19th International Symposium of Ballistics, 7–11 May 2001, Interlaken, Switzerland

NUMERICAL HEAD AND COMPOSITE HELMET MODELS TO PREDICT BLUNT TRAUMA

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The ballistic impact response of composite helmets was evaluated numerically, using a previously presented numerical composite damage model. The simulations revealed that the helmet interior exhibited higher deformations than previously observed in flat panels fabricated from the same material. It was also found that the impact effects were localised and that the global motion of the helmet was negligible. In addition, ballistic impacts on the helmeted head were analysed, using the helmet model developed as part of this study and a state-of-the-art head model. These simulations showed that the helmet deformation can exceed the stand-off, resulting in an impact of the helmet interior with the skull.

INTRODUCTION

The introduction of composite materials in ballistic helmet design has lead to an improvement in ballistic resistance and a reduction in weight compared to the traditional steel helmets. However, a major drawback of composite helmets is that they can deform substantially under ballistic impact. These deformations can be so severe that the helmet interior impacts the head, which can result in serious head injury even when complete helmet perforation is prevented. Therefore, to further enhance the ballistic protection offered by composite helmets, the effects of the deformation of the helmet interior need to be better understood so that it can be accounted for in helmet design and performance criteria.

The complex response of composite materials together with the high costs and limited reproducibility of ballistic impact tests renders a completely experimental characterisation of the helmet deformation expensive and time consuming. Numerical modelling can provide a partial solution to this problem, since it allows a relatively fast and inexpensive means of gaining insight into the parameters governing the response of composite helmets to ballistic impact. A numerical model capable of predicting the ballistic impact response of laminated composites has been presented previously [1]. The accuracy and limitations of the numerical model were evaluated by simulating ballistic impact tests on flat panels fabricated from the same material as ballistic helmets. In the current paper, the ballistic impact response of a flat panel is compared with that of the actual helmet. Further, a numerical analysis of the ballistic impact response of the helmeted head is presented.

MODEL DESCRIPTION

Damage Model

Penetration failure, fibre breakage, matrix cracking, and delamination are generally considered to be the principal damage mechanisms in ballistically impacted laminated composites [2–5]. A numerical model was developed as part of this research to predict the onset and growth of these damage modes during ballistic impact of laminated helmets [1]. The model was based on Continuum Damage Mechanics (CDM) theory [6] and implemented within the explicit three-dimensional finite element code LS-DYNA.

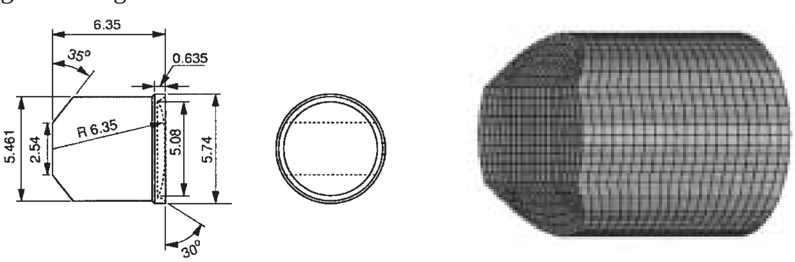
A distinction was made between the prediction of intralaminar (in-plane tensile and penetration failure) and interlaminar failure (delamination). The intralaminar failure modes were modelled within the element constitutive routines, implemented in a so-called user-defined material subroutine. The interlaminar failure mode was treated using discrete interfaces, allowing inter-ply cracking. For a more extensive description of the damage model, the reader is referred to [7].

Mesh Characteristics

Finite element models of the projectile, target panel, and the helmet were built using I-DEAS Masters Series, Version 6. All components of these models were discretised using 8-node brick elements with single point integration.

Projectile Mesh

The analyses presented in this paper focus on impacts by 1.1 g, 22 calibre chisel nose Fragment Simulating Projectiles (FSPs), which are commonly usod to assess the ballistic protection provided by body armour (MIL-P46593). The FSP dimensions and mesh are given in Figure 1.



a) Dimensions [mm] b) Mesh
Figure 1: FSP dimensions and mesh.

Panel Mesh

In a previous study [1], the accuracy and limitations of the composite damage model were evaluated with ballistic experiments on woven fabric Kevlar-29/phenolic laminated panels with planar dimensions of 101.6 x 152.4 mm (4x6 inches) and a thickness of 9.5 mm. Similar to the physical panels, the panel model consisted of 19 plies, each 0.5 mm thick, resulting in a total thickness of 9.5 mm. Each ply in the panel model was 2 elements thick and adjacent ply meshes were connected by a discrete delamination interface to model the initiation and growth of impact induced delaminations. The computation time was reduced by modelling only one quarter of the problem utilising symmetry. A gradient in mesh density was applied with sufficient detail in the impacted area and larger elements elsewhere, thereby providing accurate results at reasonable computational costs. The panel mesh is presented in Figure 2.

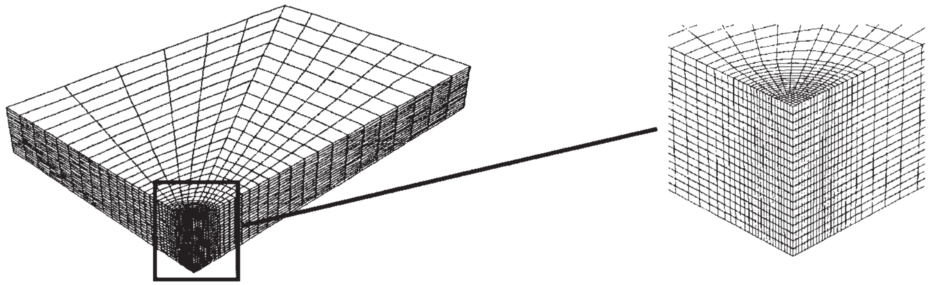


Figure 2: Finite element model of the woven Kevlar-29 laminated panel.

Helmet Mesh

The geometry of a PASGT helmet was characterised experimentally, reconstructed in I-DEAS, and discretised with brick elements. To limit the total number of elements in the helmet mesh, only part of the mesh was allowed to delaminate during the simulated impact. To avoid artificial boundary effects on the delamination growth in the simulations the size of the area for which delamination was enabled was chosen to be larger than the delaminated area measured in impact tests on Kevlar helmets [8] and flat panels [1]. The discretisation in the delamination zone was based on that of the panel to avoid mesh effects in the comparison between the helmet and panel response. Similar to the panel model, the delamination area in the helmet mesh consisted of 19 layers and each layer contained 2 elements over its thickness. Delamination was enabled by inserting a discrete delamination interface between adjacent layers. The mesh density was gradually decreased outside the delamination area to 20 and 10 elements over the helmet thickness. The parts with different mesh densities were connected by tied interfaces. Figure 3 shows the helmet mesh developed to simulate frontal impacts, together with a close-up view of the refined mesh in the impacted area.

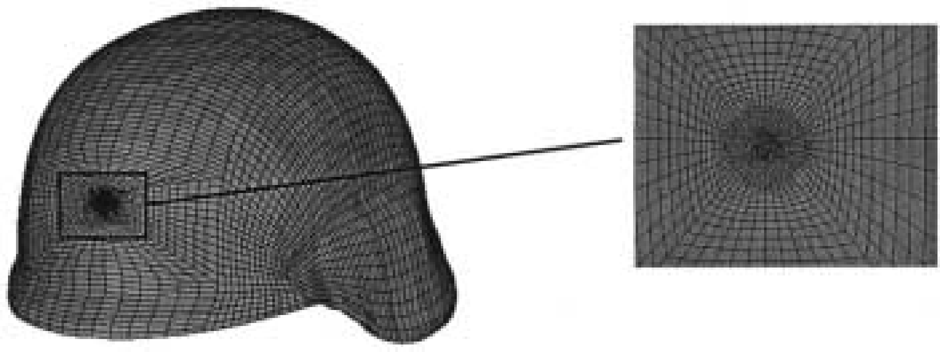


Figure 3: Helmet mesh for frontal impacts.

Constitutive Models

The FSPs were fabricated from 4340 steel and heat treated to 29 HRc. The 1.1 g FSP was modelled as an elastic-plastic material with isotropic hardening (Table 1).

Table 1: Material properties adopted for 1.1 g FSP.

E [GPa]	ν [-]	S_y [MPa]	H [MPa]	ρ [g/cm^3]
206.8	0.3	1034.2	685.0	

E: Young's modulus *v*: Poisson's ratio S_y: yield strength H: hardening modulus ρ: density

The panels and ballistic helmets considered in this study were fabricated from woven Kevlar-29 fabric laminae embedded in a phenolic resin (MIL-C-44050, MIL-H-44099A). Material properties were obtained from data found in literature, which were modified to obtain closer agreement with experimental data trom ballistic impact tests [1] (Table 2).

Table 2: Elastic and strength properties adopted for woven Kevlar in helmet model.

$E_{11,22}$ [GPa]	E_{33} [GPa]	G_{12} [GPa]	$G_{23,31}$ [GPa]	ν_{21} [-]	$\nu_{31,32}$ [-]	ρ [g/cm^3]
18.5	6.0	0.77	2.715	0.25	0.33	1.23
$S_{11,22}$ [MPa]	S_{33} [MPa]	S_{12} [MPa]	$S_{23,31}$ [MPa]	S_n [MPa]	S_s [MPa]	
555.0	1200.0	77.0	1086.0	34.5	9.0	

E: Young' s modulus G: shear modulus *v*: Poisson's ratio ρ: density
S: strength values 1–3: principal material directions n,s: interlaminar normal & shear directions

RESULTS

Panel vs. Helmet

The simulations with the helmet model were compared to previously performed simulations with flat panels [1] to check the effects of the helmet curvature on the deformation response. The deformed mesh plots obtained from impacts with a 1.1 g FSP at 586 m/s are presented in Figure 4. The deformed meshes were obtained at the time of maximum backplane deformation, where the term backplane refers to the side of the laminate opposite to the impact site. The figure shows a similar trend in both the panel and helmet simulations, including the formation of a crater and the delamination of the composite due to the advancing projectile.

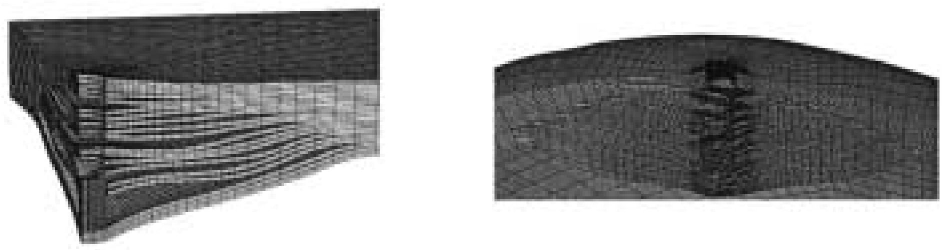


Figure 4: Deformed mesh plots of panel and helmet at time of maximum backplane deformation.

Figure 5 shows that the projectile velocity and backplane displacement for the helmet and flat panel simulations are similar until the point of maximum panel backplane displacement. At this point, the projectile is pushed back upwards by the panel backplane, whereas in case of the helmet the projectile continues to deform the backplane. Figure 5 also contains experimental data from IMAX and VISAR measurements obtained during a ballistic impact test on a panel under the same impact conditions. These measurements provide an indication of the accuracy of the simulations. A more thorough evaluation of the accuracy of the panel simulations is presented in [1]. Unfortunately, similar measurements on helmets are currently not available.

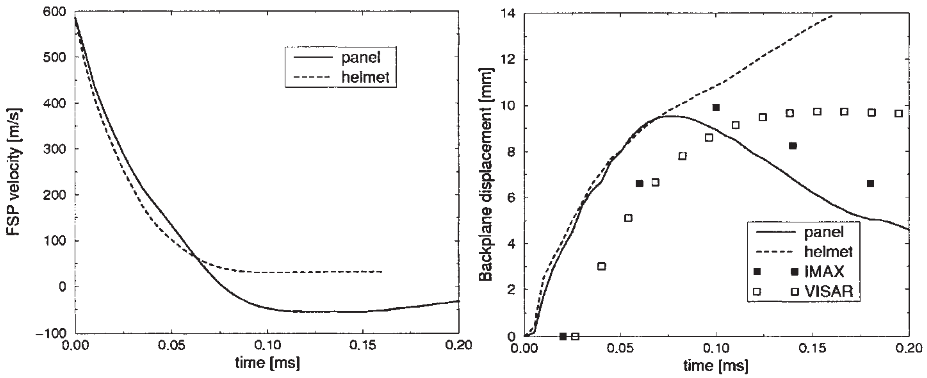


Figure 5: Comparison between simulations of Kevlar flat panel and helmet impacted by 1.1 g FSP at 586 m/s.

The rigid body motion of the helmet is presented in Figure 6. The helmet model was not supported and, therefore, free to move under the impact. The figure shows that the global helmet motion is negligible compared to the backplane, indicating that the effects of the impact are confined in the impacted area.

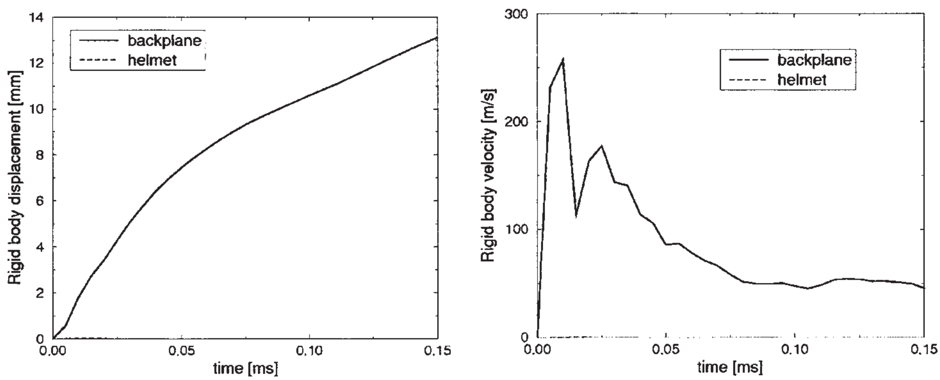


Figure 6: Rigid body motion of helmet outside delamination area.

Helmeted Head

Simulations of the helmeted head were also performed. Since the helmet simulations revealed that the impact effects were confined to the impacted area, only the delaminating part of the helmet was included in these simulations to save computation time. A state-of-the-art finite element model of the skull made available by the French Délégation Générale pour l'Armement (DGA) was used to represent the head. The average stand-off between the actual helmet and the head is about 12–15 mm. However, due to the curved shape of the helmet, the stand-off is larger at the front. For the study presented in this paper, the stand-off between the delaminating helmet area and the skull was about 20 mm to accommodate this larger stand-off at the front. The resulting model is shown in Figure 7.

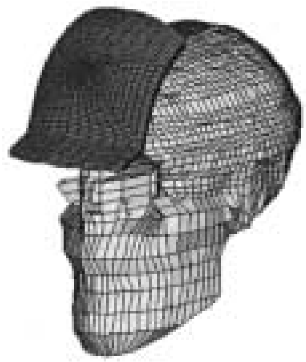


Figure 7: DGA head model with delaminating part of helmet.

Figure 8 presents the results of the simulations with the helmeted head, showing that the helmet backplane exceeded the 20 mm stand-off and impacted the head. The contact pressures in the skull resulting from the impact with the backplane are also presented, with a maximum contact pressure in the order of 20 MPa.

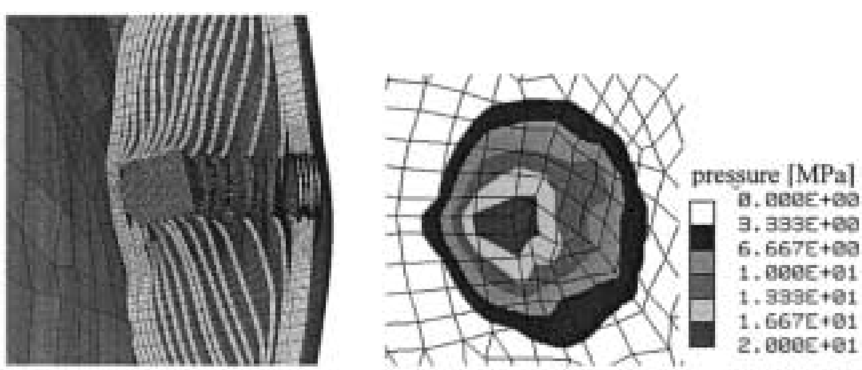


Figure 8: Impact of delaminating helmet backplane on skull (FSP impact velocity = 586 m/s).

DISCUSSION AND CONCLUSIONS

The ballistic impact response of laminated helmets was evaluated numerically in this study. The results indicated that the predicted backplane deformation was greater for the helmet than for flat panels fabricated from the same material. The helmet simulations also indicated that the impact event is very localised and its effects are restricted to the impacted area. The global motion of the helmet is negligible compared to that of the backplane. Simulations of ballistic impacts to the helmeted head showed that the backplane deformation exceeded the stand-off, resulting in an impact between the helmet interior and the skull.

The numerical findings presented in this paper need to be verified experimentally. As was previously done for the flat panels, the accuracy of the helmet simulations should be evaluated with ballistic impact tests performed on actual helmets. In addition, experiments should be performed to verify the skull contact pressures found in the helmeted head simulations, using either an anthropomorphic test device (Hybrid-III dummy) or post-mortem subjects.

ACKNOWLEDGEMENTS

The authors are grateful to the Defence Research Establishment Valcartier (DREV) for their financial support for this project. The authors would also like to thank the Délégation Générale pour l'Armement for providing the finite element head model.

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