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A Numerical Study on the Ballistic Trauma of B_4C ceramic backed UHMWPE Composite Armor System

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ABSTRACT

A ceramic-based armor system is required to stop bullet penetration and effectively dissipate high-impact energy. Exceeding the threshold value of behind-armor ballistic/blunt trauma (BABT), which denotes the momentum transferred to the human body, can lead to grave harm or fatality to the wearer, irrespective of whether the target is penetrated. This research delves into the ballistic response of body armor comprising a boron carbide (B_4C) plate supported by a unidirectional ultrahigh molecular weight polyethylene (UD-UHMWPE) fiber composite. The armor is subjected to kinetic energy resulting from a hard steel projectile impacted with velocity of 800 m/s. A gelatin block serves as a surrogate model to replicate the human torso. The numerical analysis of three-dimensional nonlinear deformations of ceramic-composite armor system is performed using ASNSYS/AUTODYN® software, employing the full integration rule to compute the Lagrangian elemental matrices. The study evaluates the mechanism of deformation of the ceramic integrated composite target, where the gelatin block demonstrates a maximum cavity depth of 21.65 mm. Additionally, the calculation includes the impact pressure resulting from momentum transfer to human tissue, with a maximum pressure of 15.2 MPa detected near the cavity area and gradually diminishing towards the back surface of the gelatin block. This analysis enables the assessment of body injury extent caused by impact, considering the depth of temporary cavity and peak pressure formed in the gelatin block.

KEYWORDS: B_4C; UHMWPE; Numerical simulation; Behind-armor blunt trauma; Gelatin.

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1. Introduction

Ballistic armors are specifically engineered to effectively stop and mitigate the impact of projectiles, thereby dispersing the associated energy and momentum, while ensuring the wearer remains unharmed. When a ballistic projectile strikes armor, it induces dynamic deformation and displacement in the target. Even in the absence of penetration, this impact can result in blunt trauma to the wearer, referred to as behind armor blunt trauma (BABT) [1,2]. Because of ethical limitations, it is impractical to conduct an experiment to investigate BABT. Therefore, numerical simulation can be employed as an alternative method [3]. Furthermore, numerical models offer a means to analyze deformation in detail that is not feasible through experimental methods.

The analysis of BABT requires developing models to understand the detailed dynamic behavior of systems that consist of multiple materials. These systems commonly consist of protective layers, projectiles, and backing materials. To precisely simulate the deformation and damage of both the projectile and target layers, it is crucial to utilize a suitable material model. Nevertheless, the simulation of the backing material poses a greater difficulty due to the necessity of incorporating materials that accurately mimic human tissue properties in order to effectively anticipate the transmission of pressure and momentum to the individual wearing the material. Ballistic gelatin is often considered a suitable material for simulating human tissue [4]. In addition, gelatin-backed targets are employed to forecast the potential human injuries resulting from the penetration of projectiles into targets. In order to simulate the impact of an object on gelatin, it is necessary to consider material properties that are dependent on both high strain rates and temperature. However, it is worth noting that these specific material properties are currently not accessible in the publicly available literature, particularly for events involving relatively high impact velocities.

In contemporary hard armor, the front ceramic plate usually comprises alumina (Al_2O_3, silicon carbide (SiC) or boron carbide (B_4C), supported by fiber-reinforced composites (FRCs). These composites commonly feature high-performance fibers like ultrahigh molecular weight polyethylene (UHMWPE), Kevlar, glass, and others. The unidirectional (UD) UHMWPE fibre exhibits superior specific strength and modulus characteristics, making it a more desirable choice compared to alternative composites [5,6]. Additionally, the enhanced impact resistance of UD-UHMWPE fabrics can be attributed to their lack of undulation, unlike woven composites [7].

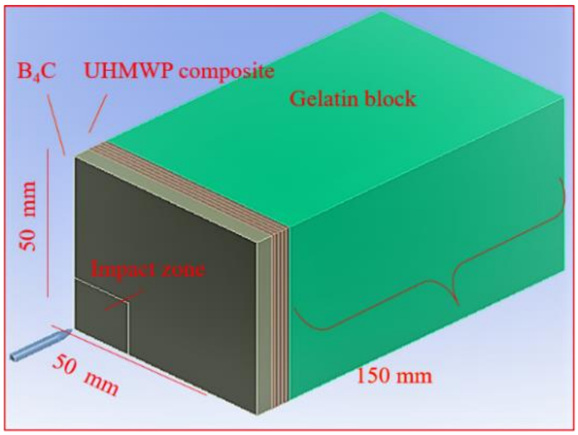
To investigate the damage induced on humans by ballistic impact, researchers conducted both experimental and numerical studies [8–10]. Gelatin was utilized as a substitute material in assessing injuries to human tissues.
Nevertheless, there exists a paucity of research regarding the ballistic effectiveness of ceramic integrated composite armor. The foremost ceramic layer of these armors mitigates the pointedness of the projectile's tip and attenuates its velocity, while the subsequent layer intercepts the disintegrated ceramic fragments and dissipates the residual kinetic energy of the projectile. Wen et al. [11] conducted investigations employing a high-speed alumina-backed UHMWPE composite, evaluating back face deformation and ballistic thresholds through measurements of temporary cavity dimensions and pressure exerted on gelatin block. Comparative analysis between experimental and numerical outcomes revealed a robust quantitative correlation. In a more contemporary exploration, Batra et al. [12] scrutinized the impact of incorporating a thin polymer layer as a protective sheath on ceramic-composite armor under low-velocity circumstances, with specific focus on the armor system's ballistic threshold. The introduction of a polyether-ether-ketone (PEEK) layer anterior to the ceramic material resulted in a diminution of pressure transmitted to the gelatin block, as per their findings.

The primary objective of this investigation is to assess the deformation and damage mechanism of ceramic backed composite armor when interfaced with a gelatin block. Furthermore, the study endeavors to predict the momentum transfer experienced by the wearer upon encountering a 4340-steel projectile, employing numerical simulation techniques. Comprising a boron carbide (B_4C) frontal layer integrated with unidirectional (UD) UHMWPE) fiber composites, the ceramic-composite target is the focal point of examination. Utilization of ballistic gelatin as a support layer serves as a surrogate model to accurately anticipate tissue response. Emphasis is placed on delineating the failure mechanisms of the ceramic-composite target under impact velocities of 800 m/s. Additionally, the analysis entails predicting the maximum cavity depth within the gelatin block and quantifying the transmitted pressure.

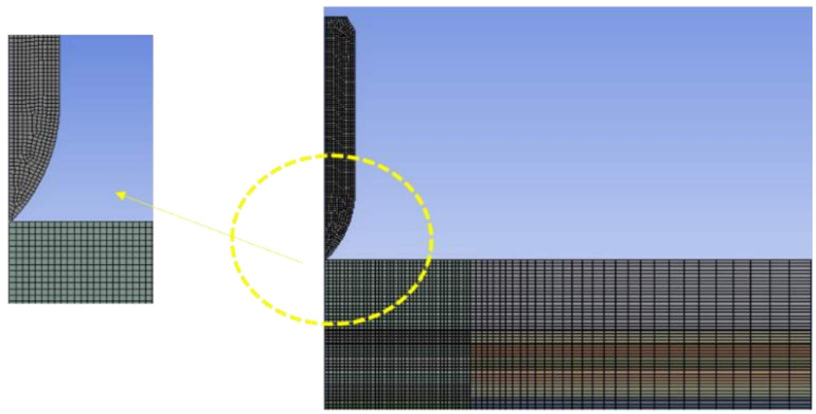
2. Numerical Model

A 3D Lagrangian solver within the ANSYS/AUTODYN® was utilized to simulate the response of ceramic-composite target supported by gelatin, impacted by a steel projectile. The cross-sectional area of the target face and gelatin block measures 100 mm × 100 mm. For computational efficiency and symmetry considerations, the model encompasses only a quarter of the geometry, as illustrated in **Fig. 1(a)**. Both the B_4C ceramic and UD-UHMWPE fiber composite possess a thickness of 8 mm, as depicted in **Fig. 1(b)**. The gelatin block is 150 mm thick for the current analysis. The projectile exhibits an ogive nose and dimensions of 34.3 mm in length and 6.2 mm in diameter, consistent with 7.62 mm armor-piercing rounds. Delamination between layers of the UD-UHMWPE composite is simulated using a sub-laminate approach [13], wherein the entire composite is subdivided into five 2-mm-thick sub-laminates. The quarter finite element model is illustrated in **Fig. 1(b)**.

The impact response of brittle materials is characterized using the Johnson-Holmquist (JH-2) phenomenological model, which has been incorporated into the AUTODYN® library. The model incorporates pressure-dependent strength, strain rate, and material damage phenomena in the context of ballistic loading. The material parameters of B_4C were available in AUTODYN® library. The UD-UHMWPE composite laminates are considered to be macroscopically homogeneous materials and treated as followed a non-linear orthotropic constitutive response, exhibiting rthotropic hardening and softening governed by energy-based criteria [14]. Gelatin is characterized as a viscoelastic substance and adheres to the Mie-Grüneisen equation of state (EOS) and the Johnson-Cook (J-C) failure model. Table 1 presents the material properties of gelatin. The projectile was simulated using the ANSYS/AUTODYN® material library, specifically the 4340-steel model. This model incorporates a linear equation of state (EOS) and the J-C strength and failure criteria.



(a)



(b)

Fig. 1(a) Quarter geometry of the ceramic-composite with gelatin backing, (b) Finite element model.

Table 1. Gelatin material properties [15].

Parameters	Value
Density (ρ), g/cm^3	1.030
Viscoelastic properties	
Instantaneous shear modulus (G_0), GPa	0.214×10^{-3}
Shear modulus (G), GPa	0.158×10^{-3}
Decay constant, (β), s^{-1}	0.00087
Equation of state	
Gruneisen coefficient	0.17
C_1, m/s^{-1}	1553
S_1	1.93
S_2, s.m^{-1}	0

J-C damage	
d_1	-0.13549
d_2	0.6015
d_3	0.25892
d_4	0.030127
d_5	0
Melting temperature, ^{0}C	20
Reference strain rate	0.001

The delamination between B_4C and sub-laminates of UHMWPE composite is modeled using a linear failure criterion based on normal and shear strength at the interface as shown in Equation (1).

$$\left(\frac{\sigma_n}{F_n}\right)^p + \left(\frac{\sigma_s}{F_s}\right)^q \geq 1. \quad (1)$$

Where σ_n and σ_s are the normal and shear stress, and F_n and F_s denotes the normal and shear strength at the interface, respectively. The value of exponents p and q are set to 1 in the present analysis. Normal and shear strengths are 65 MPa and 45 MPa [16] between the SiC and UD-UHMWPE layers, while they are 43 MPa and 25 MPa, respectively, between the layers of the UHMWPE and B_4C [10]. The value of the inter-laminar strength governed by the shear and normal strength between the UHMWPE sub-laminates are 7.85 MPa and 5.35 MPa, respectively [16].

The entire model, as depicted in **Fig. 1(b)**, is discretized using an eight-node Lagrangian linear element. The geometry of the composite material consisting of B_4C and UHMWPE near the impact zone was simulated using mesh elements of size 0.3 mm. The mesh element size was then uniformly increased to 1.3 mm in the outer region. The size of the gelatin elements exhibited variation, ranging from 1 mm in proximity to the contact zone to 4 mm at the terminal point. The projectile is discretized into elements with a size of 0.25 mm. The numerical model consists of a total of 396,626 mesh elements. To address the convergence issue caused by highly distorted elements, a numerical model incorporates a global geometric failure strain of 1.4. The mass of the elements that were removed was conserved during the analysis. The target does not have any boundary condition imposed on it.

3. Results and Discussion

3.1. Validation of numerical model

Nguyen et al. [14] documented the ballistic threshold of a UHMWPE fiber composite at 394 m/s when confronted with impact from a fragmented, segmented projectile (FSP) measuring 20 mm in diameter. To validate the precise integration of the composite material model within the ANSYS/AUTODYN® software framework, a thorough numerical inquiry into the UHMWPE target is conducted. The investigation centers on evaluating impact velocities ranging from 350 to 450 m/s. The findings reveal an 11% reduction in the ballistic threshold, suggesting an inadequacy in the implementation of the composite material model. This discrepancy may be attributed to several factors, including the oversimplified application of the sub-laminate approach and the presence of strain rate-dependent discrepancies. Notably, the properties of B_4C ceramic and projectile materials are derived from the AUTODYN® library and lack explicit validation.

3.2. Ballistic evolution

The evaluation of the ballistic efficacy of ceramic-composite armor was conducted at an impact velocity of 800 m/s. In order to prevent target perforation and ensure a more precise determination of cavity evolution and pressure values within the gelatin block, the impact velocity in our investigation was capped at 800 m/s, given that projectile penetration was detected at velocities surpassing 900 m/s. Illustrated in **Fig. 2** are time-evolving fluctuations in the velocity of a hard steel projectile upon impact, depicting the sequential progression of events during projectile penetration into the target. Notably, the projectile tip undergoes complete erosion around 0.038 milliseconds, while the kinetic energy of the bullet undergoes significant reduction upon fracture of the B_4C composite at a velocity of 0.067 m/s. Subsequent layer debonding and laminate plastic deformation further contribute to velocity reduction. **Fig. 3** shows the evolution of energy throughout the ballistic impact, revealing a gradual decline in energy throughout the event, indicative of the absence of stability issues in the numerical simulation.

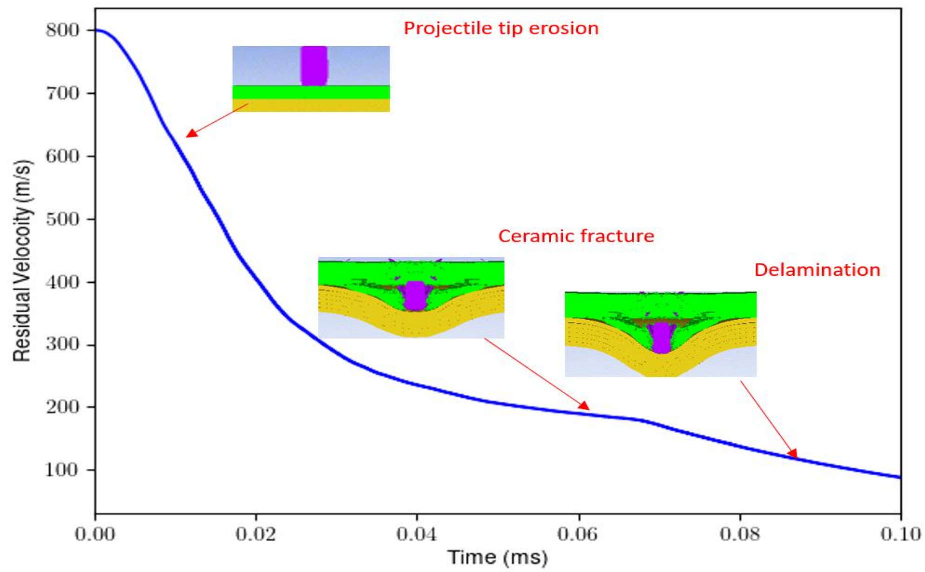


Fig. 2. Variation of residual velocity during the ballistic events.

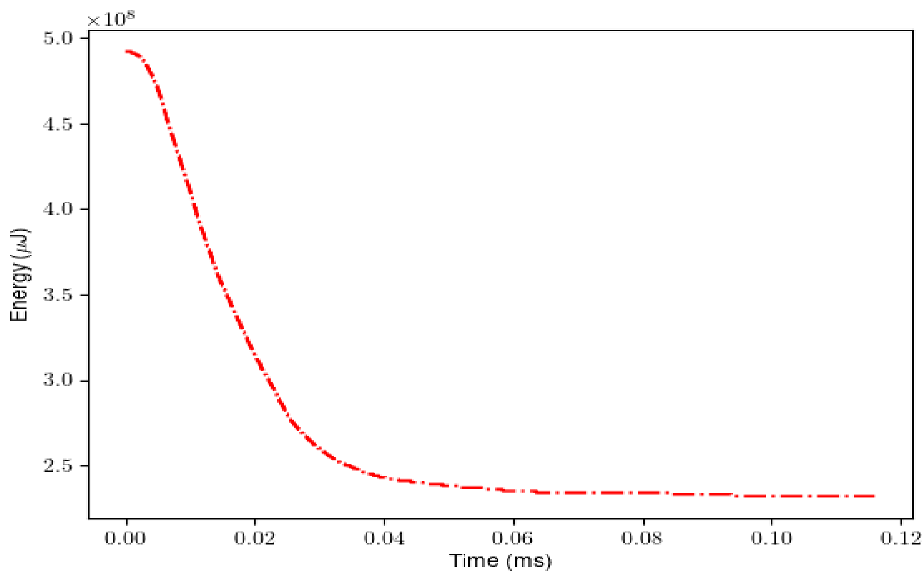


Fig. 3. Variation of energy during ballistic events.

Fig. 4 presents the chronological progression of damage inflicted upon the target material at each time interval excluding the gelatin block. However, it was included in the numerical analysis. The illustration portrays the projectile's point eroding upon impact with the target, resulting in a mushroom-shaped surface. Beneath the projectile, the B_4C ceramic material assumes a conoid shape due to intense compressive forces. The erosion process by the projectile continues as it penetrates the previously damaged volume of ceramic material. The conoid, located amidst the backing panel and the projectile, facilitates momentum dispersion across a wide range over the backing plate surface. Furthermore, the UHMWPE composite laminate exhibits ongoing bulging and bending.

3.3. Deformation of gelatin backing

At three distinct time periods, **Fig. 5** depicts the progression of cavity formation or deformation in the gelatin block. At time t = 0.036 ms, the cavity in the gelatin was found to be of minimal depth. However, at t = 0.056 ms, it was increased to 11.65 mm. The gelatin block experiences a peak deformation of 21.65 mm when the velocity of the projectile decreases to 91 m/s within a time frame of 0.1 ms. The assessment also includes the evaluation of the impact pressure resulting from the transfer of momentum to human tissue. In the vicinity of the cavity, a maximum pressure of 15.2 MPa was observed, exhibiting a gradual decline in pressure from the location of the cavity to the rear face of the gelatin. As per the specifications outlined in NIJ 0101.04 [17], it is permissible for hard armor that has been struck by a ballistic projectile to exhibit a cavity depth not exceeding 40 mm. The pressure measurement of 8.41 MPa was obtained at a distance of 40 mm from the upper surface of the gelatin block.

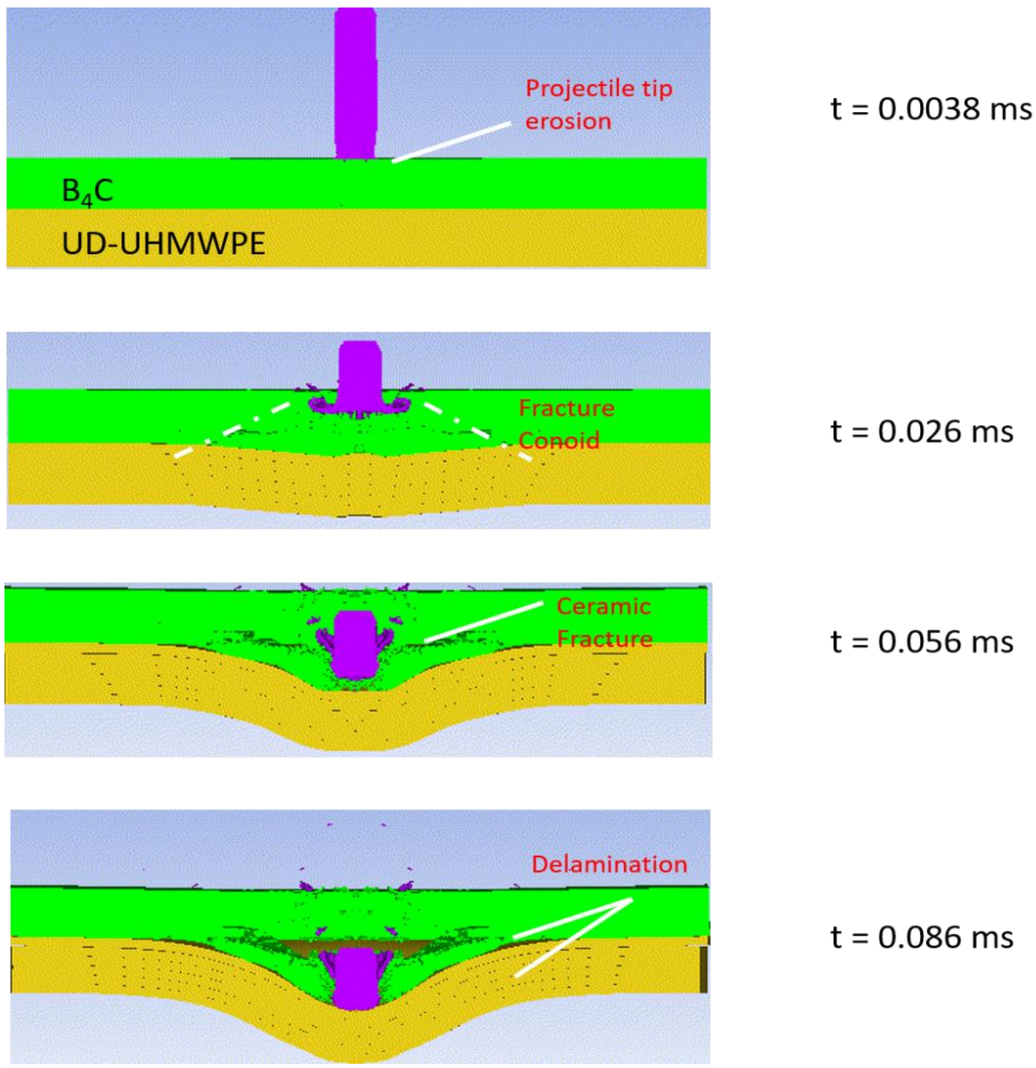


Fig. 4. Sequence of damage events during the ballistic impact on gelatin backed ceramic-composite target.

Fig. 5. Cavity formation in the gelatin backing at different time intervals.

4. Conclusions

To evaluate the blunt trauma resulting from behind armor, a numerical investigation was conducted on the ballistic impact response of a B_4C ceramic integrated unidirectional ultrahigh molecular weight polyethylene (UD-UHMWPE) composite target backed by gelatin block. The analysis employed a three-dimensional Lagrangian solver within the ANSYS/AUTODYN® software platform. Predictions were made regarding the progression of injury in the gelatin block when subjected to impact from an 800 m/s steel projectile against the ceramic integrated composite target. In order to characterize the behavior of the bullet upon impacting the ceramic backed composite target, both the displacement in transverse direction in gelatin block and the values of pressure resulting from the impact were assessed at a depth of 40 mm within the cavity. At this specific distance from the upper surface of the gelatin, 8.41 MPa of pressure reading was recorded.

Disclosure statement

The authors declare no relevant financial or non-financial interests.

Data availability

Raw data of the research article is available with the authors and will be provided as per a request from the journal.

Ethical approval

Not applicable.

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