FEM model of protection bullet helmet made from composite material.

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Abstract
Damage evolution, mechanical behaviour, energy absorption, back-face deformation (BFD) and the perforation performance of Kevlar epoxy woven composite with and without foam (PU foam) were examined for various impact energies based on the drop weight test. The Kevlar woven composite induces different damage and deformation depending on its hybrid patterns. The Kevlar composite with PU foam decreases significantly, and the BFD of shell composite and transform locally deformation become a global nature. In addition, damage type - as fibres break - is primary dominant for Kevlar composite without PU foam. However, the role major damage as delamination, significantly appear for Kevlar composite with PU foam. In order to investigate the damage mechanism, energy absorption and BFD, FEM simulation were also performed. The FEM simulation is in very good agreement with the drop weight test. Finally, the FEM study showed that PU foam is able to decrease significantly, the BFD of composite shell, and the contact force on the skull, during ballistic impact.

Keywords: Helmet, Ballistic Impact, Perforation Impact, Back-Face Deformation, Polyurethane Foam

1. Introduction
Currently, the protection bullet helmet was developed for use in battlefields. The first model of the helmet made of steel (Steel M1) was good against perforation from bullets, but it weighed a lot. Consequently, helmet weight and perforation performance needed to be considered. The Personal Armor System for Ground Troops (PASGT) model and Advance Combat Helmet (ACH) model made from Kevlar fiber and resin/epoxy were developed for use in the U.S. Army and the U.S. Marines [1-3].

The previous study found that the helmets worked against ballistic impact based on two standards. The first is the MIL-H-44099A standard which used 1.1g of 0.22 Caliber FSP with an impact velocity of 610 m/s and impact energy of 204.66 J [1]. The second is NIJ-STD-0106.01 Type II standard which used the 9 mm FMJ bullet with an impact velocity of 358 ± 15 m/s, mass of 8 g, and impact energy of 512.66 ± 15 J [1-4]. Both of them are considered only with ballistic impact performance. However, head injuries are not only due to perforation impact but also due to BFD affecting the BHBT. Then, BFD is
another one parameter that should be considered for ballistic impact analysis on the helmet shell composite. The previous study [2] found that BFD values is dependent on the helmet size. Nowadays, the helmet is considered to increase the comfort effect and decrease the energy imparted to the human head. The PU foam is a good candidate inserted between the helmet shell composite and the skull. Its density is 63 kg/m$^3$ for hard foam and 61 kg/m$^3$ for soft foam [2]. The simulation result shown that the foam pad is capable of absorbing impact energy and reducing the energy imparted to the human head [3]. In addition, the effect of foam pad hardness results in the decrease BFD values about 25% after ballistic impact on the combat helmet [3].

The aim of this study is to understand the absorption energy due to the drop weight test of Kevlar shell composite, and to simulate for ballistic impact by using FEM simulation based on NIJ-STD-0106.01 Type II. A simple skull model with Kevlar shell composite and PU foam was created to study its performance, and BFD effect.

2. Material model & identification of mechanical properties

2.1 Kevlar Composite

In this study, the woven Kevlar fabric as an orthotropic material with resin/epoxy are used. In order to identify composite behavior and damage evolution for FEM simulation, the tensile test was performed based on ASTM D638-14 standard [5]. The identification parameters from the tensile test are shown as Figure 1 and its mechanical properties are listed in Table 1.

Table 1. The elastic constants, Hashin Damage and Damage Evolution of the Kevlar composite.

| Elastic Constants (Mechanical Properties) | $E_{11} = 14158$ MPa | $E_{22} = 14158$ MPa | $E_{33} = 1948$ MPa | $v_{12} = 0.08$ | $v_{13} = 0.7$ | $v_{23} = 0.08$ | $G_{12} = 1152.16$ MPa | $G_{13} = 1100$ MPa | $G_{23} = 1100$ MPa |
|------------------------------------------|------------------------|------------------------|------------------------|-----------------|-----------------|-----------------|------------------------|------------------------|------------------------|
| Young's Modulus                          |                        |                        |                        |                 |                 |                 |                        |                        |                        |
| Poisson's Ratio                          |                        |                        |                        |                 |                 |                 |                        |                        |                        |
| Shear Modulus                            |                        |                        |                        |                 |                 |                 |                        |                        |                        |
| Hashin Damage (MPa)                      |                        |                        |                        |                 |                 |                 |                        |                        |                        |
| Longitudinal Tensile Strength            | 360                    |                        |                        |                 |                 |                 |                        |                        |                        |
| Longitudinal Compressive Strength        | 360                    |                        |                        |                 |                 |                 |                        |                        |                        |
| Transverse Tensile Strength              | 360                    |                        |                        |                 |                 |                 |                        |                        |                        |
| Transverse Compressive Strength          | 360                    |                        |                        |                 |                 |                 |                        |                        |                        |
| Longitudinal Shear Strength              | 105                    |                        |                        |                 |                 |                 |                        |                        |                        |
| Transverse Shear Strength                | 105                    |                        |                        |                 |                 |                 |                        |                        |                        |
| Damage Evolution (mJ)                    |                        |                        |                        |                 |                 |                 |                        |                        |                        |
| Longitudinal Tensile Fracture Energy     | 8.42                   |                        |                        |                 |                 |                 |                        |                        |                        |
| Longitudinal Compressive Fracture Energy | 8.42                   |                        |                        |                 |                 |                 |                        |                        |                        |
| Transverse Tensile Fracture Energy       | 8.42                   |                        |                        |                 |                 |                 |                        |                        |                        |
| Transverse Compressive Fracture Energy   | 8.42                   |                        |                        |                 |                 |                 |                        |                        |                        |
2.2 Foam pad model and material identify

In order to investigate the comfort effect, PU foam was inserted between the helmet shell and skull [3]. From a previous study [6-8], Ogden’s material model was used to simulate the mechanical behavior of PU foam as in Equation (1).

\[
W = \sum_{i=1}^{2} \frac{2\mu_i}{\alpha_i^2} [\lambda_1^{\alpha_i} + \lambda_2^{\alpha_i} + \lambda_3^{\alpha_i} - 3] + \sum_{i=1}^{N} \frac{1}{D_i} (\varepsilon^e - 1)^{2i}
\]  

(1)

Where \(\lambda_i\), \(\mu_i\), \(\alpha_i\) and \(D_i\) are material parameters identified by compressive test is used [9, 10]. Dimension of specimen is 18 mm x 36 mm x 36 mm (Figure 2). The head speed in the compressive test base on ASTM D 1621 standard is 0.3, 3, 15, 30 and 45 mm/min, respectively. The experimental set-up is shown as Figure 3.

The experimental result shows that the mechanical properties of PU foam are independent with strain rate (Figure 4). Identification of Parameter based on Ogden’s material model order2nd are listed Table 2.
Table 2. Material parameters of Ogden’s material model

|   | $\mu_1$ | $\mu_2$ | $\alpha_1$ | $\alpha_2$ | $D_1$ | $D_2$ |
|---|---|---|---|---|---|---|
|   | $1.78 \times 10^{-5}$ | 0.02 | 16.4 | 12.2 | 0 | 0 |

Figure 4. Relation graph between Compression Stress and Strain of PU foams.

2.3 Bullet and skull

The bullet is the 9 mm FMJ base on NIJ-STD-0106.0 Type II. The ABAQUS geometry model of 8 g is shown as Figure 5. Johnson-Cook Model was used as in Equation (2) [2, 3]. The parameter constants are listed in Table 3.

![Figure 5. Geometry of 9 mm FMJ Bullet.](image)

$$\bar{\sigma} = (A + B\bar{\varepsilon}^n) \left(1 + C\ln\frac{\dot{\varepsilon}}{\varepsilon_0}\right)[1 - (T^*)^m]$$  \hspace{1cm} (2)

Where $A$, $B$, $C$ and $n$ are Johnson-Cook constants, $\bar{\sigma}$ is the von Mises equivalent stress, $\bar{\varepsilon}$ is the equivalent plastic strain, $\dot{\varepsilon}$ is the plastic strain rate, $\varepsilon_0$ are reference strain rate and $T^*$ is the homologous temperature defined by $T^* = (T - T_r)/(T_m - T_r)$ when $T_r$ is room temperature, $T_m$ is melting temperature and $T$ is specimen temperature.

Table 3. Material constants of Johnson-Cook Model [3]

| Material     | Yield Stress $A$ (MPa) | Strain Hardening $B$ (MPa) | Strain Hardening $n$ | Strain Rate $\varepsilon_0$ ($s^{-1}$) | Temperature Softening $T_r$ (K) | $T_m$ (K) | $m$ |
|--------------|------------------------|---------------------------|---------------------|---------------------------------------|-------------------------------|------------|-----|
| Lead Core    | 24                     | 300                       | 1.00                | $5 \times 10^{-4}$                    | 293                           | 760        | 1.00 |
| Brass Jacket | 206                    | 505                       | 0.42                | $5 \times 10^{-4}$                    | 293                           | 1189       | 1.68 |
As mentioned above, the skull injuries will be analyzed during the ballistic impact. The mechanical properties of the skull are listed in Table 4.

**Table 4. Mechanical properties of skull [11, 12].**

| Property                  | Value |
|---------------------------|-------|
| Young modulus (MPa)       | 15000 |
| Density (Kg/m³)           | 2000  |
| Tensile strength (MPa)    | 132   |
| Compressive strength (MPa)| 90    |

3. Experimental set-up

3.1 Drop Weight Test

In order to validate the FEM simulation, drop weight tests were used. The experimental set-up of the drop weight test is shown as Figure 6. The impact event is recorded by a high-speed camera. The impact energy varying with the height is 0.9, 1.0, and 1.4 m with the impact velocity (V_in) is 3665.43, 3952.01 and 4709.91 mm/s, respectively. The mechanical behavior of PU foam for impact absorbed will be studied. Figure 7 presents the specimen for drop the weight test.

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![Figure 6. The experimental set up of the Drop weight test.](image)

![Figure 7. Specimen of the Drop weight test.](image)

4. FEM simulation

4.1 Drop Weight

In order to understand and validate the experimental result, the drop weight simulation is performed. Figure 8 presents the FEM simulation set-up which consist of head impact, Kevlar composite, PU foam and upper/lower support.

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![Figure 8. Assembly model of drop weight test simulation.](image)

![Figure 9. Assembly model of 9mm FMJ, Kevlar Shell, PU foam and Skull.](image)
4.2 Ballistic Impact
In order to analyze the skull injuries, the FEM simulations were performed for the ballistic impact based on NIJ-STD-0106.01 Type II. Figure 9 presents the FEM model for the ballistic impact model which consists of the bullet, Kevlar shell composite, PU foam and the skull. The bullet with velocity of 358 ± 15 m/s and the impact energy of 512.66 ± 15 J is used [2, 3]. The Kevlar composite, PU foam, skull and brass jacket with lead core are simulated by using a hexahedral element. Mesh size of 4 mm for the Kevlar shell composite, PU foam and the skull, 1.8 mm for the brass jacket and 1.6 mm for the lead core were used [13, 14]. To simulate, the skull are fixed at x, y, z directions and the bullet is striking in y-direction and to be impacted on the Kevlar shell composite. The PU foam and skull appeared to be perfect bonding with the Kevlar shell composite.

5. Result
5.1 The experimental result
The experimental result showed that all energy impact levels, of the Kevlar shell composite with PU foam, is not perforation. Figure 10 presents the high-speed images of the drop weight test at 0.9 m. Figure 11 shows the BFD results with and without PU foam. Figure 12 presents the small damage area occurring after impact for Kevlar shell composite with PU foam. The presence of PU foam allows to increasing time response induce global deformation on Kevlar shell composite. As a result, delamination can be observed primarily after impact (Figure 13). While Figure 14 shows local damage occurring on the impact zone for the Kevlar shell composite without PU foam. The fiber break had primary damage.
The delamination damage of Kevlar shell composite with PU foams with different height (different energy impact levels): (a) 0.9, (b) 1.0 and (c) 1.4 m

Figure 14. Kevlar shell composite without PU foams at 0.9 m: (a) Upper and (b) Lower side.

Furthermore, the presence of PU foam in the Kevlar shell composite aid to increase the perforation performance but to increase significantly the BFD (Table 5). However, its increased is necessary to analyze head injury by considering the pressure stress on skull that we will discuss in section 5.3.

Table 5. Comparison the BFD of with and without PU foam case of experimental

| Kevlar shell composite without PU foam | Kevlar shell composite with foam |
|---------------------------------------|----------------------------------|
| Height (m)       | BFD (mm)  | Remark     | Height (m)       | BFD (mm)  | Remark     |
| 0.9              | 6.15      | Not-Perforation | 0.9              | 24.62     | Not-Perforation |
| 1.0              | 10.18     | Perforation   | 1.0              | 30.89     | Not-Perforation |
| 1.4              | -         | -            | 1.4              | 31.61     | Not-Perforation |

5.2 The comparison between the simulation and the experimental result

In order to validate the drop weight test, the FEM simulation was performed. In the case of - without foam, FEM shows that BFD induces locally the deformation response. On the other hand, the BFD response of Kevlar shell composite with PU foam occurs globally the deformation as shown in Figure 15. To consider the simulation result, we found that the Kevlar shell composite is not perforate. The FEM model with damage evolution allow more production of material deformation due to its damage such as fiber break during impact. As a result, a good correlate between the BFD simulation and experiments can be obtained. Then, we can summarize that when the Kevlar shell composite become a large deformation due to its damage, the FEM simulation with damage evolution models are necessaries. The comparison results between the experiment and FEM simulation is listed in Table 6.

Figure 15. The BFD on Kevlar plate at 0.9 m height: (a) Without foam and (b) With foam.
Table 6. Comparison Result of experimental and simulation.

| Values                  | Experimental (Without Damage Evolution) | Simulation (Without Damage Evolution) | Simulation (With Damage Evolution) |
|-------------------------|-----------------------------------------|--------------------------------------|-----------------------------------|
| Height 0.7 m            | Without foams                           |                                      |                                   |
| $V_{in}$ (mm/s)         | 3178.00                                 | 3178.00                              | 3178.00                           |
| $V_{out}$ (mm/s)        | 1734.50                                 | 3173.83                              | 1433.94                           |
| BFD (mm)                | 12.35                                   | 9.55                                 | 14.78                             |
| Perforation             | No                                      | No                                   | No                                |
| Height 0.9 m            | With foams                              |                                      |                                   |
| $V_{in}$ (mm/s)         | 3665.43                                 | 3665.43                              | 3665.43                           |
| $V_{out}$ (mm/s)        | 1425.85                                 | 3451.47                              | 1973.21                           |
| BFD (mm)                | 24.62                                   | 9.23                                 | 16.16                             |
| Perforation             | No                                      | No                                   | No                                |
| Height 1.0 m            | With foams                              |                                      |                                   |
| $V_{in}$ (mm/s)         | 3952.01                                 | 3952.01                              | 3952.01                           |
| $V_{out}$ (mm/s)        | 1581.86                                 | 3717.79                              | 1944.06                           |
| BFD (mm)                | 30.89                                   | 9.63                                 | 21.42                             |
| Perforation             | No                                      | No                                   | No                                |
| Height 1.4 m            | With foams                              |                                      |                                   |
| $V_{in}$ (mm/s)         | 4709.91                                 | 4709.91                              | 4709.91                           |
| $V_{out}$ (mm/s)        | 1524.13                                 | 4425.00                              | 703.92                            |
| BFD (mm)                | 31.61                                   | 10.90                                | 30.07                             |
| Perforation             | No                                      | No                                   | No                                |

In addition, the fiber breaks on the Kevlar shell composite are also considered. We found that the fiber breaks respond more with height (Figure 16). The presence of PU foam on the Kevlar shell composite aids to significantly reduce the fiber breakage. Figure 17 presents the fiber breakage on the Kevlar shell composite with and without foam cases at 0.9 m. However, Hashin’s damage model with shell element type cannot predict the delamination onset due to the absent of out-of-plan stress. As results, the BFD prediction is not precision since the damage evolution due to delamination does not take into account.

Figure 16. Hashin’s tensile fiber initiation criterion failure on Kevlar plate at the height of drop weight test of with foam case: (a) 1.0 m and (b) 1.4 m.
Figure 17. Hashin’s tensile fiber initiation criterion failure on Kevlar plate at the height of drop weight test at 0.9 m: (a) without foam case and (b) with foam case

5.3 The FEM simulation result for the ballistic impact

In order to consider the skull injuries under ballistic impact, the FEM simulation on simplified models were studied. The FEM simulation showed that the von Mises stress on the skull with and without PU foam is significantly different (Figure 18). The von Mises stress decrease considerably for the Kevlar shell composite with PU foam. While, the bullet for both cases is deformed similarly after impact with the mushroom shape.

Figure 18. The maximum von Mises stress of the skull: (a) With foam and (b) Without foam case.

Figure 19. The maximum pressure of the skull: (a) With foam and (b) Without foam case.
6. Conclusions
In this paper, the experimental investigations and FEM simulation have been presented. This study can be summarized as follows:

- The drop weight test is able to predict the energy absorbed by the Kevlar shell composite; this procedure can be used to preliminary assess the perforation performance of ballistic impact.
- The effect of PU foam is able to significantly increase the perforation performance. They against to damage initiation and allow to increasing time response induce global deformation on Kevlar shell composite.
- The FEM simulation is a good prediction for the fiber break damage. However, Hashin’s criterion model with shell element type cannot predict the delamination onset due to the absent of out-of-plan stress.
- The ballistic simulation was carried out and shown that PU foam is able to decrease the maximum von Mises stress and the maximum pressure of the skull. As a result, they can reduce the head injuries effect and increase comfort.

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