Analysis of dynamic back face deformation of a body armor impact by a rifle bullet using 3D-DIC

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Abstract. Body armor that defeats the threat can still cause severe trauma by striking the thorax with its back face deformation (BFD). In this study, the 3D digital image correlation (DIC) technology was adopted to capture the dynamic BFD of a ceramic/UHMWPE body armor impact by a rifle bullet. The shape and size of the BFD time histories, deformation velocity, acceleration and line slices profile on armor back face were obtained. The maximum BFD height can reach to 34.3 mm within about 1.2 ms, and then slowly decreases to the static deformation height of about 24 mm for the impact velocity 675.4 m/s. The maximum deformation velocity and acceleration are 129.9 m/s and 1.29e6 m/s², respectively.

1. Introduction

The use of body armor has significantly reduced penetrating injuries and saved the lives of many soldiers. The body armor can stop the projectile, but the resultant behind armor blunt trauma (BABT) can still cause serious injury to the body [1, 2]. The back face deformation (BFD) is the main cause of BABT. As body armor becomes lighter, the likelihood of larger BFD under ballistic impact increases. The mechanisms of BABT are still not well understood.

Digital image correlation (DIC) has emerged as a new technique for measuring surface deformations of materials. This technique has been used to measure dynamic deformations of composite laminates and combat helmets under ballistic impact [3, 4]. DIC can not only provide the time history of the tested material dynamic deformation, but also reconstruct the three-dimensional (3D) deformation process. DIC technique can provide more comprehensive deformation information to help better understand the BABT [5, 6].

Yu et al. [7] and Weerasooriya et al. [8] adopted 3D-DIC technique to measured the transient deformation of the rear surface of the bulletproof laminate and combat helmet under the impact of high-speed projectiles. Furthermore, the results of dynamic deformation and full-field strain were used to improve their finite element model. Wen et al. [9] adopted 3D-DIC to study the pistol bullet penetrating combat helmet covered human head surrogate, and the dynamic response of helmet front face was obtained. Hisley et al. [5] developed an experimental methodology using 3D-DIC data to assess ballistic helmet blunt trauma. They used the BFD kinetic energy measured from 3D-DIC results to calculate the blunt criterion, and then based on the relationship between blunt criterion value and abbreviated injury scale (AIS) levels to predict the severity of head blunt trauma, especially the
probability of skull fracture. Freitas et al. [1] measured the dynamic BFD for a dozen composite plates when engaged by ballistic impact using the DIC technique. By comparing the deformation process, deformation velocity, strain time history and spatial distribution, the optimal composite design scheme was determined.

In this research project, a synchronous test system was constructed to study the rifle bullet penetrating body armor. The 3D-DIC methodology was used to directly measure the shape and size of the BFD time histories, deformation velocity, acceleration and line slices profile on armor back face.

2. Methods

2.1. 3D-DIC concepts
DIC is an optical, non-contact technique for obtaining accurate measurements of deformation, velocity, acceleration and strain data using images from digital cameras and analyzed with DIC software. In addition, DIC allows for full-field, time-dependent measurements to capture non-uniform deformations, with the field of view width scaling from sub-millimeter to over 10 meters [1]. DIC can be used in place of conventional strain gauges and extensometers where their application would be cumbersome, difficult or impossible to apply [1]. 3D-DIC uses two high-speed cameras to stereoscopically track the movement of the speckle pattern, some random distribution of black dots on the surface of the sample. For this study, the speckle pattern is applied to the back face of an armor. During the ballistic impact of the body armor, the cameras and software track changes in the speckle pattern. The 3D coordinates of specific surface locations are determined using suited calibration board, and the movement of those discrete locations relative to each other over time is computed. In addition, the software has the capability to compensate for full-body motion such that only local deformations are tracked [5].

2.2. Experiment setup
The schematic diagram of the test system is shown in figure 1. The 3D-DIC system uses a pair of Phantom V2511 high-speed cameras at an angle to capture the same image simultaneously but from different perspectives. High-speed photography was taken at 20,000 frames per second with a resolution of 1,280 X 800 pixels and exposure time 50 μs. The appropriate lighting was used to increase speckle brightness and clearly visualize the ballistic phenomenon. The shooting distance is approximately 15 m from muzzle to the frontal surface of the armor. The speed of the bullet was measured with a chronograph at a distance of 3 m from its front face to muzzle. The two cameras receive a simultaneous trigger from an infrared trigger, which is tripped by the muzzle flame of the rifle.

![Figure 1. Schematic of the experimental setup.](image-url)
The body armor studied here consists of 99.5% Al$_2$O$_3$ ceramic tiles with UHMWPE fiber-reinforced laminate backing. In order to prepare armors for DIC testing, the back face of the armor was sprayed with white matte paint called speckles. Speckles on the back of body armor are the basis for DIC photography and analysis. To obtain effective correlation result, speckle patterns must meet the criteria of non-repeatability, isotropy and high contrast. If the speckle is too large, it will appear that the calculation of some analysis domain contains only white or black, which makes it impossible to get a good match. On the contrary, if the speckle is too small, the camera will not be able to distinguish the speckle accurately. This is called confusion. The confusion will cause the speckle cannot move smoothly with the movement of the specimen, but to appear the jitter phenomenon caused by the interaction between sensor pixels, and the result will show obvious overlapping pattern. The optimal speckle size was determined to be between 1.17mm and 2.34mm based on the relationship between resolution and picture size, and 1.524mm (0.06in) was finally selected. The speckle pattern was generated by a program based on the area of interest. Then, the speckles were printed on a tattoo sticker and were applied to the armor’s back face where deformation was expected to occur (figure 2).

![Speckles on the back face of the body armor](image)

Figure 2. Create the speckles on the back face of the body armor (a) tattoo sticker, (b) Paste the speckles, (c) armor with speckles.

The 3D-DIC system must be calibrated before testing. The recommended size of the calibration board is approximately 80% field of camera view. Figure 3 shows the calibration board used in this effort. Then, a series of calibration images with the different posture of the calibration board were captured by two high-speed cameras synchronously. The software can convert the dot pattern into a field of x, y and z deformations. It performs this operation by breaking the image into interrogation areas called facets and then deforming these facets by maximizing the 2D correlation coefficient of pixel intensity. These deformed facets are then mapped into 3D space using the calibration images [1]. After calibration, it is not possible to make any adjustments to the camera position. Otherwise, the coordinates need to be re-calibrated.
Figure 3. Establish a 3D coordinate system using the calibration board.

By using the 3D-DIC technique, the ballistic impact of a rifle bullet penetrating an NIJ III level ceramic/UHMWPE body armor fixed on a shelf is then conducted (figure 4). Before shooting, confirm whether the high-speed 3D-DIC test system, speed measurement system, and infrared trigger are in the trigger mode. Three group experiments were conducted by firing a 7.62x39 mm bullet shooting at the center of each body armor front surface. The speeds are 675.4 m/s, 676.1 m/s and 675.1 m/s, respectively. After the tests, the 3D data and the full-field deformation information of the back face of body armor were obtained from the 3D-DIC post-processing software.

Figure 4. DIC test system.

3. Results and discussion
Time histories of the 3D-DIC measured BFD at the maximum deformation point of body armor are shown in figure 5. As can be seen from the curves, the experimental results for the impact velocity 675.4 m/s and 675.1 m/s are agreement with each other. However, the experimental results for the impact velocity 676.1 m/s were higher than those of the other two groups, which may due to the
impact point position too close to the edge of the ceramic tile. Taking impact velocity 675.4 m/s as an example, the height of the BFD sharply increased to the maximum value of 34.3 mm within about 1.2 ms. After reaching the maximum value, it begins to spring-back to 28.4 mm as elastic deformations of the UHMWPE laminate are recovered. After that, it slowly decreases to the static deformation height of about 24 mm during 25 ms, which indicated the permanent plastic deformation of BFD. Figure 6 shows the bullet hole at the front face and back face deformation of body armor after shooting. The bullet consumed much kinetic energy during the penetration into the ceramic, and the ceramic tile at the bullet hole was severely cracked. However, the surrounding ceramic tile was no visible fracture. The steel core of the bullet turned into a mushroom shape during the interaction with ceramic, so that it did not penetrate the UHMWPE backing plate. The UHMWPE backing absorbs the remaining impact kinetic energy through plastic deformation, and a prominent bulge appeared on the back of the body armor after the shooting.

Figure 5. Time histories of the BFD height at the point of maximum deformation.

Figure 6. The bullet hole at (a) strike face and (b) the back face deformation of body armor after shooting.

Figure 7 presents DIC measured dynamic BFD results for a 7.62x39 mm rifle bullet impact a body armor with a striking velocity of 675.4 m/s. From figure 7 we can see, the shape of the BFD resembles a cone, the height and bottom diameter of the cone increased with time before 11.90 ms, and the entire back face of the armor was almost deformed during loading. The maximum height of the cone can reach 34.3 mm. After that, the volume of the cone began to decrease with the elastic energy, and the final height was 24 mm.
Figure 7. The 3D shape of the BFD created by DIC software.

As shown in figure 8, O is the point with the maximum deformation height on the back face, the \( L_{AB} \) is the horizontal line passing point O, and the \( L_{CD} \) is the vertical line passing point O. The DIC measured line slices profile of \( L_{AB} \) and \( L_{CD} \) is displayed in figure 9. Each curve shows the contour of the BFD at a specific instance in time. The red curves present the BFD outline at the loading stage, while blue curves present the unloading stage. From figure 9 we can see, during the period of 10.70ms-10.85ms, the height of the BFD rapidly increased from 6.2 mm to 21.7 mm. After that, the deformation rate slowed down and the maximum BFD was reached at 11.90 ms. Then the BFD began to decrease, and the height of BFD is 32.1 mm, 28.5 mm and 24.1 mm at 12.5 ms, 13.3 ms and 22.45 ms, respectively. The variation law of the profile line in figure 9b is consistent with that in figure 9a. However, due to the influence of the curvature of body armor, the width of \( L_{CD} \) is slightly smaller than \( L_{AB} \).

Figure 8. Schematic of line slices position.
Figure 9. Line slices profile of BFD during load and unloading, (a) L_{AB} and (b) L_{CD}.

Figure 10 exhibit the time history curves of displacement, velocity and acceleration for the point of maximum BFD. Three red points represent the corresponding physical quantities at the maximum BFD. The maximum velocity of front face deformation is sharply increased to 129.9 m/s within 0.1 ms. Then the speed began to decrease, and a negative speed can be found after 11.9 ms indicates that the height of BFD is starting to decrease. Two peaks can be observed from the time histories of the acceleration curve. After reaching the maximum positive value of 1.29e6 m/s^2, the acceleration sharply decreases and reaching the maximum negative value of -6.6e5 m/s^2 at 10.80 ms.

Figure 10. The time history curves of (a) displacement, (a) velocity and (a) acceleration for the point of maximum BFD.
4. Conclusions
In this research project, the dynamic response of a ceramic/UHMWPE body armor impacting by 7.63x39 mm rifle bullets were investigated. The 3D-DIC method provides the results of full-field deformation, line slices profile of BFD, deformation velocity and acceleration on armor back face. These results could then be used to assess of ballistic performance of body armor and the severity of blunt trauma.

Acknowledgments
This work was supported by the National Natural Science Foundation of China (Grant No.11872215) and Funds for Science and Technology on Transient Impact Laboratory (Grant No. JCKYS2019209C001).

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