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Modelling ballistic impact on military helmets: The relevance of projectile plasticity

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Abstract

The need to develop armour systems to protect against attacks from various sources is increasingly a matter of personal, social and national security. To develop innovative armour systems it is necessary to monitor developments being made on the type, technology and performance of the threats (weapons, projectiles, explosives, etc.) Specifically, the use of high protection level helmets on the battlefield is essential. The development of evaluation methods that can predict injuries and trauma is therefore of major importance. However, the risk of injuries or trauma that can arise from induced accelerations is an additional consideration. To develop new materials and layouts for helmets it is necessary to study the effects caused by ballistic impacts in the human head on various scenarios. The use of numerical simulation is a fundamental tool in this process. The work here presented focuses on the use of numerical simulation (finite elements analysis) to predict the consequences of bullet impacts on military helmets on human injuries. The main objectives are to assess the level and probability of head trauma using the Head Injury Criterion, caused by the impact of a 9 mm NATO projectile on a PASGT helmet and to quantify the relevance of projectile plasticity on the whole modelling process. The accelerations derived from the impact phenomenon and the deformations caused on the helmet are evaluated using fully three-dimensional models of the helmet, head, neck and projectile. Impact studies are done at impact angles ranging from 0 to 75°. Results are presented and discussed in terms of HIC and probability of acceleration induced trauma levels. Thorough comparison analyses are done using a rigid and a deformable projectile and it is observed that plastic deformation of the projectile is a significant energy dissipation mechanism in the whole impact process.

Keywords: Ballistic impact , helmet impact , plasticity , finite element analysis , injury , trauma , HIC

1. Introduction and scope

On the battlefield, the use of high performance and high protection level systems (including vests, helmets, etc.) is of utmost relevance. The need to improve the performance of the protection is constantly increasing through the development, design and use of new materials and innovative systems and layouts that can, for example, better resist blast waves, projectile and fragment impacts and penetration. To help this development it is necessary to study and better understand the effects induced by blast waves and ballistic impacts on soldiers in different scenarios. The use of numerical simulation is an essential tool to help predict the consequences of such effects on the human body. This work focuses on the assessment of the level of brain damage, using the Head Injury Criterion (HIC), caused by the impact of a ballistic projectile on a PASGT (Personal Armour System for Ground Troops) standard NATO model helmet. The PASGT helmet is one of the most widely used and is often the base for the development of better and improved models.

This generic topic is of utmost importance as can be corroborated by the fact that it has been addressed with different approaches by other researchers. Van Hoof *et al.* [1] analysed the ballistic impact response of woven composite helmet materials both experimentally and numerically. The ballistic impact tests were performed on flat plates of the same material as ballistic helmets and the corresponding numerical model was implemented in LS-Dyna to predict the penetration and backplane response of composite materials under ballistic impact. Good agreement was observed between the simulated backplane displacement and the data obtained from the ballistic experiments. Van Hoof *et al.* [2] studied the mechanical response of a composite helmet to a frontal ballistic impact. These authors developed a numerical model based on the finite element method (FEM), to predict the interactions between the helmet and the human head. They used a .22 calibre FSP (Fragment Simulating Projectile) with a mass of 1.1 g and an impact velocity of 586 m/s. Van Hoof *et al.* concluded that the helmet back face deflection (BFD) were significantly higher than expected and predicted by previous analyses from other authors. Other relevant conclusions by these authors were that local effects are much more significant than any global (e.g. rigid body) movements of the helmet-head system, thus neglecting the latter. Van Hoof and Worswick [3] reached similar conclusions, stating that the back face deflection could reach values larger than the helmet-head clearance distance, leading to indirect impact lesions/injuries. Baumgartner and Willinger [4] studied the rear-effect caused by a high velocity projectile impacting a military helmet. The rear-effect is a phenomenon that describes the deformation of the helmet shell and eventual contact with the head (e.g. as reported by van Hoof and Worswick [3]). They developed a detailed finite element model of a human head (an approach not used by van Hoof *et al.* [2]), including the main anatomic parts (skull, brain, etc.) and modelled the ballistic helmet as a thin aluminium alloy sheet. A rigid steel projectile was used and the obtained results led to the prediction of linear fractures on the skull. The injury tolerance limit was, however, not reached for any of the simulations. Aare and Kleiven [5] studied the influence of the rotation of the head induced by non-orthogonal impacts. This rotation was shown to strongly affect injury levels. These authors also studied the influence of the helmet shell stiffness on eventual injury levels during impacts at different angles, using a 9 mm Parabellum projectile and an impact velocity of 360 m/s. An expected conclusion was that the helmet shell stiffness is another factor that strongly affects the injury levels. These authors state that impacts at angles close to 45° are the ones leading to more serious lesions because rotations are transferred to the head when the impact has a tangential component [6, 7]. Tham *et al.* [8] conducted a series of experiments where a spherical projectile was launched from a gas gun striking the helmet at 205 m/s. The helmet-projectile interaction was then compared to the AUTODYN-3D simulation conducted with similar conditions to those of the experiments. The results show that the simulations were consistent with the ballistic impact experiments.

Gerald [9] published an interesting study on the use of new materials as energy dissipating layers in ballistic helmets. This author tested the use of polymeric foams such as polyurethane foam (PU), and expanded polypropylene (EPP) and expanded polystyrene (EPS) as energy absorbing materials. They predicted that, as expected, the density of the foam has a strong effect on the maximum stress levels on the head. Authors such as Othman [10] and Dai [11] studied the influence of the material (mechanical properties, composite material layout, the use of additional materials and layers, etc.) on the rear-effect and, consequently, on the induced stress levels on the skin, tissue, skull and brain.

Li *et al.* [12] simulated the ballistic impact of an Advanced Combat Helmet (ACH) and the model was validated against experimental data. They found that ballistic impacts with different impact angles and at different locations deliver different BFD results, and the BFD decrease as the oblique impact angle decreases. Additionally, these authors studied the effect of helmet size on the overall performance, concluding that the smaller size presents the largest BFD, while the largest exhibits the lowest deformation. Millan *et al.* [13] developed a finite element model of a combat helmet subjected to ballistic impacts and compared the results with real impact tests. They concluded that their numerical model is able to correctly represent the behaviour of the tested helmet and appears to be an effective tool for designing and evaluation purposes. More recently, Palta *et al.* [14] investigated the performance of the ACH subjected to ballistic impacts both numerically and experimentally. The authors suggested that the front side had the highest post permanent deformation while the back side had the lowest.

The generic phenomena described above is thoroughly analysed and discussed in the present work. To develop innovative helmets, and higher performance armour systems in general, it is necessary to develop evaluation methods that can efficiently predict injuries and trauma, thus ensuring that soldiers can resist specific threats. The risk and injury or trauma levels that can arise from head and neck movements (accelerations, rotations, displacements, etc.) are additional considerations. When performing experiments and developing numerical models some authors consider the impacting projectile to be rigid [4, 5, 15, 16, 17, 18] rather than deformable [12, 13, 14, 19, 20], neglecting the contribution of its deformation in the energy absorbing process. Having this in mind, the main aim of the work here presented is to assess the role of plastic deformation in the energy dissipation process during a ballistic impact. Additionally, the authors propose, test and validate a reliable helmet-head model that can be used to assess head injury levels in situations such as impacts from projectiles and fragments (on different helmet locations and with distinct impact energies, orientations, etc.) The main aim of this work is to assess and quantify the relevance of projectile plasticity on the whole ballistic impact phenomena. This is achieved by comparing the response of the helmet-head model in the two described scenarios, that is, considering the projectile to be either rigid or deformable.

2. Numerical modelling

The use of numerical simulation is a fundamental tool in the design and development of armour and protection systems (ballistic impacts, blast waves, etc.) As previously stated, the main objective of this work is to propose a reliable numerical system/model that can help predict trauma from bullet impacts on military helmets. This model should also lead to an assessment of the level of head injury and will be used to quantify the relevance of mechanical response of the projectile, namely its plasticity, on the overall performance of the model. This is done using the Head Injury Criterion (HIC) and tested with the impact of a 9 mm NATO projectile on a PASGT helmet. Fully three-dimensional models of a dummy head, including neck, helmet and projectile are used to perform numerical simulations using the LS-Dyna package. The Hybrid-III dummy used in this work has been validated under the impact of a ballistic pendulum, after comparison with a standard test used in dummy calibration, which provides a good level of confidence on the accelerations registered by the model [21]. The accelerations derived from the ballistic impact and the deformations induced on the helmet are evaluated.

A Hybrid-III dummy (50% percentile) head and neck is modelled as shown in Figure 1 (a), and the PASGT helmet [5] and projectile models are shown in Figures 1(b) to (f). Chin and head straps and bands were designed and adapted/positioned in such a way as to ensure a perfect fit to the head model, as shown in Figures 1(b) to (d).

Figure 1: Finite element models for (a) the Hybrid Dummy III 50% percentile head and neck, and (b) the PASGT helmet [5]. Inside view of (c) a PASGT helmet and (d) detailed view of the helmet suspension system. (e) Side and (f) front views of the complete finite element model, including 9 mm NATO projectile.

2.1. Material behaviour — Helmet

The helmet model [5] has three main parts: (i) the shell, in light blue in Figures 1(b), (e) and (f); (ii) the chin and head straps, that can be seen in Figures 1(b) to (d); and (iii) the head band, also shown in Figures 1(b) to (d). The helmet model used in this work has Nylon chin and head straps, and a leather head band. The helmet shell was modelled using two materials commonly used in ballistic helmet systems: Kevlar 29 and titanium alloy Ti-6Al-4V. The most relevant material properties for the shell and the chin and head straps are listed in Table 1. The Kevlar helmet shell has a maximum thickness $e = 10$ mm, an exterior surface area $A_1 = 0.1228\ \mathrm{m}^2$ and a total volume $V = 1.2\times10^{-3}\ \mathrm{m}^3$. The titanium helmet shell has a maximum thickness $e = 5$ mm, an exterior surface area $A_2 = 0.1092\ \mathrm{m}^2$ and a total volume $V = 0.53\times10^{-3}\ \mathrm{m}^3$. The thickness of the straps and leather band is 1 and 3 mm, respectively. Their surface area is $A_3 = 0.0456\ \mathrm{m}^2$ and the mass is approximately $M = 0.053$ kg.

Table 1: Material properties for the shell (Kevlar and titanium), and chin and head straps (Nylon and leather) used in the PASGT helmet numerical models [24, 25, 26].

Material	Property	Value	Units
Kevlar 29	Density, ρ	1,230	$\mathrm{kg/m}^3$
	In-plane elastic moduli, $E_1 = E_2$	18.5	GPa

	Through-thickness elastic modulus, E_3	6.0	GPa
	In-plane Poisson's ratio, ν_{12}	0.25	–
	Through-thickness Poisson's ratios, $\nu_{13} = \nu_{23}$	0.33	–
	In-plane shear modulus, G_{12}	0.77	GPa
	Through-thickness shear moduli, $G_{13} = G_{23}$	2.72	GPa
	In-plane shear strength, S_{12}	0.077	GPa
	Through-thickness shear strength, $S_{13} = S_{23}$	1.086	GPa
	In-plane tensile strength, $X_t = Y_t$	0.555	GPa
	Through-thickness tensile strength, Z_t	1.2	GPa
	Compressive strength, $X_c = Y_c = Z_c$	1.2	GPa
Titanium	Density, ρ	$4,430$	kg/m ^{3}
	Shear modulus, *G*	55	GPa
	Yield strength, *A*	1.051	GPa
	Hardening constant, *B*	0.924	GPa
	Hardening coefficient, *n*	0.52	–
	Strain rate sensitivity, *C*	0.00253	–
	Thermal softening coefficient, *m*	0.98	–
	Melting temperature, T_m	1,878	K
	Damage model, D_i $(i = 1,\ldots,5)$	-0.09, 0.27, -0.48, 0.0, 3.87	–
Nylon	Density, ρ	1,160	kg/m ^{3}
	Elastic modulus, *E*	2.4	GPa
	Poisson's ratio, v	0.35	–
Leather	Density, ρ	810	kg/m ^{3}
	Elastic modulus, *E*	0.3	GPa
	Poisson's ratio, v	0.3	–

The materials described above and listed in Table 1 were implemented in the developed numerical models in LS-Dyna. The constitutive behaviour of Kevlar is described by the damage model of Cheng and Hallquist [22], implemented in LS-Dyna with the *Mat_Composite_Failure model [23], and considers several distinct possible damage mechanisms grouped in three main classes, which describe damage (i) by tensile failure, (ii) by through-thickness failure and (iii) by compressive failure. The longitudinal and transverse tensile failure criteria are, respectively, described by the following two conditions:

$$\left(\frac{\sigma_1}{X_t}\right)^2 + \left(\frac{\tau_{12}}{S_{12}}\right)^2 + \left(\frac{\tau_{31}}{S_{31}}\right)^2 \geq 1 \quad \text{and} \quad \left(\frac{\sigma_2}{Y_t}\right)^2 + \left(\frac{\tau_{12}}{S_{12}}\right)^2 + \left(\frac{\tau_{23}}{S_{23}}\right)^2 \geq 1 \qquad (1)$$

X_t and Y_t are in-plane longitudinal and transverse tensile strength, and σ_i and τ_{ij} are the normal and shear stress components (the indexes 1, 2 and 3 are the composite material (local) longitudinal, transverse and through-thickness directions, respectively). S_{ij} is the shear strength. The through-thickness shear (and shear combined with transverse tension) damage criterion is described by the relations

$$\left(\frac{\sigma_1}{X_t}\right)^2 + \left(\frac{\tau_{31}}{S_{31}}\right)^2 \geq 1 \quad \text{and} \quad \left(\frac{\sigma_2}{Y_t}\right)^2 + \left(\frac{\tau_{23}}{S_{23}}\right)^2 \geq 1 \quad (2)$$

The compression damage criterion can be described as a function of the longitudinal, transverse and through-thickness directions, respectively, with the following relations:

$$\left(\frac{\sigma_1}{X_c}\right)^2 \geq 1$$

$$\left(\frac{\sigma_2}{S_{12}+S_{23}}\right)^2 + \frac{\sigma_2}{Y_c}\left[\left(\frac{Y_c}{S_{12}+S_{23}}\right)^2 - 1\right] + \left(\frac{\tau_{12}}{S_{12}}\right)^2 + \left(\frac{\tau_{31}}{S_{31}}\right)^2 \geq 1 \qquad (3)$$

$$\left(\frac{\sigma_3}{S_{31}+S_{23}}\right)^2 + \frac{\sigma_3}{Z_c}\left[\left(\frac{Z_c}{S_{31}+S_{23}}\right)^2 - 1\right] + \left(\frac{\tau_{31}}{S_{31}}\right)^2 + \left(\frac{\tau_{23}}{S_{23}}\right)^2 \geq 1,$$

where Z_c is the normal compressive strength.

The constitutive behaviour of Nylon and leather is considered to be fully elastic and described by the properties listed in Table 1 and using the *Mat_Elastic model [23] in LS-Dyna.

The constitutive behaviour of titanium is described by the Johnson-Cook model. This constitutive law is widely used to describe the mechanical response of ductile metals and incorporates the effect of strain, strain rate and temperature. The flow stress is given by

$$\bar{\sigma} = [A + B\left(\bar{\varepsilon}_{\mathrm{pl}}\right)^n]\left(1 + C\ln\dot{\varepsilon}^\star\right)[1 - \left(T^\star\right)^m] \qquad (4)$$

where *A*, *B*, *C* and *m* are experimentally obtained material parameters, *n* is the hardening coefficient, $\dot{\varepsilon}^\star$ is the normalised equivalent plastic strain rate and $T^\star$ is the homologous temperature, which can be defined as

$$T^\star = \frac{T - T_{\mathrm{r}}}{T_{\mathrm{m}} - T_{\mathrm{r}}}. \quad (5)$$

where T_{m} and T_{r} are the melting point and room temperature, respectively.

Johnson-Cook's damage model is formally similar to the flow relation above in the sense that is also accounts for the effects of strain, strain rate and temperature on the damage thresholds, that is,

$$\bar{\varepsilon}_{\mathrm{pl}} = \left(D_1 + D_2 e^{-D_3\eta}\right)\left(1 + D_4\ln\dot{\varepsilon}^\star\right)\left(1 + D_5 T^\star\right), \quad (6)$$

where $\eta = -p/\bar{\sigma}$ relates the pressure to the equivalent stress and D_1 to D_5 are material constants. The ratio between the incremental plastic strain and the fracture strain is described by the global damage variable *D*. Damage occurs when [27, 28]

$$D = \sum \frac{\Delta\bar{\varepsilon}_{\mathrm{pl}}}{\bar{\varepsilon}_{\mathrm{pl}}} > 1. \qquad (7)$$

When modelling impact phenomena it is critical to correctly define contacts between parts, that is, adequate contacts must replicate with precision the interaction behaviour between all actual helmet and head components. On the real helmet system, the head leather band is connected to the helmet shell through a circumferential flexible strap, fixed on six alternate points on the inner side of the shell and on the head band, as can be seen in Figure 1(d). This strap ensures that there is always an approximately fixed separation (≈ 10 mm) between the outer shell and the head of the soldier, while simultaneously ensuring that this connection has some degree of flexibility. When developing such a head-helmet model it is necessary is to determine the equivalent stiffness and mechanical response of this connection. In the present work, this task was done through the inclusion of a set of discrete elements with finite spring stiffness. The stiffness of these elements was determined and validated by comparison with tests done by Yang and Dai [29]. Tests were done with stiffness values ranging from 0.0001 to $1,000$ kN/mm for the 0° and 45° impact angles, and from the comparison with the results of Yang and Dai [29] the stiffness was determined to be $K = 0.001$ kN/mm.

The helmet shell and all Hybrid III dummy head parts were modelled using hexahedral eight node solid elements with reduced integration, whereas the straps and head band were discretised with shell elements. No symmetries were considered to allow for asymmetric dynamic effects and off-axis (non-orthogonal) impact.

2.2. Material behaviour — Projectile

It is frequent for researchers to consider projectiles to be rigid when modelling ballistic impacts [5, 6, 30, 31, 32, 33]. On this work, however, two alternative modelling approaches were used for the 9 mm NATO projectile: (i) rigid and (ii) deformable with non-linear behaviour. The projectile is composed by a brass jacket and a lead core. The projectile has a total mass $m = 8.4$ g. The constitutive behaviour of brass is described with the Johnson-Cook material model while the lead core is described by the *Mat_Plastic_kinematic model, suited to model isotropic and kinematic hardening plasticity with the option of including rate effects, where the yield stress is scaled with the Cowper-Symonds model [23], which is described by

$$\sigma_y = \left[1 + \frac{\dot{\varepsilon}}{c}^{\frac{1}{p}}\right] \quad (8)$$

where σ_0 is the static yield strength and *c* and *p* are strain rate constant and coefficient, respectively. The corresponding material properties are listed in Table 2. The projectile was discretised using heaxahedral constant stress solid elements, as shown in Figure 2.

Table 2: Material properties for the jacket and core of the 9 mm NATO projectile [34, 35].

Parameter	**Brass (jacket)**	**Lead (core)**
Density, ρ	$8,800$ kg/m^3	$11,270$ kg/m^3
Elastic modulus, *E*	–	17 GPa
Shear modulus, *G*	44 GPa	–
Poisson's ratio, ν	–	0.4
Cowper-Symonds strain rate constant	–	$c = 0.6$
Cowper-Symonds strain rate coefficient	–	$p = 3$
Hardening parameter, β	–	0.2
Yield strength, *A*	0.112 GPa	8 MPa
Hardening constant, *B*	0.505 GPa	–

Hardening coefficient, *n*	0.42	–
Strain rate sensitivity, *C*	0.009	–
Thermal softening coefficient, *m*	1.68	–
Melting temperature, T_m	1,189	–
Damage model, D_i ($i = 1, \ldots, 5$)	0.54, 4.89, -3.03, 0.014, 1.12	–

Figure 2: (a) Dimensions and (b) finite element discretisation of the jacket and core of the 9 mm NATO projectile [36].

3. Assessing injury

The development of efficient protection systems and better and more adequate evaluation and analysis methods [29] is essential in the process to reduce serious lesions and/or fatal injuries arising from direct or indirect impacts on the head.

A number of criteria are available to estimate injury levels, which can be separated in three main groups: (i) those based on linear accelerations measured at the centre of gravity of the head; (ii) the ones based not only on linear but also on angular (rotational) accelerations at the centre of gravity of the head, and (iii) those derived from measured or estimated brain stress and strain levels. This work focuses on the Head Injury Criterion (HIC), which is part of the first group. Other criteria on this group are the Wayne State Tolerance Curve (WSTC), based on the tolerable average accelerations along the AP (Anterior-Posterior) direction; the Severity Index (SI), based on the total integral of the resultant acceleration; and the Maximum Resultant Head Acceleration (MRHA) [37, 38, 39, 40, 41].

3.1. The Head Injury Criterion

Although not the simplest to determine, the HIC is the most widely used injury assessment criterion. Its most relevant disadvantages have to do with the fact that this method does not account for injuries resulting from rotation induced accelerations. Additionally, it does not allow for an objective identification of the type of injury [42, 43]. The HIC is a numerical scalar value that can be obtained by integrating the acceleration history on a limited time interval, using the following relation:

$$\mathrm{HIC}_\Delta = \max_{[t_1, t_2]} \left\{ (t_2 - t_1) \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t)\, \mathrm{d}t \right]^\alpha \right\} \qquad (9)$$

where $a(t)$ is the resultant linear acceleration time history, measured in multiples of *g*. $\alpha = 2.5$ and t_1 and t_2 are two time instants chosen in such a way as to maximise the HIC value, subject to the constraint that they do not differ by more than a prescribed time interval Δ. Usually,

$$3 < | t_2 - t_1 | < \Delta[\mathrm{ms}] \quad \text{with} \quad \Delta \in \{15, 36\}\,[\mathrm{ms}] \quad (10)$$

This restriction on the integration lower and upper bounds reflects the fact that low accelerations over relatively long periods of time often lead to low injury levels [44]. The prescribed time limit Δ was initially defined to be 36 ms (i.e. in the HIC_{36} criterion) to contemplate long duration impacts (approximately 50 ms) such as airbag impacts or crashworthiness analyses. More recently, however, this interval was reduced to 15 ms (i.e. in the HIC_{15} criterion) to allow for the analysis of shorter duration impacts, such as those resulting from terminal ballistics phenomena.

Once the HIC value is known, the assessment of injuries can be done using the Abbreviated Injury Scale (AIS) curves shown in Figure 3, where the probability of a specific level of head injury can be estimated for a specified HIC value [44].

Figure 3: Abbreviated Injury Scale (AIS) limit curves: probability of head injuries of varying severity for different Head Injury Criterion (HIC) ranges (adapted from [44]).

3.2. Direction and angle of impact

Experimental results obtained by Dai [11] show that the angle of impact is one of the most important factors when assessing the response of the helmet, head and neck system. It is expected, for example, that when a projectile impacts the helmet at a steep angle it deforms less and more kinetic energy is transmitted to the head. It is worth noting, however, that HIC values do not necessarily show similar tendency to maximum stress and strain levels, and not even to maximum pressure or principal stresses in the brain. This has to do with the fact that the HIC value only depends on the resultant linear acceleration (through $a(t)$ in equation 9), not the induced pressure. Additionally, the stiffness of the human skull is not constant. In fact this stiffness is significantly higher on the forehead when compared to the back of the skull. This explains why impacts on the front are often less serious that on other parts of the head.

The Hybrid III dummy head FEA model has 6 accelerometers, three to measure linear accelerations and three other to measure angular accelerations. It should again be noted, however, that angular accelerations due to the eventual rotation of the head are not considered for the calculation of Head Injury Criterion values. The accelerometers in the dummy head model are located as shown in Figure 4(a), and oriented in such a way as to record the three orthogonal linear acceleration components.

A set of disks and articulated connections guarantees that the behaviour of the neck model is as similar to the human neck as possible, both in linear and in angular motion. Acceleration time histories are registered from the Ox, Oy and Oz linear accelerometers and equation 9 is used to determine the corresponding HIC values, which for the purpose of this work will be with a chosen maximum time interval $\Delta = 15$ (i.e. HIC_{15}).

Figure 4: (a) Location of the accelerometers at the centre of gravity of the Hybrid III dummy head model and (b) FE model of the helmet shell [5] showing impact orientation and angles.

3.3. Test configurations and boundary conditions

The boundary conditions applied to the neck-head-helmet model were defined in such a way as to concentrate all movements above the shoulder line, leading to a conservative approach to the reaction of the whole system (i.e. maximising induced accelerations). To do this, the bottom of the neck was fixed. Although this could lead to an overestimation of the stiffness of the neck and head system, this approach is believed not to significantly influence the results due to the impulsive and localised nature of the load, and the inertia of the whole neck, head and helmet system.

Three simulation control parameters were used: the accuracy, the time step size and the termination time. The first one — accuracy — forces the stiffness matrix to be calculated twice on each time increment, at instants $(n+1)/2$ and $n+1$. This naturally increases the computational time by approximately 25% but is essential for explicit integration schemes where finite element rotations may be relevant. The time step size is set to a value significantly lower than the time required for a strain wave to cross the minimum distance between two consecutive nodes in the finite element mesh ($h_{\min}$) at the wave speed in the material. Disregarding this would lead to significant computational errors and hence poor and unrealistic results. In generic terms, the critical (maximum) time step size is $\Delta t_c = h_{\min} / c$ where $c = \sqrt{E/\rho}$ is the wave speed, E is the modulus of elasticity and ρ is the density of the material. An additional 10% time step reduction is applied in order to minimise the possibility of occurrence of errors in the computation (e.g. negative volumes due to the high strain rates and pressure levels).

4. Results and discussion

Tests were done for impact angles ranging from 0° (orthogonal) to 75° at 15° intervals, on the Oxy plane, the horizontal plane going through the bullet axis, as shown in Figure 4(b), and for a constant impact velocity $v_0 = 255$ m/s (at $t = 0$). This velocity was chosen to ensure non perforation of the helmet by both projectiles (rigid and deformable), thus allowing to assess the relevance of plastic deformation in the energy dissipation process. Accelerations were recorded on all three accelerometers located on the centre of gravity of the head model (see Figure 4(a)).

The acceleration time histories for the impact at 45° are shown in Figure 5. The results in Figure 5(a) show the acceleration profiles for the Kevlar helmet, for both the rigid and deformable projectiles, measured in the helmet shell and in the centre of the head. It is evident that there is a significant wave attenuation effect from the point of impact on the helmet shell surface to the centre of the head. This also enhances the role of the helmet suspension system, which includes all the connection and supporting devices (chin and head straps, leather bands, etc.).

The first strain/pressure waves take approximately 10 and 12.5 ms (wave time) to reach the centre of the head, where the accelerometers are positioned, for the Kevlar and titanium helmets, respectively, as can be seen in Figure 5(b). This difference is most certainly due to the added ductility of the metallic titanium helmet when compared to the Kevlar shell.

The effects of the plasticity of the projectile become evident on the magnitude of the pressure waves, as can be seen from these plots, and the numerical results listed in Table 3 and plotted in Figure 6 for all tested impact angles. Contrary to the case of the titanium helmet, the deformable projectile is more detrimental than the rigid projectile in the case of Kevlar helmet. This can be explained by the fact that, in the absence of deformation, the rigid projectile induces the layers of the composite material to fail upon impact, forcing elements to erode after reaching the material strength threshold. This allows the projectile to penetrate the helmet with a reduced energy transfer level to the helmet system, when compared to configuration with a deformable projectile. An additional visible effect is the longer time it takes for the waves to reach the centre of the head. This is shown in Figure 5, where there is a 3.5% increase in this time between the rigid and deformable projectiles for both helmets (from 10.2 to 10.6 ms for the Kevlar helmet and from 12.4 to 12.8 ms for the titanium helmet).

Figure 5: Acceleration: (a) at the helmet shell and centre of the head for the 45° bullet impact on the Kevlar helmet and (b) at the centre of the head for the 45° bullet impact on both Kevlar and titanium helmets.

Table 3: Peak head acceleration for all impact angles for the kevlar and titanium PASGT helmets (accelerations in *g*).

Impact angle	**Kevlar**			**Titanium**		
	Rigid	Deformable	Diff. [%]	Rigid	Deformable	Diff. [%]
0°	477.7	600.9	–25.8	335.6	230.5	35.2
15°	465.1	550.1	–18.3	329.8	110.5	66.5
30°	294.1	360.7	–22.7	391.7	136.0	65.3
45°	131.2	208.1	–58.5	298.2	126.1	57.7
60°	171.7	208.4	–21.4	238.3	171.4	28.1
75°	144.5	244.8	–69.4	191.4	92.6	51.6

Maximum accelerations in the head for all angles are plotted in Figure 6(a). Peak accelerations are lower for the titanium helmet considering the deformable projectile, when comparing to the Kevlar helmet, as would be expected due to its higher ductility. The same trend is, however, not observed when the projectile is modelled as a rigid body. This is most evident for impact angles above 30°, an observation that might be induced due to the unrealistic approach of the projectile modelling. It can be seen from these results that generically, the severity of the impact decreases for increasing angles. Figure 6(b) shows the HIC dependency on the impact angle (corresponding numerical values are listed in Table 4). From an overall view of the HIC values it becomes evident that the ductility inherent to the metallic helmet shell plays the most relevant role in absorbing energy from the impact, and thus minimising injury probabilities. This is mostly evident for angles below 30°, where the contact time between the projectile and the helmet is the highest.

Figure 6: (a) Maximum (peak) acceleration as a function of the impact angle for all tested models and (b) HIC dependency on the impact angle for all tested models.

Table 4: HIC values for all impact angles for the kevlar and titanium PASGT helmets.

Impact angle	**Kevlar**			**Titanium**		
	Rigid	Deformable	Diff. [%]	Rigid	Deformable	Diff. [%]
0°	509.3	644.9	–26.6	117.6	53.6	54.4
15°	216.7	548.9	–153.3	183.3	18.0	90.2
30°	121.3	140.3	–15.7	132.7	33.1	75.1
45°	29.3	100.6	–243.3	73.0	19.9	72.7
60°	41.3	57.7	–39.7	61.0	19.6	67.9
75°	16.3	49.1	–201.2	30.6	4.2	86.3

Figure 7: Frame sequence for the ballistic impact at an angle of 45° and impact velocity $v_0 = 250$ m/s for the titanium helmet.

A sequence of frames is shown in Figure 7 for the impact at an angle of 45°, for illustration, where the ricochet effect is clearly visible, as expected for an impact at such a steep angle. It was observed that the impact angle has a determinant effect on the kinematics of the impact: for orthogonal and low angle impacts the projectile always bounced back, and ricocheted for higher angle impacts. These observations are corroborated by several other researchers [5, 6, 7, 11, 29].

From the results presented above it becomes clear, once again, that impacts at low angles ($< 45^\circ$) are more drastic in terms of induced head accelerations and, consequently, HIC values. The maximum HIC value observed for all tests is lower than 700, meaning that there is approximately 95% probability of minor head injuries and about 70% probability of moderate injuries, as can be seen from the AIS curves in Figure 3. For these impacts, the probability for fatal injuries is always very low (under 3%).

5. Impact energy dissipation and balance

A thorough analysis was done of the energy absorption of the two numerical models: considering the projectile to be fully rigid or deformable with non-linear plastic behaviour. From this analysis it will be possible to draw further conclusions on the relevance of projectile plasticity when modelling ballistic helmet impacts. Both the Kevlar and titanium helmets were used for all impact angles.

In an event of this nature, the kinetic energy of the impactor is partly converted into internal energy of the helmet components, due to structural deformation of the helmet-projectile system. Since the total energy of the system is assumed to remain constant throughout the entire simulation time, the total absorbed energy of the system $\Delta\bar{e}$ was measured as

$$\Delta\bar{e} = \left(\frac{e_i}{e_t}\right)\times 100 \quad [\%] \ (11)$$

where e_i and e_t are the internal and total energy of the system, respectively. It is initially assumed that the energy absorbed by the head-neck system remains constant. Table 5 compares these results for all impact angles. The dependency of the total absorbed energy with the impact angle is also show in Figure 8.

Table 5: Energy balance for all impact angles for the kevlar and titanium PASGT helmets, with both rigid and deformable projectiles.

Impact angle	**Kevlar**		**Titanium**	
	Rigid [%]	Deformable [%]	Rigid [%]	Deformable [%]
0°	19.8	42.3	51.9	68.4
15°	17.4	40.1	50.8	66.5
30°	17.3	37.5	48.5	66.5
45°	15.1	26.9	38.9	55.5
60°	12.9	20.9	16.5	47.8
75°	6.1	22.4	4.6	33.5

Figure 8: Dependency of the ratio of the absorbed energy on the total energy of the system, for different impact angles for the Kevlar and titanium helmet systems.

According to these results, it becomes evident that the total absorbed energy by the system decreases with increasing impact angle. This is due to a combination of effects, the first and probably most relevant being the lower duration of contact during the impact for increasing impact angles. Other effects are related to the projectile plasticity and ricochet dynamics.

It was also observed that there was a significant difference in the energy absorbed by the titanium helmet system when compared with its Kevlar counterpart, for both the system with the projectile modelled as deformable and fully rigid, with this difference reaching 32.1% for the impact at 0° for the case of rigid projectile. Another relevant finding is that, for both titanium and Kevlar helmet system, the total absorbed energy is clearly higher for the case of a projectile modelled as deformable. Given the model definitions (see Section 2), this difference is mostly due to projectile plasticity.

Figure 9: Plastic strain of the projectile for each impact angle using (a) the Kevlar and the (b) titanium helmet models.

To further corroborate this, Figures 9(a) and (b) show the deformation and plastic strain of the projectile for the different impact angles using both Kevlar and titanium helmet models, respectively. As expected, deformation and plastic strain levels decrease significantly for increasing impact angles. This becomes more evident for angles above 45°, where the effect of the helmet response becomes reduced, which is reflected in the deformation of the projectile.

In order to further understand the influence of the impact energy on head accelerations and injury levels, the titanium helmet was used with a deformable projectile and impact angle of 45°. A set of simulations were done with impact energies between 42 J ($v_0 = 100$ m/s) and $1,505$ J ($v_0 = 600$ m/s). To be consistent with the results discussed above, the reference test ran for an impact kinetic energy of 272 J ($v_0 = 255$ m/s). Helmet-head-neck system behaviour and HIC values are also analysed and discussed.

From the tests described above, the influence of the impact energy on the maximum resultant (peak) accelerations at the centre of the head (i.e. as measured by the accelerometers) is described by the plot in Figure 10(a) and values listed in Table 6. It can be observed that maximum accelerations do not increase proportionately to the impact velocity, resulting in a non-linear dependency of the maximum acceleration from the impact energy. The dependency of the HIC on the impact energy is also plotted in Figure 10(a) (secondary Oy axis), and the dispersion of results is much lower, most probably due to the filtering effects of the helmet suspension systems. Finding a trend on the impact energy-HIC dependency is not obvious. However, assuming the trend is approximately linear, the following relation could be used to relate the impact energy to the HIC value,

$$\mathrm{HIC} = 0.119 U_\mathrm{i} \qquad (12)$$

for the specific case being analysed (dotted line in Figure 10(a)), (with $R^2 = 0.95$) and where U_i is the impact kinetic energy.

Figure 10: (a) Dependency of the maximum resultant acceleration at the centre of the head model (i.e. measured by the accelerometers) and Head Injury Criterion (HIC) on the impact energy for the 45° impact on the titanium helmet and (b) dependency of the maximum plastic deformation on the impact energy for all tests done at 45° on the titanium helmet system.

Table 6: Impact energy, peak accelerations and HIC values for all tests done at 45° with the titanium helmet system.

Velocity	**Impact energy**	**Peak acceleration**	**HIC**
[m/s]	[J]	[g]	[–]
100	42	167.9	11.4
150	94	138.8	7.8
255	272	126.2	19.9
350	512	189.1	41.2
450	846	283.7	122.1
550	1,265	328.7	130.6
600	1,505	365.1	191.1

Results in Figure 10(b) show how the maximum plastic deformation changes for increasing impact energy, again for all tests done at 45° with the titanium helmet system. Although for impact energies of 42 and 94 J, the helmet shell did not exhibit any plastic deformation, it can be seen that for a higher impact energy there is an almost perfect linear dependency between the plastic deformation and the impact energy.

6. Conclusions

One of the main aims of the work here presented was to show that the use of numerical simulation is a fundamental tool in the design and development of armour and protection systems, as well as being essential when researching the energy absorption capability of new materials, structures and specific targets, such as military helmets. The work focuses on the use of the finite element method to predict the consequences of bullet impacts on military helmets on probabilistic brain injury levels (i.e. assess the level of head trauma using the Head Injury Criterion). Additionally, the work focuses on assessing the relevance of projectile plasticity on the efficiency and precision of the numerical results.

The impact of a 9 mm NATO projectile onto a PASGT helmet is modelled and acceleration profiles and time histories derived from the impact phenomenon. The helmet and projectile deformations are evaluated using fully three-dimensional models of a complete helmet, head, neck and projectile. The head and neck were modelled using a 50% percentile Hybrid-III dummy model and tests are done to analyse impact parameters such as the impact orientation, velocity, etc. Results are presented and discussed in terms of HIC values and probability of acceleration induced trauma to assess the relevance of a number of modelling specific conditions and definitions, such as, the consideration and relevance of projectile deformation and plasticity.

From the obtained results it can be seen that, for the modelled phenomena (equivalent to a 272 J impact energy) the highest observed value of the Head Injury Criterion occurs for the lower angles of impact, the 0° impact being the most severe. The effects of the angular motion transferred to the head and neck due to an oblique impact, are more noticeable for small angle impacts due to the balance between the tangential and the normal components of the induced acceleration. Nonetheless, the procedure to determine HIC values does not account for angular accelerations. This is most probably the reason why the impact at 75° is the one leading to the lowest values of HIC.

Although the obtained Head Injury Criterion values are not extreme — the highest HIC value is lower than 700 —, in the sense that they do not lead to high probabilities of serious, critical or fatal injuries, the rear effect deformations could become higher than the helmet shell to head clearance gap, potentially leading to behind helmet blunt trauma. This can induce serious lesions due to direct wounds and/or fractures on the head that are not predicted by the Head Injury Criterion, corroborated by, for example, [2, 3].

A thorough comparison analysis was also done using a rigid and a more realistic deformable projectile. Although computational efficiency decreases when using the deformable projectile, it was observed that there is a significant difference in the results, with the total absorbed energy of the system becoming clearly lower for the case of a fully rigid projectile. This is clear evidence that plasticity should always be considered in such tests.

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