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Modeling and simulation of the impact behavior of soft polymeric-foam-based back protectors for winter sports

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Abstract

Objectives: Winter sports are high-energy outdoor activities involving high velocities and acrobatic maneuvers, thus raising safety concerns. Specific studies on the impact mechanics of back protectors are very limited. In this study analytical and numerical models are developed to rationalize results of impact experiments and propose new design procedures for this kind of equipment.

Design: Different soft-shell solutions currently available on the market are compared. In particular, the role of dynamic material constitutive properties, of environmental temperature (which affects mainly material stiffness), and of multiple impact on energy absorption capability is evaluated.

Methods: Starting from dynamic mechanical-thermal characterization of the closed-cell polymeric foams constituting the protectors, we exploited analytical modeling and Finite Element Method simulations to interpret experimental data from drop weight impact

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test and to characterize protectors in terms of different temperatures and multiple impacts.

Results: The temperature and frequency dependent properties of these material characterize their impact behavior. Modeling results are in good agreement with impact tests. Results demonstrate how ergonomic soft-shell solution provides an advantage with respect to traditional hard-shell in terms of impact protection. Moreover, they maintain their protective properties after multiple impacts on the same point.

Conclusions: The coupled analytical-simulation approach here presented could be extensively used to predict the impact behavior of such equipment, starting from material characterization, thus allowing to save costs and time for physical prototyping and tests for design and optimization.

Keywords: Back protectors, Winter sports, Back injuries, Soft polymeric foams, Impact testing, FEM modeling

1. Introduction

Winter sports are performed by an estimate of 200 M people in the word, including different ages and skill groups [1]. This number is in constant growth, also thanks to increasing popularity in new Asian markets, pushed by recent PyeongChang 2018 and future Beijing 2022 Winter Olympic Games. Winter sports, especially alpine skiing and snowboard, are generally high-energy outdoor activities involving high velocity, jumps and acrobatic maneuvers and the inherent risks, coupled with an increasing congestion on ski slopes, raise serious safety concerns. Traumatic injuries affect an average of 1.5/1000 skiers/day and 1.6 snowboarders/day [1, 2] and, also due to the high healthcare expenses connected with these injuries, there is a strong interest in prevention. The statistics of the injuries distribution over the body have discording results depending on the country taken into exam [3, 4]. Nevertheless, all these studies agree that the most affected areas are head, shoulders, spine and knees. In particular, a Swiss study reports that back injuries are more common in snowboarding with respect to skiing (18.3 % vs. 10.2 %) [5]. Moreover, snowboarders sustain 4–5.7 spinal injuries per 100000 days [6]. Risk reduction can be pursued at different levels, from regulation of ski activities and risk-awareness [7] to the development of more efficient individual protective equipment, such as helmets [8, 9] and back protectors [10, 11] or external passive system, such as safety barriers [12].

Historically, all the back protectors had a *hard-shell* construction consisting of a hard outer shell of thermoplastic material (e.g., polypropylene) with an inner soft padding foam and some textiles, forming the lining. In these products the shock attenuation relies on the distribution of the impact force over a wider area by the outer rigid material, also resistant to abrasive and puncture injuries. The main collateral disadvantage of this solution is the bad air flow which causes excessive sweating and poor thermal comfort during activity [13]. Also the ergonomics is highly limited, since the rigidity does not allow complete freedom of movements and may lead to compression of the zones in contact with the body, resulting in pain or incorrect body movements. To overcome these problems, an increasing number of products based on the new *soft-shell* technology, which adopt soft polymeric foams, has been proposed recently by manufacturers. In this solution the protection is given by energy dissipation through reversible deformation of cell walls [14]. Moreover, the pseudo-dilatant nature of the polymeric foams ensures an adaptive behavior, reacting like hard and rigid materials when subjected to high deformation rate enabling a high level of protection and like soft viscous materials at service load condition [14], providing good flexibility and comfort during movements. Their higher comfort arises also from their excellent thermal characteristics, since the production processes and the material properties allow to obtain perforated breathable structures. Usually the protective elements are enclosed in a high resistance stretch fabric vest which adheres perfectly to the body and retains the correct position of the protector element during crash, ensuring its effectiveness. A pseudo-dilatant behavior can be also obtained by the employment of auxetic foams where the negative Poisson's ratio causes a local increase of density under the impact area due to induced compressive stress. These solutions have already been demonstrated to perform better with respect to the traditional counterparts [15].

Despite the peculiarity of ski back protectors, there is no specific performance standard related to snow sports. Companies are currently borrowing motorcycling standards [16, 17] to test impact performances, design, and market their products. However, their adequacy has already been questioned [18]. Drop weight impact testing [19] is a common technique to assess the shock absorbing properties and has been applied in different fields (e.g., sports, defense, health care) and classes of materials. Dynamic Mechanical Thermal Analysis (DMTA) [20–22] is acknowledged in the field to correlate material properties and impact performances, also accounting for aging effects [23]. This method consists in applying an oscillatory force to a beam sample and analyzing its viscoelastic frequency-dependent mechanical response. DMTA is of relevant importance since this kind of equipment is subjected to large temperature changes during use and storage. A limited influence of temperature on the visco-elastic properties is desirable in a material for ski back protectors allowing a constant performance in different scenarios, both in terms of impact absorption and ergonomics. By the way, the usage statistics and specific studies on the mechanics of back protectors are very limited [2, 11, 18] and generally mechanical studies are limited to experimental performance assessment without an engineering optimization of the product. While several works exploited both analytical and numerical modeling to assess the impact protection of motorcycle helmets [24, 25], there is no analogous research, up to the best of authors' knowledge, applied to back protectors for winter sports and addressing specific needs for practitioners.

Following a previous experimental work by the authors on commercial protectors [26], we here rationalize the obtained results by finite element method (FEM) impact simulation and analytical modeling to compare different soft-shell solutions currently available on the market. The role of the constitutive behavior, environmental temperature, and multiple impact on the energy absorption capability is evaluated. A characterization procedure is proposed and a simulation tool is developed for the design and optimization of such equipments.

2. Methods

2.1. Impact testing

Impact tests have been performed using an Instron Dynatup 9250 HV drop weight (gravity driven) impact testing machine using a flat circular impact head with a diameter of 4.5 cm. The sample is supported by a flat aluminum anvil which reproduces the real scenario where the protector adheres to the skier's back. The basic assembly is described in [19]. To avoid the influence of the curvature of the protectors the impacts have been performed only on flat sections at a distance of at least 5 cm from the edge of the protectors. The samples have been tested at +20 °C and after being kept at -5 °C for 24 hours. The total testing time was below 30 seconds, so it can be assumed that the samples maintained their temperature during the tests. All the samples were impacted using a mass of 5 kg dropped from a height of 1 m, to ensure an impact energy of 50 J. Sample deflection, impact force and velocity were computed with a sampling rate of 600 Hz. This type of tests provides a more complete information set on the material properties compared to the EN 1621-2 standard [17], which only requires measure of the transmitted force.

2.2. Analytical dynamic model

To describe the impact process in the drop weight configuration we recall the solution to the problem of a perfectly rigid flat punch in frictionless contact with a semi-infinite elastic solid. Under the hypothesis that mechanical vibrations can be neglected -and this is the case of soft materials- the impact event between two colliding bodies can be described by the following differential equation:

$$m\ddot{w}(t) + c\dot{w}(t) + kw(t) = 0, \tag{1}$$

where $w(t)$ is the displacement of the substrate at the center of the impact contact area (hence equal to the displacement of the impactor, assuming it as rigid), $m = \frac{m_1 m_2}{m_1 + m_2}$ with m_1 and m_2 being the mass of the impactor and of the substrate respectively, c is the coefficient of viscous damping, and $k = 2ER/(1-\nu^2)$ is the contact stiffness of the substrate in case of flat punch impact [27], with R being the radius of the impactor, E is the Young's modulus of the deformable substrate, and ν its Poisson's ratio. Note that in our case $m_2 \to \infty$ and thus $m = m_1$, since the protector is supported by a rigid and fixed substrate. Hence, Equation (1) represents a single degree of freedom (SDOF) damped harmonic oscillator. The integration of Equation (1) with initial condition $\dot{w}(0) = v_0$ and $w(0) = 0$ yields to the following relation:

$$w(t) = \frac{v_0}{\omega_{\mathrm{D}}} \mathrm{e}^{-\xi\omega t} \sin \omega_{\mathrm{D}} t, \tag{2}$$

where $v_0 =$ is the initial impact velocity, $\xi = c/(2\sqrt{km})$ is the ratio between the damping coefficient c and its critical value, $\omega = \sqrt{k/m}$ is the pulse, and $\omega_{\mathrm{D}} = \omega\sqrt{(1-\xi^2)}$ is the damped pulse. The value of damping coefficient to be used in both analytical and FEM model can be related to the phase angle measured from the DMTA analysis as [28]:

$$c = \frac{k_{\mathrm{b}}}{\bar{\omega}} \tan \delta, \tag{3}$$

where $\bar{\omega} = 2\pi\bar{f}$, with $\bar{f}$ being the imposed oscillation frequency of DMTA analysis and $k_{\mathrm{b}} = 3EJ/l^3$ is the bending stiffness of the cantilever samples used in the DMTA analysis (see Supplementary Section S1.3). Computed values of ξ are reported in Supplementary Table S4.

The maximum average impact pressure $\bar{\sigma}_{max}$ within the substrate occurs at the instant of zero relative velocity ($\dot{w} = 0$), thus at a time:

$$\tau = \frac{2}{\omega_{\mathrm{D}}} \arctan \left[-\frac{\xi}{\sqrt{1-\xi^2}} + \sqrt{1 + \left(\frac{\xi}{\sqrt{1-\xi^2}} \right)^2} \right], \tag{4}$$

which, consistently, is inversely proportional to the ratio k/m showing how softer materials can increase the time-to-peak τ. From Equation (4) it is evident how this particular formulation is valid for subcritical damping ($\xi < 1$) and this is the case of the material tested in this work (see Supplementary Table S4). Finally, by inserting the value of the time-to-peak obtained by Equation (4) into Equation (2) it is possible to derive the maximum deflection w_{peak} and force F_{peak}. The corresponding mean contact pressure is:

$$\bar{\sigma}_{max} = \frac{2Ew(\tau)}{\pi R(1-\nu^2)}. \tag{5}$$

2.3. Finite Element model

Finite Element Method (FEM) simulations were performed to analyze and complement the experimental results. A rigid cylindrical impactor of radius $R = 2.25\,\mathrm{cm}$ and mass $m = 5\,\mathrm{kg}$ hits a deformable target at a impact velocity $v_0 = 4.47\,\mathrm{m/s}$, hence replicating exactly the setup of the the drop weight test. The substrate is represented by a cylindrical plate of radius 100 mm supported at the bottom (fixed boundary condition) to reproduce the experimental configuration. Only a quarter of the plate was modeled due to the symmetry of the system by setting proper boundary conditions (see Supplementary Figure S3). Thickness, density and material properties were changed case by case according to the values obtained by the characterization of protectors (see density and thickness reported in Supplementary Table S1 and DMTA-derived properties at different temperatures reported in Supplementary Table S4). The used material properties refer to DMTA analysis operated at a characteristic frequency of 50 Hz. This frequency was the highest that could be reach by our instrumentation and it was demonstrated to properly characterize the material properties for modelling the specific impact regime (energy and strain rate) tested in the experiments. The material model used for the polymeric protector is a constitutive law specifically developed for low density, closed cell foams [29]. This constitutive theory accounts both the elastic and inelastic responses of rigid polyurethane foams by decomposing the foam behavior into two parts: a skeleton and a nonlinear elastic continuum in parallel. The skeleton accounts for the foam behavior in the elastic and plateau regimes. The nonlinear elastic continuum accounts for the lock-up of the foam due to internal gas pressure and cell-wall interactions. Both the impactor and the substrate are modeled with hexahedral under-integrated solid elements. Spurious deformation modes (hourglass) were properly controlled and the related energy was monitored and verified to not affect simulation results. Two-way penalty based contact is implemented between the impactor and the target and friction in neglected in the model. The numerical models were implemented and solved within the explicit finite element solver ABAQUS. Additional modeling details are reported in the Supplementary Material (Section S2).

3. Results and discussion

3.1. Protector testing and thermal effects

The results of the force-displacement curves obtained from impact test at +20 °C are reported in Figure 1.a. In general, a good shock absorbing material should present a low impact force spread over a longer time, resulting in a reduced impulse and thus to a smaller probability of injury. In this regard protector 1, 2, and 4 have similar behavior while protector 3 shows sensibly higher impact force and low time-to-peak. Note that, since the specific characteristic of the test, the absorbed energy (area under the stress strain curve) is the same for all protectors and equal to the initial impactor kinetic energy K_0 but the protectors differ from each other in the way they dissipate this energy. All protectors are able to sustain the impact without damage as the applied impact energy is below the Level 1 protection level to which all samples are certified.

The force-displacement curves of all protectors have similar characteristics, typical for this kind of materials [30]: a first linear elastic region, controlled by cell walls bending and stretching, is followed by a deformation plateau, controlled by non-linear elastic buckling of the cell walls. These two regions can be clearly distinguished by a "yield" point. Finally, the force increases sharply due to the densification of the foam whose stiffness tends to the one of the bulk material. Experimental curves are compared to the ones obtained by the FEM simulations. Results by different methods in terms of peak force F_{peak}, time-to-peak τ and mean impact pressure at peak force $\bar{\sigma}_{\max}$ are summarized in Table 1 showing good agreement between all methods of analysis.

Complementary results at -5 °C are reported in Figure 1.b. At low temperature all the soft-shell protectors present an increase of the curve slope (hard behavior) with respect to the behavior at +20 °C, since the material is more rigid due to the reduced motions of polymer segments, with the result of an increase of the apparent stiffness and yield point. Protectors 2 and 4 show the largest increase of the peak impact force and shortening of the time-to-peak (Table 1). This result can be directly imputed to the highest thermal sensitivity showed in the material stiffness (Supplementary Section S1.3 and Table S4) and thus the effectiveness of this kind of protector should be thoroughly investigated since its apparently lower performance at lower temperatures, with a behavior more similar to the hard-shell protectors, i.e. high impact force spread in a short time. Thus, on the basis of impact analysis at different temperatures protector 1 seems to be the most preferable solution among the all tested to reduce the severity of the injury after a fall. In this sense soft-shell protectors differ from hard-shell technology which do not show a significant change at low temperature since the mechanism of impact protection does not rely on viscous damping, almost negligible, but on material stiffness [26], which is not significantly affected in those kind of materials. FEM snapshots of Figure 1.a-b show how the stiffening of the material at low temperature yields to lower deflection and lets the stresses to distribute over a wider area with respect to the same protectors analyzed at room temperature. Characteristic results from all performed analyses at -5 °C are reported and compared in Table 1.

3.2. Multi-impact performance

The behavior of protector 2 has been tested at +20 °C under multiple impact by repeating the drop weight test five times on the same area, with an interval of 1 minute between tests. Figure 2 shows the force-displacement curves of the 5 impact events under the same conditions. It is evident the increase in w_{peak} and a reduction of the yielding force prior to the plateau. The explanation of this behavior can be connected to the damage that occurs in the foam structure after each impact event, which leads to a softening of the material [30]. However, at high deformation, an increase in the peak impact force (+23.5 %) is observed. This behavior, apparently in contrast with the reduction softening of the materials can be explained by the fact that the damaged occurred in the material enhances its non-linear constitutive response, yielding higher elastic modulus at higher compressive strain, since the accumulated permanent deformation yields to a progressively denser material. Secondly, the increase of F_{peak} may be attributed to the fact that the higher deflection makes the impactor to feel more the effect of the rigid substrate. This should not be accounted as a test artifact as it represents the real scenario offered by the skier's back. Thus, a compromise between material properties and thickness (ergonomics) must be properly evaluated as well as the degradation of properties after several impacts. However, it must be noted that the increase in the impact force after 5 events is much limited with respect to hard-shell protectors which have proven to be less sensible to temperature but have poor multi-impact capabilities [26].

4. Conclusions

The study of the thermo-mechanical and impact properties of materials used for soft-shell back protectors showed their strain-rate-sensitive behavior. Indeed, the viscoelastic properties, elastic modulus and damping coefficient, depend on the frequency of the applied stress. These protectors are more rigid at high speed impacts (high-frequency load) while are softer for low strain rates, resulting in a good ergonomic comfort during during natural movements but protecting the body in case of a collision. Results on some commercially available back protectors show that some products are very sensitive to temperature, and in the real environmental can lead to a significant increase (up to about 2-3 times) of the impact force. In this sense, polymeric foams with low temperature dependence should be preferred. The high sensitivity to temperature with respect to traditional rigid protectors is counterbalanced by a better multi-impact behavior, which make soft-shells preferable. The developed FEM impact model is able to reproduce the experimentally observed behavior for the different protector, and can give extra information regarding the deformation and stress states that could be of help for future advanced design and optimization of such equipments. The procedure presented in this paper can be used as a protocol during the design of body protectors and ski helmets pads in order to select the best performing materials and geometries, thus reducing cost and time of the development process. Future investigations should include a wider range of scenarios -limited in this work-, accounting different impact energies/velocities, impactors of different shapes (also simulating cutting and high penetrating objects), and variable angle on incidence. Moreover, a more thoroughly understanding of the behavior of these materials in a wider temperature range is necessary as well as a deeper correlation between material characterization by DMTA and actual impact conditions for better prediction capability of models.

Practical implications

- The analytical and numerical models presented here can predict with good reliability the impact behavior polymeric-foam-based protectors. These methods could represent a viable alternative for manufacturers to save in physical prototyping and experiments during the design stage, especially for optimization studies.

- More real and specific impact scenarios can be included in the models, overcoming limit of current standardized test and classification by protection levels, which are borrowed from motorcycling standards. Tailored design of protectors, e.g. zoning of properties, according to specific needs of different sport activities is an example.
- The results presented here can provide guidelines for future studies and development of standards dedicated to winter sports protectors.

Conflict of Interest

The authors have no financial or other interest with producers and distributors of the products tested in this work.

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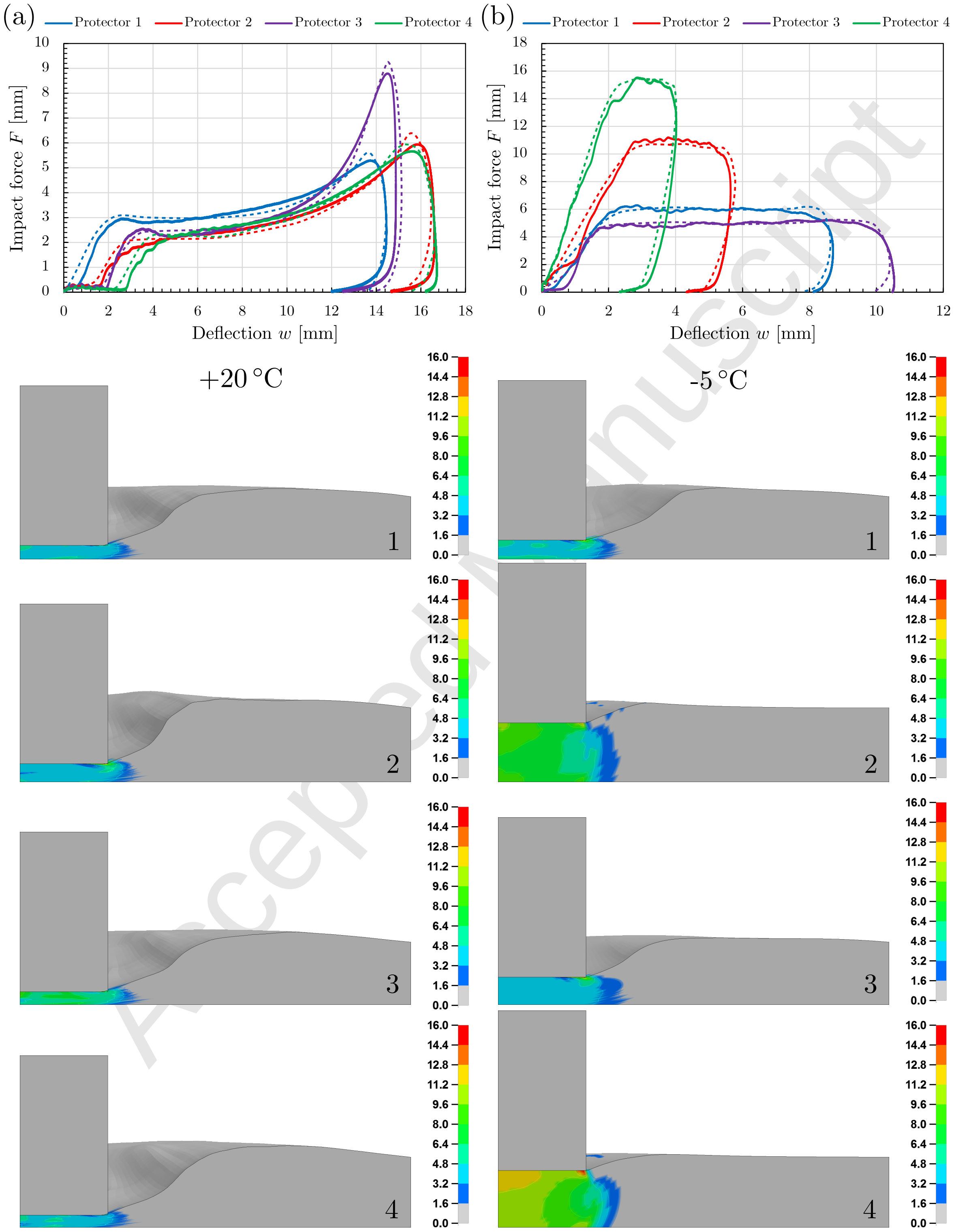

Figure 1: Experimental (continuous) and FEM (dashed) force-deflection curves for the four tested protectors at (a) +20 °C and (b) -5 °C. In the bottom panels the snapshots from FEM simulation at the characteristic impact point ($t = \tau$) are depicted with contour plot of impact pressure (units in MPa). Values can be compared to the experimentally derived and analytically predicted stresses in in Table 1.

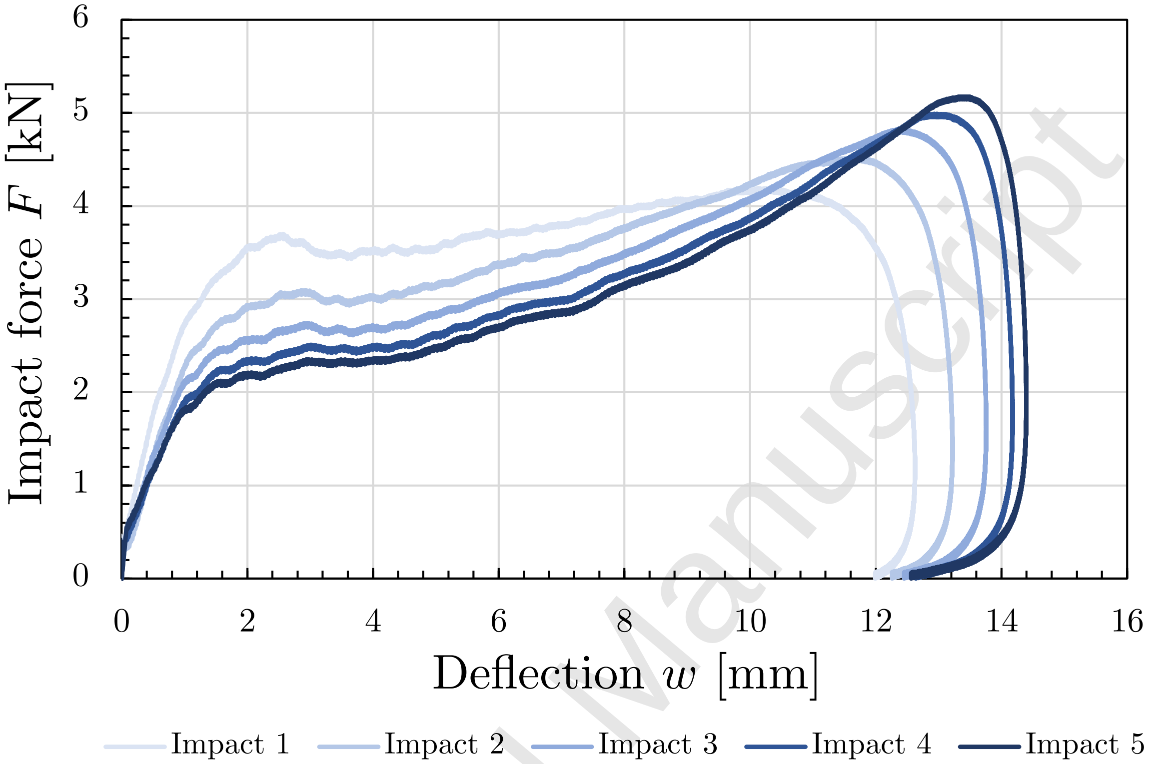

Figure 2: Experimental force-deflection curves for protector 2 under multiple impact at +20 °C.

Table 1: Comparison of characteristic impact properties among all methods used in this analysis for tests at +20 °C and -5 °C.

T	**Protector**	**Experiments**			**FEM Simulations**			**Analytical model**		
		$F_{\mathbf{peak}}$ [kN]	τ [ms]	$\bar{\sigma}_{\mathbf{max}}$ [MPa]	$F_{\mathbf{peak}}$ [kN]	τ [ms]	$\bar{\sigma}_{\mathbf{max}}$ [MPa]	$F_{\mathbf{peak}}$ [kN]	τ [ms]	$\bar{\sigma}_{\mathbf{max}}$ [MPa]
+20 °C	1	5.30	4.8	3.33	5.58	4.7	3.51	4.08	5.2	2.57
	2	5.73	4.8	3.60	6.40	4.6	4.02	4.17	4.8	2.62
	3	8.64	4.3	5.43	9.30	4.2	5.85	7.93	4.6	4.99
	4	5.55	4.3	3.49	5.87	4.3	3.69	4.87	4.7	3.06
-5 °C	1	6.29	2.6	3.95	6.10	2.8	3.84	6.38	2.9	4.01
	2	11.20	1.7	7.04	10.80	1.8	6.79	10.21	2.3	6.42
	3	5.22	2.9	3.28	5.31	2.8	3.34	5.05	2.5	3.18
	4	15.53	0.8	9.76	15.38	0.8	9.67	14.83	1.6	9.35