.0 (0.83)	1.81
	60	4.8	3.8 (0.79)	1.70
	30	4.8	4.2 (0.88)	1.12
Scenario (2) impact at 60 km/h	90	10.8	8.4 (0 77)	2.21
	60	10.8	7.8 (0.72)	1.93
	30	10.8	9.6 (0 88)	1.41
Scenario (3) impact at 80 km/h	90	19.3	13.8 (0.72)	2.47
	60	19.3	12.7 (0.66)	2.17
	30	19.3	14.9 (0.77)	1.53
Scenario (4) impact at 100 km/h	90	30.1	22.7 (0.75)	2.80
	60	30.1	20.0 (0.66)	2.63
	30	30.1	23.8 (0.79)	2.10

[a]The ratio between the absorbed energy and the initial kinetic energy is shown in parentheses.

Table 6. Oblique impact simulation: energy balance and net maximum displacement.

	Impact angle (°)	HIC[b] (–)	TTI[b] (g)	TCC[b] (mm)
Scenario (1) impact at 40 km/h	90	118 (0.12)	15 (0.25)	15 (0.29)
	60	55 (0.06)	12 (0.2)	8 (0.15)
	30	4 (∼0)	12 (0.2)	2 (0.04)
Scenario (2) impact at 60 km/h	90	266 (0.27)	25 (0.42)	24 (0.46)
	60	170 (0.17)	23 (0.38)	14 (0.27)
	30	148 (0.15)	21 (0.35)	6 (0.12)
Scenario (3) impact at 80 km/h	90	708 (0.71)	50 (0.83)	37 (0.71)
	60	357 (0.36)	55 (0.91)	26 (0.49)
	30	201 (0.20)	32 (0.53)	10 (0.20)
Scenario (4) impact at 100 km/h	90	1801 (1.80)	96 (1.60)	44 (0.86)
	60	1630 (1.63)	92 (1.53)	44 (0.84)
	30	915 (0.92)	85 (1.42)	36 (0.70)

[b]The ratio between the obtained results and the allowable values is shown in parentheses.

Table 7. Oblique impact simulation: injury criteria.

In simulations with impact velocity lower than 80 km/h, all the injury criteria were under the allowable values. In the simulation of the impact at 100 km/h, the HIC and the TTI were higher than the allowable values that means that this impact scenario is characterised by a high risk of serious injury.

Discussion

The results of the simulations showed that only impact at 100 km/h represent a serious threat for the skier against the Type ‘A’ safety net here considered. In fact, the largest net displacement, 2.80 m, was obtained for the 100 km/h impact at 90°. HIC and TTI are higher than the maximum allowable values. Although the impact velocity exceeded the maximum velocity for Type ‘A’ safety net (i.e. 80 km/h), this impact scenario seems to be extremely dangerous and potentially lethal for the skier.
Further tests and analysis are needed before giving conclusions, but the simulations provided a good indication on how to install safety nets in this case.
Other simulations using different ATD or considering different impact scenarios might be of some interest in order to better study the risks for skiers. It was also observed that the main displacement of Type ‘A’ net was of about 2.8 m at 100 km/h, and this must be taken into account during the installation of this kind of structure.

Conclusions

The technological advances in ski equipment allows non-professional skier to reach velocities higher than in the past. As a consequence, the number of serious accidents is increasing. The use of safety net can help to prevent tragic consequences.
In literature only a few research works deal with skiers’ impact dynamics and effects on human beings were performed. In this paper, experimental tests and finite element simulations were performed to assess a Type ‘A’ safety net.

Initially, experimental tests were carried out both on single and knotted braids and simple net system to characterise the materials used to manufacture the net and to evaluate the net behaviour under static and dynamic loads. Numerical models of these tests were then created and validated using experimental test results: a good correlation was obtained. The numerical model of an anthropomorphic test device was then used to evaluate the performances of the safety system with regard to the injury criteria typical of crash analyses.
Two different impact scenarios were also considered: a free fall onto the safety net and lateral impacts at various impact angles. For all the impact conditions, injury criteria were calculated and compared with the allowable values to assess the safety level of the net system. It was observed that impacts at high speeds and large impact angles bring the most severe consequences to the skiers. It was also observed that under 80 km/h all injury criteria were below the limits, but for higher velocity there is a high risk of serious injury for the skiers in case of incident.
The method used to approach the problem, consisting of a preliminary study of the net tensile and dynamic behaviour and the analysis of a case study to simulate a real accident, seems to be very efficient.

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