FE Modeling of Innovative Helmet Liners

D. Hailoua Blanco*, A. Cernicchi*, U. Galvanetto†

** Dainese S.p.a
via dell'Artigianato 35, Molvena, Italy*

*† University of Padua – Department of Structural and Transportation Engineering
via Marzolo 9. Padua, Italy*

Email: *david.blanco@dainese.it*, *alessandro.cernicchi@dainese.it*, *galva@dic.unipd.it*

Abstract

A key component of a safety helmet is the energy absorbing liner, which absorbs the greatest portion of impact energy during an accident. The aim of the present work was to study innovative structures for energy absorption that minimize the likelihood of head injuries for standard impact cases.

The innovative helmet liner consists of an ABS plastic lamina with deformable cones on it. Energy is absorbed via a combination of folding and collapsing of the cones. The main advantage that such liner may introduce over common EPS pads is that it allows a better optimization of energy absorption for different impact sites and configurations.

Numerical crash simulations of the novel liner employed in a ski helmet were carried out with LS-DYNA®. The model reproduced the testing conditions defined by the standards EN1077. Experimental and numerical results were compared and possible causes of discrepancies were discussed. The finite element model so validated paves the way for a future numerical parametric optimization of the novel structure.

Keywords: Helmet, Crashworthiness, Energy Absorbing Structures, Drop testing

Introduction

The use of helmets as a head protection device is widespread in many areas such as motorcycling, cycling, skiing, motorsport and other dynamic sports. All these have in common high speeds and, therefore, potential hazards due to crashes, falls or impacts with fast travelling objects [1].

The structural parts of helmets responsible for impact management are basically two: the outer rigid shell and the energy absorbing liner. The outer shell is usually made of thermoplastic materials such as Acrylonitrile Butadiene Styrene (ABS) or Polycarbonate (PC), or composite materials such as Glass Reinforced Fibers (GRP). The main function of the outer shell is to spread the impact load over a wide area of the head in order to reduce local pressure and avoid direct contact with sharp objects. The liner is the part of the helmet that absorbs the greatest portion of impact energy during crashes by providing a stopping distance and is usually made of Expanded Polystyrene (EPS) [2].

The high crushing stress to weight ratio and low manufacturing cost of EPS have made it the best liner material to manage consistent amounts of impact energy. Nonetheless, EPS use has some drawbacks, such as the difficulty to optimize energy absorption in different areas of the head and the excessive insulation that prevents heat evacuation. In this study, a new concept of helmet

liner was analyzed. The novel liner consists of a plastic lamina shaped into deformable cones. Energy is absorbed via a combination of folding and collapsing of the cones. The main advantage that such liner may introduce over common EPS pads is that it allows a better optimization of energy absorption for different impact sites and configurations.

Over the past years, the concept of using folding structures for energy absorption has been already used in several engineering fields such as automotive, aerospace, protective equipment and packaging. Examples are now available in a wide range of products: vehicle bumpers, crash barriers, protectors, oil tanks etc. Common energy absorbing structures include circular tubes, square tubes, frusta cones, struts, honeycombs and sandwich plates [3]. Essentially, all these structures aim at absorbing totally or partially the impact kinetic energy, thus ensuring that human injuries or damage to equipment are minimal.

The crashworthiness of the cones liner was investigated with a FE model of a ski helmet prototype. Impact simulations reproducing the standards EN1077 [4] were performed with the FE solver LS-DYNA®. Numerical tools are of great importance in a novel product development, as its performance is examined and optimized before investments are made in moulds and production lines. Therefore, it is fundamental to develop realistic numerical models, which can be used to analyze the limit of and suggest possible improvements to the initial concept. Experimental crash tests were carried out and their results were compared to the numerical ones. Possible reasons for discrepancies are discussed.

Material and Methods

Numerical and experimental analyses were performed according to the class B procedure of the EN1077 standards for ski helmets. For the experimental tests, an instrumented headform equipped with a triaxial accelerometer was employed. The accelerometer model 353B manufactured by PCB Piezotronics Inc. was placed at the center of gravity of the headform. The headform used is made of magnesium alloy and weighs 4.7 kg corresponding to size 575 of the EN1077. The headform-helmet assembly was dropped in a free fall from a specific height so as to strike a flat anvil at 5.4 m/s. The acceleration time histories were recorded during the impacts carried out on two different sites: one at the crown and one at the front. The prototype was tested at room temperature (25°C).
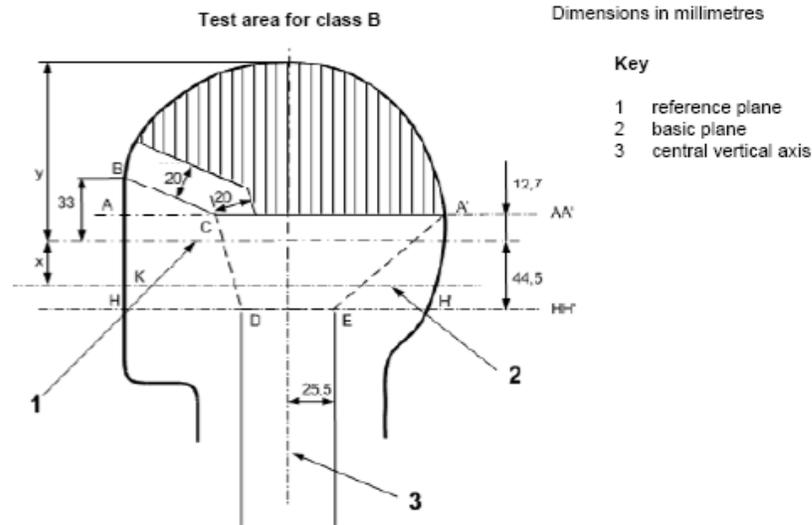
Fig. 1   Test area (dashed) of EN1077 class B.

Fig. 2   Ski helmet prototype on the headform.

The impact tests were simulated with LS-DYNA explicit FE solver. The model was composed of four parts: a PC shell, an ABS cones liner, a retention system and a headform. In order to reduce the computational time required for the simulations, the helmet was positioned at short distance from the anvil and given an initial speed of 5.4 m/s instead of being dropped. The different components of the FE model are analyzed in the following sections.

Outer shell and inner liner
The outer shell must be stiff enough to resist penetration and distribute the impact load over a wide area of the head. The present shell was made of transparent Polycarbonate (PC) and had an even thickness of 1.8 mm. 4-noded shell elements with full-integrated formulation (ELFORM 16) and five integration points through the thickness were used to model the outer shell. Material model 101 (*MAT_GEPLASTIC_STRATE) of LS-DYNA was used to represent the constitutive behavior of PC. The material parameters were determined from dynamic and static experimental tests performed on samples of a similar material by Dainese S.p.a.

The cones liner was made of Acrylonitrile Butadiene Styrene (ABS). The liner thickness slightly varied from the crown to lateral sites due to the manufacturing process. The experimental thickness measured at the top was around 0.75 mm while on the lateral, front and rear site was 0.65 mm. Fully integrated 4-noded shell elements with five integration points through the thickness were also employed to model the ABS liner. Furthermore, material model 101 with parameters fitted from experiments was also used to model the material constitutive behavior.

Material model 101 was selected to account for the strain rate dependency and complex post yield behavior of both ABS and PC. It is well reported in the literature that the yield stress of a thermoplastic material is affected by the strain rate [5] and this was taken into account in the simulations.

The cones liner and outer shell were simply in contact and a low dynamic friction coefficient of 0.2 was employed for the simulations. The undeformed height of the cones was 16 mm.
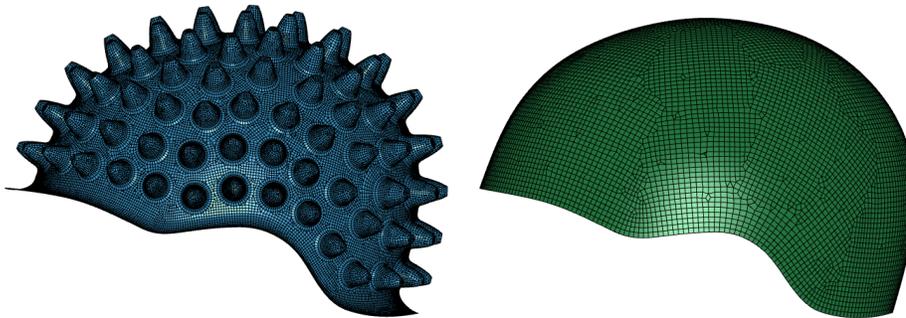

Fig. 3   Discretized geometry of ABS liner and PC shell.

LS-PrePost® was used to generate the mesh. The average element size was 1.5 mm for the liner, which was deemed to be a good trade off between accuracy and computational effort. Besides, this element size guaranteed that the mesh had no influence on the cone buckling mode. The average element size for the shell was 3 mm and the number of elements was 82.277 for the cones liner and 11.634 for the shell.

Headform and retention system
The headform geometry in the model was generated according the dimensions specified by EN1077 standards for a headform of size 575. This component was modeled with 4-noded tetrahedral elements and a rigid material model (*MAT_20). Indeed, its stiffness is orders of magnitude higher than that of the other helmet components and as a consequence the headform deformation could be neglected. Mass, inertia and the position of the center of gravity were manually introduced using the _INERTIA option in *PART. Values were set up according to the 575 headform used in the testing of protective helmets [6].
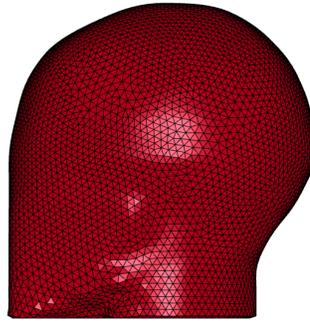
Fig. 4   575 headform model.

The retention system has the important task of keeping the helmet in place during a crash. It was modeled in accordance with the procedure outlined in [7]: two non linear springs connecting the chin of the headform with the outer shell. Constrained interpolation (*CONSTRAINED_INTERPOLATION) was applied to the shell anchoring point in order to distribute the tensile load over a certain number of elements. The retention system force was applied to the anchoring node (dependent) and redistributed to the five surrounding nodes (independent).This constrain implies that the motion of a dependent node is interpolated from a set of independent nodes [8].

Anvil and contact modeling
The impact anvil was in accordance with the apparatus described by the standard EN 13087-2:2000 [9]. The appropriate anvil is made of steel with a flat circular impact face and a diameter of 130 mm. The anvil was modeled with the *RIGIDWALL option available in LS-DYNA, since it is a simple way of treating contacts between a rigid body and a deformable body [8].

To consider the self contact, which is expected during the cone folding process, the contact algorithm *AUTOMATIC_SINGLE_SURFACE without friction was used. Contacts between headform and liner and between liner and shell were treated with *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE with dynamic friction coefficient of 0.2. The soft constraint SOFT=1 was used in the contact between the headform and liner.

Regarding the contact, another aspect reviewed in this article is the interface between the cones and outer shell. The difference in terms of impact response for a new helmet configuration where the cones were constrained to the shell was studied numerically. It was noticed experimentally that in high curvature impact areas such as the front site, the cones were partially subjected to bending instead of axially collapse. Therefore, this behavior may have an important repercussion in terms of helmet performance and it was investigated if it could be improved by constraining the cones tips to the outer shell.

Results and discussion

To validate the FE model, two experimental impact tests according to the EN1077 standards were carried out. The impact points corresponded to the typical crown and front sites at room temperature (25°C). The acceleration-time curve was registered with an acquisition system developed by AD. Engineering and the results were compared to those of the simulations. The

impact duration was approximately the same in all the cases, around 8 ms, and the resultant simulation curves were consistent with those obtained experimentally. Peak linear acceleration is the parameter commonly associated to the likelihood of head injuries in helmet standards, therefore comparisons in this paper are shown in terms of linear acceleration magnitude against time.

Crown site (Point P)
There was a good agreement between experimental and numerical results in terms of deformation shape (see fig. 5). In total, nine cones were deformed. The cone that absorbed the higher portion of the impact energy was the one situated in the middle of the anvil area; however the surrounding cones contributed relevantly to energy absorption. The central cone folded axially, while the others slightly bent as no bond was present between the liner and shell.
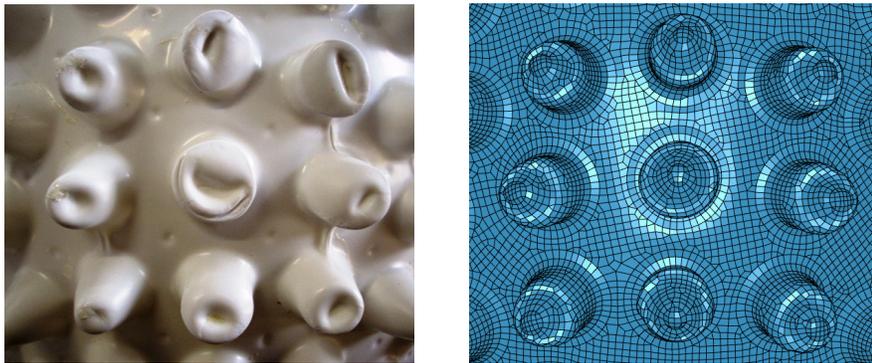

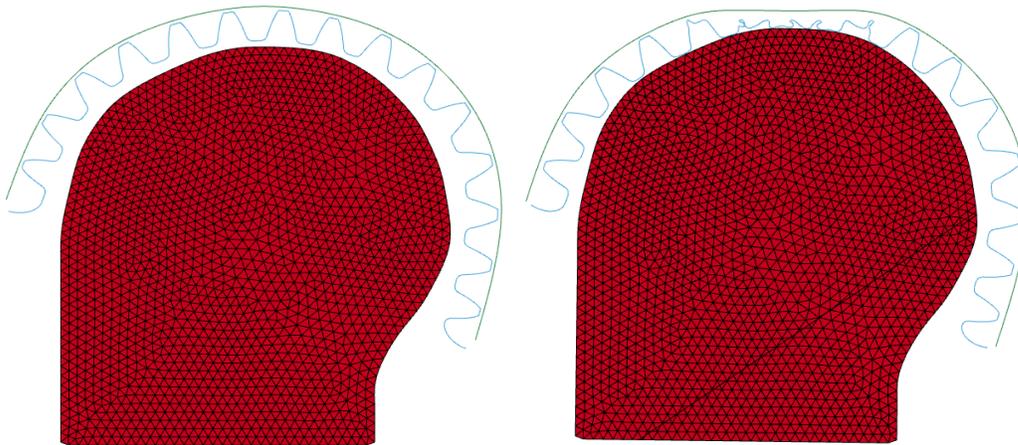Fig. 5   Experimental and numerical deformed shape at the crown.

Fig. 6   Cross section of the helmet at initial time step (left) and after the impact (right).

The acceleration curve was characterized by four regions and two main acceleration peaks. The first region showed a rapid increase in acceleration due to elastic deformation of the cones and shell, which ended to the first maximum peak corresponding to the collapse of the central cone. At this stage, energy absorption was mostly driven by the central cone. The second region showed a decrease in acceleration corresponding to the folding of the cones. Subsequently, in the third region the acceleration ramped up again due to the onset of densification in the central

cone. Eventually, in the last unloading stage, all the impact energy was absorbed and the headform-helmet system bounced back.
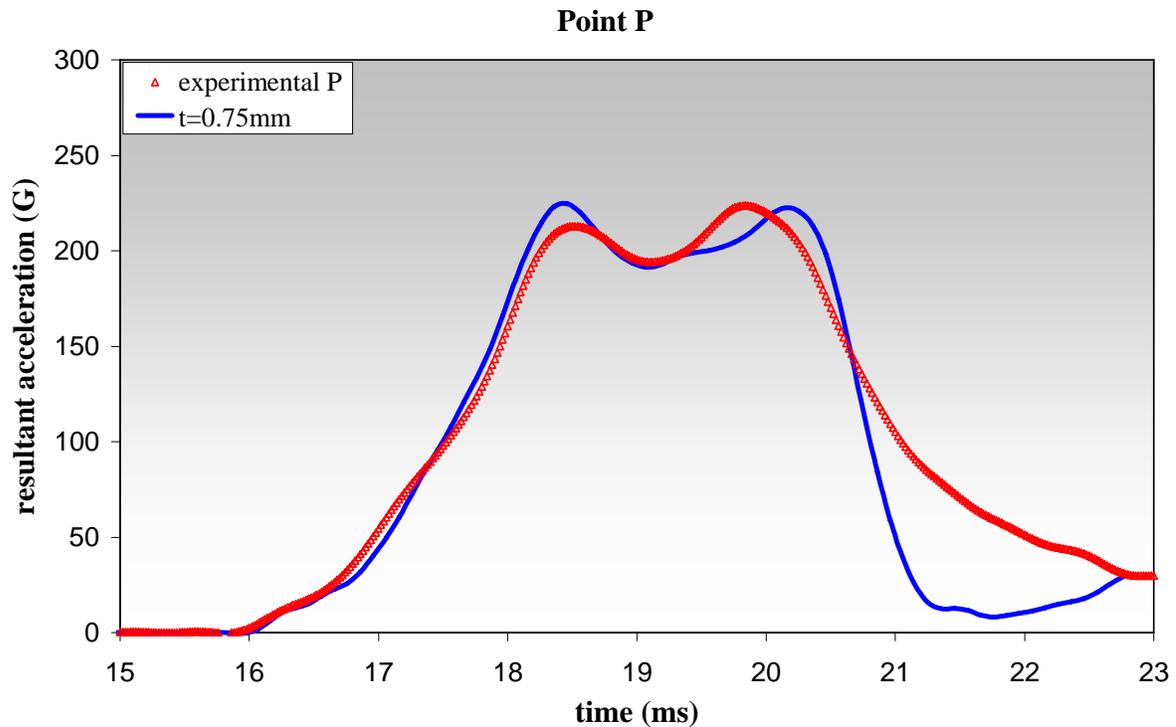
Point P

Fig. 7   Experimental versus numerical acceleration at the crown.

Comparing the experimental and simulated results two differences were perceptible. The first peak from the experimental results was lower compared to that of the simulations. This may reflect the difference between real and modeled material properties as well as some small crack propagation in the real material that were not numerically modeled. Another difference was that the simulated acceleration curve decayed more rapidly as compared to the experimental one. This may be attributed to the high steepness of the unloading path curve of the material model used (the material unload elastically with the same Young modulus as for the loading phase).

Front site (Point B)
From experiments, it was noticed that the current configuration at the front site was not able to manage safely the impact energy prescribed by the standards. This was also predicted by the simulations that showed a steep acceleration peak meaning that the energy absorbing capacity of the conical structure was overshot.
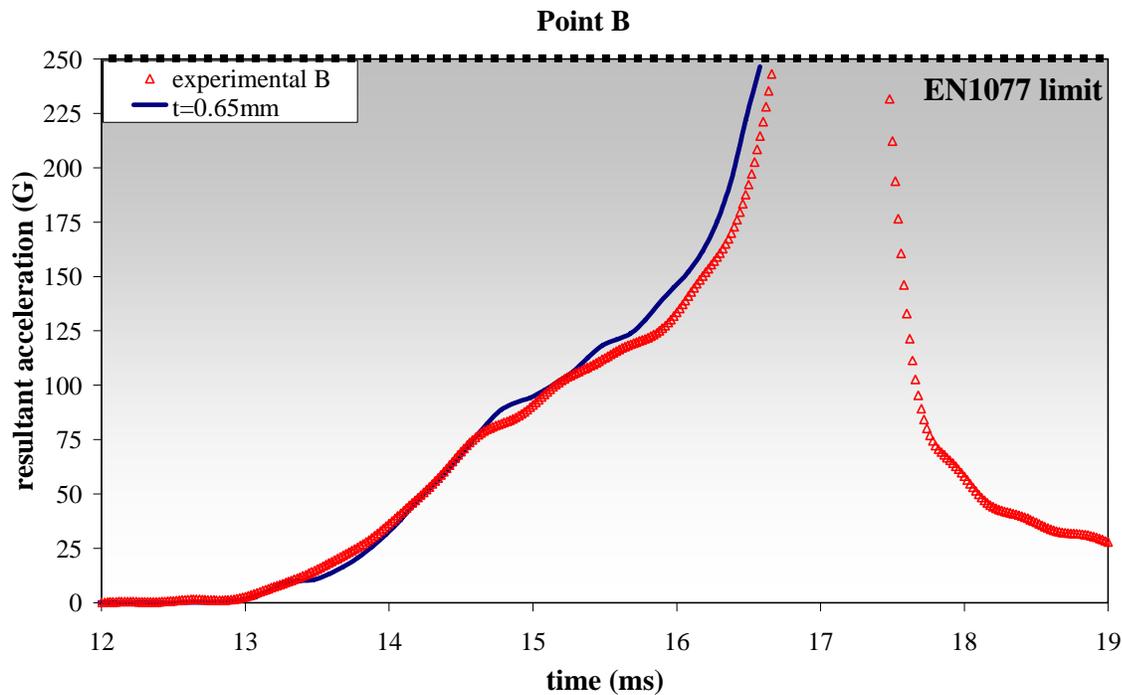
Point B

Fig. 8   Experimental versus numerical acceleration at the front.

To overcome this problem, two possible solutions were analyzed. The first was to increase the cones liner thickness to stiffen the structure and thus avoid premature densification. Another point to take into consideration is the fact that the curvature of the helmet varies from point to point. The regions with higher curvature may cause initial bending of the cones due to shear contact forces between the tip of the cones and shell. The onset of bending may result in a less efficient energy absorption folding as compared to the cone axial collapse. Therefore, the second solution was to investigate the influence of the interface between the cones liner and outer shell. A new helmet FE model in which the liner was constrained to the shell was built. The outer shell and cones tips were coupled together in such a way that both shared common nodes. In this way, lateral bending of the cones should be prevented and the bending stiffness of the shell-liner increased. In reality, this could be achieved by welding the top of the cones with the outer shell.

In a first simulation with constrained cones tips and no increase in cones thickness (fig. 10), no substantial difference in terms of peak acceleration was noticed as the new structure bottomed out in a similar fashion as the original one. However, an increase in helmet stiffness was achieved, which can be noticed by analyzing the first part of the acceleration curve that is higher than that of the original configuration (see fig. 10). The next step was to increase the thickness gradually until the results complied with the requirements of the EN1077.
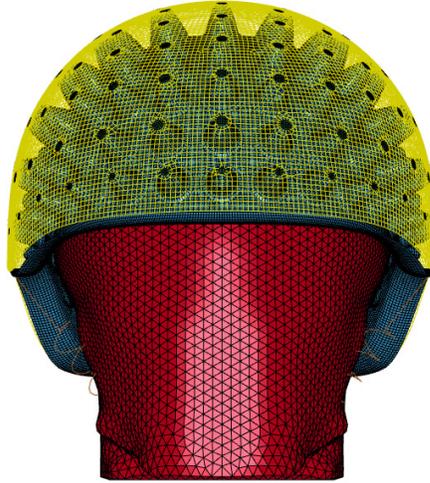
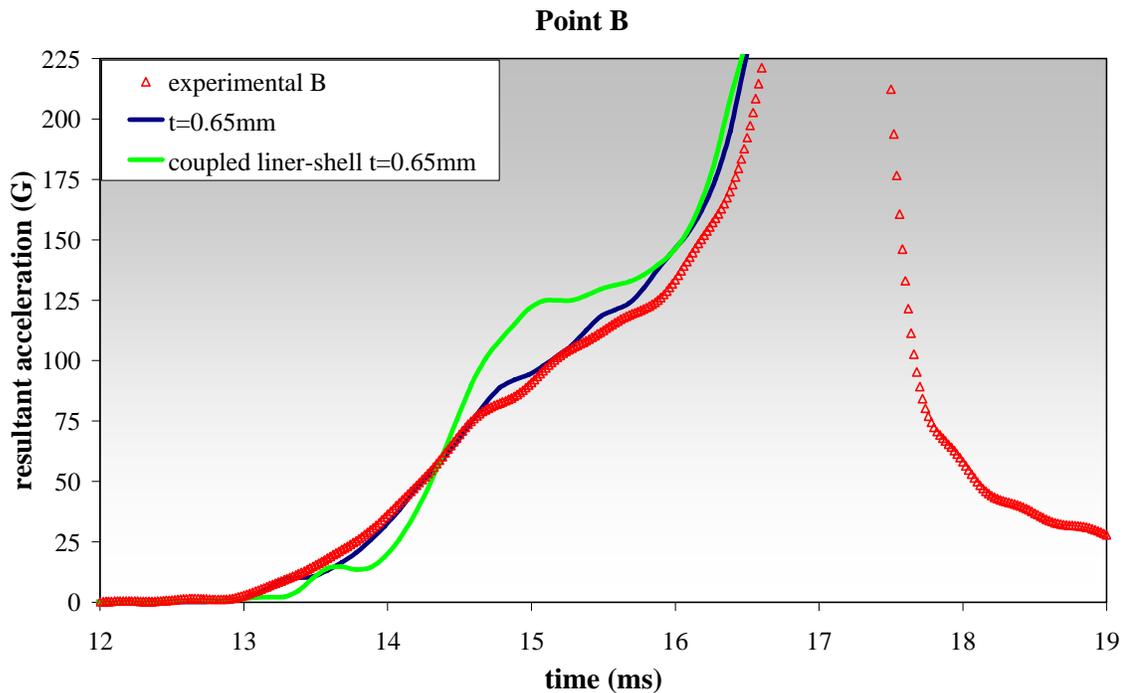Fig. 9   FE modeling of the coupled liner-shell helmet.

Fig. 10 Numerical comparison between uncoupled and coupled shell-liner configuration for 0.65 mm liner thickness.

A peak acceleration below the EN1077 threshold of 250 g was achieved for a cone thickness of 0.85 mm. Both constrained and non constrained tips were simulated with this thickness. From the results (fig. 11), it can be noticed that the constrained configuration (green graph) showed slightly lower peak acceleration compared to the non-constrained (blue graph). In the non constrained configuration a grater portion of impact energy was absorbed by the central cone as the surrounding ones bent. This made the structure a little softer (lower loading slope), but led to a higher peak due to the bottoming out of the central cone. On the other hand, for the coupled

liner-shell, due to the higher bending stiffness, the impact energy was spread over a wider area, which prevented the neighboring cones from bending.
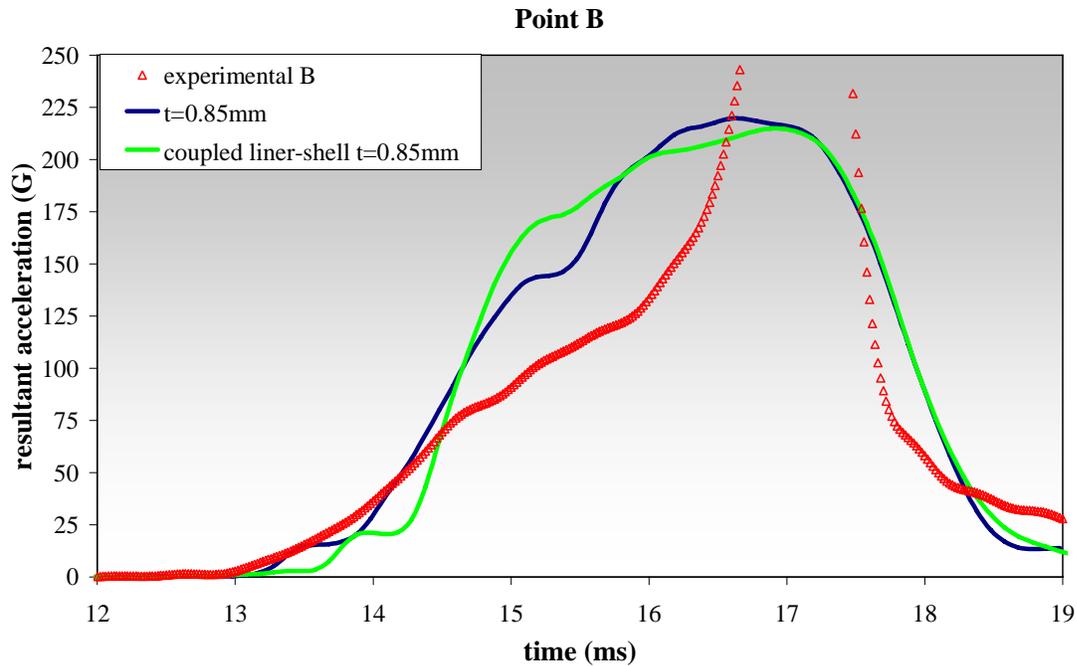

Fig. 11 Numerical comparison between uncoupled and coupled shell-liner configuration for 0.85 mm liner thickness.
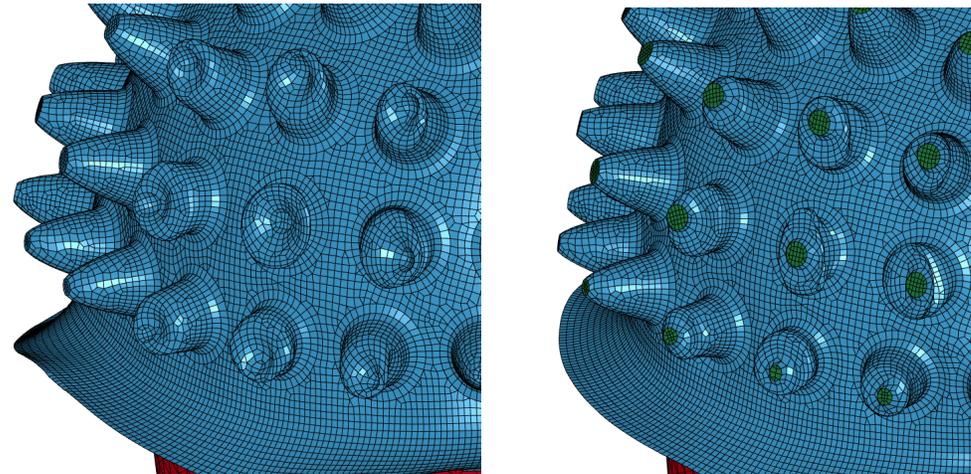

Fig. 12 Comparison between deformed shape for uncoupled and coupled shell-liner configuration for 0.85 mm liner thickness.

Helmet shells are stiffer when they are loaded at the crown, since this site has a double convex curvature and is distant from the rim [10], therefore the impact load is spread over a wide portion of the headform. For this reason, in foam based helmets, the strategy of introducing a softer EPS in that region it is usually adopted. This compensates for the increase in stiffness and makes the response independent on the site [11]. The numerical results in the current research confirmed

this tendency, and, in order to compensate for the decrease in impact force spreading, the optimal liner thickness of the frontal cones was higher than that of the crown cones. Alternative approaches may be to locally modify the geometry of the cones or to decrease the distance between cones, which will be analyzed in future numerical investigations.

Conclusion

Impact tests according to the EN1077 standards were carried out to test an innovative helmet liner. The main aim of the current work was to prove that the new concept of energy absorbing liners was a potential alternative to the current EPS ones. A FE model was created to carry out simulations of standard impacts on the helmet crown and front. Experimental and numerical results were in good agreement with each other. All the possible reasons for the discrepancies recorded were identified. The numerical analyses showed that the cones liner can be optimized by varying the cone thickness.

Other strategies for increasing the local energy absorbing capabilities are possible with this structure and will be analyzed in future studies. This first study paves the way for a numerical optimization of the liner by analyzing the effect of cone design variables on helmet performance. Further effort will be devoted at improving the current design and extend the new concept to motorbike helmets.

Acknowledgements

References

[1] B. Chinn, B. Canaple, S. Derler, D.Doyle, D. Otte, E. Schuller, R. Willinger. "Motorcycle Safety Helmets" COST 327, European Comission.

[2] V. Kostopoulos, Y.P. Markopoulos, G. Giannopoulos, D.E. Vlachos. "Finite Element Analysis of Impact Damage Response of Composite Motorcycle Safety Helmet", Composites: Part B, 33, pp. 99-107, 2002.

[3] G. Lu, T. Yu. "Energy Absorption of Structures and Materials", CRC Press, 2003.

[4] EN1077:2007 "Helmets for alpine skiers and snowboarders"

[5] P. Grant Martin. "Constitutive Modelling of Polymers Subjected to High Strain Rates", SAE, 01-0472, 2001.

[6] EN 960:2006 "Headforms for use in the testing of protective helmets"

[7] A. Cernicchi, U. Galvanetto, L. Ianucci. "Virtual modeling of safety helmets practical problems". International Journal of Crashworthiness, 13, pp:451-467, 2008.

[8] "LS-DYNA® Keyword User's Manual Version 971", Livermore Software Technology Corporation, 2007.

[9] EN 13087-2:2000 "Protective helmets – Test methods. Part 2: Shock absorption"

[10] A.Gilchrist, NJ, Mills. "Impact deformation of ABS and GRP helmet shells", Plastic Rubber composites Processes Appl, 21, 141-150, 1994.

[11] N.J. Mills, S.Wilkes, S.Derler, A.Flisch. "FEA of oblique impact tests on a motorcycle helmet", International Journal of Impact Engineering, 36, 913-925, 2009.