Analysis on Injury for Light Armored Vehicle Occupant by the After-effect Fragments of Rifle Projectile

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Abstract. Armor-piercing projectile is one of the main threats faced by light armored vehicles. The after-effect fragments formed by projectile penetrating armor will cause injuries to the occupants. It is an important reference for evaluating the impact of the armor-piercing projectile on light armored targets. The characteristics of after-effect fragments have a great influence on the lethal efficiency of internal occupants, especially those wearing bulletproof vests. In order to study the injury effect of the after-effect fragments on occupants, the 12.7 mm multifunctional bullet was tested to 10 mm armored steel to obtain the mass distribution of after-effect fragments at different speeds, and then a finite element model of the effect of after-effect fragments on the human thorax FEM with soft body armor was established. Through numerical simulation, the impact of different after-effect fragments of bullets was obtained. The stress changes, pressure changes and etc. of human model after the impact of different after-effect fragments were obtained that provides a basis for further evaluation of the injury effect of fragments on occupants in light armored vehicles.

1. Introduction
The hitting effect of an armor-piercing projectile on light armored targets is not only the direct killing of the penetrator formed by the direct impact of the projectile, but also the killing of the after-effect fragments formed in the interior of the vehicle to the occupants. According to the statistical results of battlefield injuries, the proportion of fragments injured is significantly higher than that caused by projectiles\textsuperscript{[1]}, that is to say, the effective attack on the internal occupants of the vehicle mainly depends on the after-effect fragments. At the same time, due to the improvement of the killing efficiency of projectiles and fragments, more and more occupants wear bulletproof vests in vehicles, and much research has been done on the impact of projectiles and fragments on unprotected personnel and protected bionic targets. The damage assessment of aftereffect fragments of armor-piercing projectiles to the crew of light armored vehicles has also been paid considerable attention. For the evaluation of the protective ability of bulletproof vests, most countries use $v_{50}$ as a general index to evaluate the protection, such as STANAG2920 (NATO), MIL-STD-662F (US) and GJB 4300-2002 (PRC)\textsuperscript{[2]}, which have certain credibility and advantages, but the damage assessment of after-effect fragments is slightly insufficient, because the after-effect fragments are mostly irregular shape. The American military standard Mil-P-46593 A defines the simulation of several fragments, and GJB 2936-1997 (PRC)\textsuperscript{[2]} defines the standard of fragment damage. However, there is still no scientific basis for evaluating the damage of fragments to protective personnel.
In view of the above problems, experts and scholars in the field of armor-piercing and individual protection engineering have conducted a series of studies. Zou Yu\cite{3} studied the process of fragments formation after armor-piercing projectile hit armored vehicles, and obtained the law of fragment quality and velocity characteristics of the armor-piercing projectile. Then the process of armor-piercing fragment penetrating bulletproof vest was simulated and its protective effect was discussed. Yan\cite{3} used a fragile tungsten alloy core material for armor-piercing bullets to explore the killing ability of the after-effect fragments of bullet, in his research 10 mm an after-effect test was carried out based on an armor-piercing bullet with tungsten alloy penetrator, 10 mm thick homogeneous steel plate and a typical polyethylene composite body armor, and the mass distribution and dispersion law of after-effect fragments and the penetration effects of after-effect fragments penetrating into body armor at different velocities were analyzed. Although their research considered the after-effect fragments, they only hit the bulletproof vest, not the personnel.

The after-effect fragments are likely to be blocked by bulletproof vests and can not penetrate human tissues, but some energy is still transmitted to the human body through the deformation of bulletproof vests, causing damage to human target organs, a phenomenon known as behind armor blunt trauma (BABT)\cite{4,5,6}. In this paper, by applying human torso finite element (HTFE) to establish a numerical simulation model to get the mechanical response of the human torso outfitted with soft body armor to the non-penetrating ballistic impact from the after-effect fragments, in order to provide simulation model and reference data for the after-effect damage evaluation of large-caliber armour-piercing projectiles.

2. Aftereffect fragmentation generation and distribution

In the preface work\cite{3} of this paper, the 12.7 mm armor-piercing projectiles were used as the armor-piercing body, and its core material was brittle tungsten alloy. After armor-piercing, a large number of small mass fragments could be formed. The 10 mm/0° homogeneous steel plate is placed 100m away from the muzzle, and the target I and II were placed 60 cm and 80 cm behind the steel plate, respectively. Both the target I and II were paper targets for observing fragments flying in the fragmentation test. When the typical polyethylene composite bulletproof vest was used instead of penetrating the test target I and fixed on the pine with a thickness of 25 mm, the target II was removed. A high-speed video camera was placed on the side to capture the whole process of fragmentation during ballistic penetration. The diagram of ballistic test is shown in Figure 1.

![Figure 1. Sketch of ballistic impact experiment.](image1)

![Figure 2. The distribution of after-effect fragments.](image2)

After-effect fragment generation: the prefabricated process structure of fragments such as grooves are not designed for the projectile core, according to the fragmentation principle of forming fragments, the after-effect fragments include fragments formed by the fragmentation of the core, fragments formed by the impact of steel plates, fragments formed by the fragmentation of other parts of the projectile, and so on. All the above fragments are randomly formed during armor-piercing impact, and the mass and shape of the fragments are random. Therefore, the shape of the fragment is irregular and the mass distribution of the fragment is range. The distribution of after-effect fragments is shown in Figure 2.
3. Injury analysis of after-effect fragments by HTFE

The fragments marked in the circle in Figure 2 are fragments that can effectively penetrate the bulletproof vest, that is, they can cause injury to the protected occupants, and can directly kill the unprotected personnel without protection. In this paper, the fragments in the marked area of the frame in the picture are counted and equivalent, and their injury ability is evaluated by the finite element method.

3.1. Calculation model

In this paper, the finite element model of the human body described in reference [4] is adopted, that is, the finite element model of the Chinese human trunk. The element form and material properties of the finite element model are consistent with those in the literature, and some grids are slightly adjusted due to the contact position.

The finite element model of the interaction between the fragment and the human target with soft body armor is established (as shown in Figure 3). The after-effect fragment is equivalent to the distribution of the previous analysis, and the fragment strikes the soft body armor with velocity \( v \), because the impact time is very short. Only the horizontal velocity of the fragment is considered. The soft body armor and target use a denser grid in the impact area where they interact with the fragment projectile, and a relatively sparse grid in the part away from the action area, which can ensure the calculation accuracy and speed up the calculation efficiency. Erosion contact is defined between soft body armor and fragments, automatic surface to surface contact is defined between soft body armor and various organs and organs, and at the same time, automatic single surface contact is defined for soft fiber layer.

![Figure 3. Finite element mesh.](image)

Based on the analysis of the distribution and causes of after-effect fragments in the previous article, the blunt effect is studied. When modeling after-effect fragments by the finite element method, according to the typical dispersion distribution law in the Figure 2, it is assumed that the number of tungsten alloy fragments and randomly generated steel fragments in small-sized fragments is shown in Table 1. In this paper, the process data in the simulation is analyzed with the example of Scheme C.

| Scheme       | A         | B         | C         |
|--------------|-----------|-----------|-----------|
| Tungsten Alloy | 7×0.355 g | 6×0.355 g | 5×0.355 g |
| Steel        | 0         | 1×0.152 g | 2×0.152 g |
| The total amount | 7        | 7         | 7         |
| Total mass (g) | 2.485    | 2.282     | 2.079     |

3.2. Numerical calculation results analysis

3.2.1. Impact process
Figure 4 shows the process diagram of after-effect debris cloud impacting the soft armor. From 40 μs, the fragments began to hit the soft protection, until 100 μs all the fragments hit soft protection, and the soft body armor begins to rebound obviously after the 110 μs.

![Figure 4](image)

*Figure 4.* The after-effect fragment cloud impacting the soft body armor process.

The Figure 5 shows the deformation and cross-sectional view of the soft body armor after the impact of Scheme C. The after-effect fragment cloud failed to penetrate the soft body armor, and the number of penetration layers was 28. Figure 5(a) shows the kinetic energy curve of debris. It can be seen that the fragments hit the soft body armor in turn. The kinetic energy began to decline and gradually tends to 0. The soft armor can effectively counteract the impact energy of fragments.

![Figure 5](image)

*Figure 5.* The results of impacting the soft protection. (a) kinetic energy curve; (b) deformation; (c) cross-sectional view.

### 3.2.2. Evolution of stress field and pressure field

The Figure 6 shows the evolution of the stress field of thorax epidermis after the impact of after-effect fragment cloud. When $t=40$ μs, the stress field appears on the epidermis, while a stress field appears on the soft armor at $t=25$ μs. There is a time difference between them, which also reflects the propagation of stress from the outside to the inside. The stress is maximum at the equivalent impact point, and gradually decreases around it. The epidermal stress spots gradually become larger with time, reaching the maximum at $t=160$ μs, with a diameter of approximately 12.96 cm and an area of approximately 67 cm². The maximum stress at this time is 0.169 kPa.
Figure 6. The evolution of the stress field of thorax epidermis.

Different from the stress spot formed by bullet impact, the bullet forms a circular spot with the impact point as the center, and for the fragment cloud, it is an irregular shape due to the difference in the impact position and time of the fragment.

The Figure 7 shows the evolution of the stress field of each organ after the impact of the fragment cloud. When $t=80\,\mu s$, the stress field appears on the right lung (the first impact point is close to the right lung), with the impact point as the center, and propagates around in an approximately circular shape. The stress appears 40 $\mu s$ later than the skin because the stress wave propagates from the outside to the inside, and there is a time lag. At $t=110\,\mu s$, the stress wave propagates to the heart near the right lung, and at $t=170\,\mu s$, it propagates to the liver and left lung. Among them, when $t=200\,\mu s$, the stress point of the heart is the largest, and its area accounts for approximately two-thirds of its surface area.
Figure 7. The evolution of the stress field of organs.

Figure 8 shows the evolution of the skin pressure field after the after-effect fragment cloud impact. A pressure wave appears at $t=40\ \mu s$, and diffuses around the equivalent impact point. From the beginning of the impact, the fragments have been applying pressure to the human target through the soft armor, causing the pressure waves to overlap with each other so that the pressure value on the periphery of the impact area is greater than the equivalent impact center. This phenomenon can be apparent in Figure 1. Comparing the skin stress field in Figure 6, it can be observed that the influence range of the pressure field is larger than that of the stress field, and the propagation of pressure wave and stress wave is obviously different. At $t=200\ \mu s$, the maximum pressure spot diameter is approximately 21 cm and the affected area is 245 cm$^2$.

Figure 8. The evolution of the skin pressure field.

Figure 9 shows the evolution of the pressure field of each organ after the fragment impact. At $t=70\ \mu s$, a pressure wave appears. It is 30 $\mu s$ later than the appearance of the skin pressure wave. Although the soft armor can intercept fragments, the pressure wave generated by the impact will be transmitted to the human body through the soft armor, and then gradually transmitted to the heart, lungs, and liver.
3.2.3. Analysis of feature points of human target

Five positions were selected as measurement points from the thorax epidermis for data comparison and analysis. Among them, point B can be regarded as the scattering center of the fragment cloud, and the other four places are close to the edge of the diameter of the fragment cloud dispersion circle. The point x3 of the sternum is the corresponding positions under point B. The element position shown in the figure 11 is selected as the reference measurement point in the internal organs. The meaning of the square root is regarded as the data of the measuring point.

**Figure 9.** The evolution of the organs pressure field.

**Figure 10.** The measurement diagram.

**Table 2.** Diameter and area.

|                          | A    | B    | C    |
|--------------------------|------|------|------|
| Stress spot diameter (cm)| 15.04| 14.53| 12.96|
| Stress spot area (cm²)   | 87.21| 82.41| 67   |
| Pressure spot diam. (cm) | 21.9 | 21.3 | 20.3 |
| Pressure spot area (cm²) | 252  | 245  | 236.2|

Figure 10 is a statistical schematic diagram of the stress spot area and the maximum circumscribed circle diameter of the pressure spot obtained by image processing software. The stress spot, pressure spot, stress, and pressure spot diameter are all counted by this method, ignoring the influence of error during operation. As can be seen from Table 2, the difference among the three schemes is not obvious.
It can be seen from Figure 12 that the acceleration of each measurement point varies with time. Point A of the thorax epidermis (the first point of impact) first appears at its maximum value at \( t = 85 \mu s \). The point B, which is close to the scattering center of the fragment cloud, has a maximum value at \( t = 90 \mu s \). Among the measurement points of the sternum, the point \( x_3 \) close to the scattering center of the fragment cloud has a maximum value at \( t = 155 \mu s \), and it is the maximum value among the measurement points. When the maximum value appears, each measuring point gradually oscillates and drops to 0. Similarly, the change trend of pressure and stress at each measuring point is similar.

In order to understand the propagation and attenuation characteristics of stress and pressure wave in internal organs, stress and pressure data are extracted from the measuring points of various organ. The internal stress of each organ, the projection position of the pressure measuring point on the organ surface, and the pressure waveform of the measuring point are shown in Figure 14.
It can be observed in the equivalent stress-time curve of the sternum that when t=130 μs, the equivalent stress reaches the maximum value of 29.21 MPa. This value is much higher than the equivalent stress of 3.04 kPa at the measuring point of the heart. The reason for the large difference is that the stiffness of the sternum is larger than that of the organs.

4. Discuss
The after-effect fragment cloud formed by the armor-piercing projectile hits the soft body armor, causing the body armor to protrude backward and hit thorax. Due to the characteristics of viscoelasticity and acoustic impedance of the human body, pressure wave propagation is an important mechanical mechanism of organ damage. For substantial organs such as the heart and liver, when the pressure wave strength exceeds the tensile strength of the tissue, the tissue fibers can be broken. The lungs are air-bearing organs and the propagation of pressure waves can cause the compression and expansion of the vesicles, which can lead to the alveoli and capillaries to rupture. At the same time, the protruding and squeezing action of the body armor causes instantaneous deformation and acceleration of the sternum. Therefore, it is necessary to analyze the propagation characteristics of pressure waves in heart, lungs, liver and other important organs and the accelerated motion characteristics of sternum wall, and to study the blunt injury behind bulletproof vests.

In the previous article, taking Scheme C as an example, the data trends of each measuring point were analyzed. Numerically, it is found that the selected measuring point may not be the maximum position, which will put forward higher requirements for the embedding position of the sensor in the actual test.

Statistics are started from the maximum point of different schemes (which are inconsistent with the measured point), and the total kinetic energy data of various organs, thoracic muscle, sternum, soft armor and fragment cloud are obtained from Table 3. As can be seen from the table, the soft body armor absorbed nearly half of the kinetic energy. From a numerical point of view, the energy absorbed by the internal organs due to impact is not large. The thoracic muscle absorbs the most energy, followed by the sternum.

|                | A     | B     | C     |
|----------------|-------|-------|-------|
| Heart          | 0.050 | 0.003 | 0.017 |
| Right lung     | 0.773 | 0.468 | 0.509 |
| Left lung      | 1.190 | 0.557 | 0.683 |
| Liver          | 0.078 | 0.004 | 0.014 |
| Thoracic muscles | 49.822 | 44.821 | 35.828 |
| Sternum        | 1.327 | 1.290 | 1.235 |
| Soft protection| 108.64 | 101.91 | 81.56 |
| KE             | 219.10 | 201.17 | 165.40 |
Figure 15 shows the comparison of the maximum acceleration, maximum pressure and maximum stress of the sternum and thoracic epidermis under the three schemes. The primary energy of A and B is similar, so the numerical difference is not obvious. The energy of scheme A is 32.4% higher than that of scheme C, the energy of scheme B is 21.8% higher. The maximum acceleration, maximum pressure and maximum stress of sternum and thoracic epidermis are not proportional to the initial kinetic energy.

Due to the lack of experimental verification, this paper compares previous studies and obtains simple damage assessment results. Roberts et al. used the HTFEM to calculate the mechanical response of a 9 mm pistol with the velocity of 358 m/s impacting the HTFEM with a soft body armor(Kevlar), and obtained the sternum acceleration 25. 532 $\times$ 103 g and the heart center pressure 780 kPa. The internal pressure on the left side of the liver is 34 kPa, and the internal pressure on the right side is 36 kPa. DONG used a 9 mm pistol and simulated at a speed of 360 m/s. The sternal acceleration is $63 \times 103$ g and the heart pressure is 2.304 MPa. Left liver pressure 1.167 MPa, right 382 kPa, and the sternum is the largest that is 48.527 MPa, the maximum equivalent stress of the heart is 7285.7 Pa, the maximum equivalent stress of the lungs is 3820.9 Pa, and the maximum equivalent stress on the liver is 722.27 Pa.

Tang shot the heart with the same pistol projectile as Dong, and the target speed was 341 m/s (close to the equivalent impact point in this paper). The peak pressure of the heart was 1.20 MPa. The peak value of left lung pressure wave was 0.50 MPa.

The data reported by Dong and Tang are different from those reported by Roberts. This is due to the difference of internal organs pressure measurement points in the Roberts experiment. In addition, the discrepancy between the finite element model of the human body and the material model of bulletproof vest is also an important reason for the difference of human mechanical response. The scheme C with the lowest kinetic energy simulated in this paper is compared with the research results above. The results are shown in Table 4, ignoring the differences between pressure pulse width and occurrence time, only considering the peak value, and making a preliminary comparison. The data is the maximum value of pressure and stress in the simulation, not the data of previous measurement point, and the results are shown in Table 4.

**Table 4. The comparison of the scheme C and previous studies.**

|                | Roberts  | Dong       | Tang       | This paper |
|----------------|----------|------------|------------|------------|
| Form           |          | 9 mm pistol|            | fragments  |
| Mass (g)       | 8        |            |            | 2.079      |
| Velocity (m·s$^{-1}$) | 358     | 360        | 331        | 400        |
| Sternal acceleration (10$^3$g) |      |            |            |            |
|                 | simulation | experiment | simulation | experiment |
|                 | 25.53     | 23.28      | 63         | 86         |
| Heart (kPa)    |          |            |            |            |
|                 | 780       | 381        | 2304       | 2400       |
| Liver (kPa)    |          |            |            |            |
|                 | 36/34     | 15/53      | 1667       | 1500       |
Table 5. The comparison of the scheme C and previous studies (continued).

| Form                  | Dong  | Tang  | This paper |
|-----------------------|-------|-------|------------|
| Mass (g)              | 9 mm  | 8     | 2.079      |
| Velocity (m·s\(^{-1}\)) | 360   | 360   | 400        |
| Mode                  |       |       |            |
| Sternum (MPa)         | 48.527 | 174 | 17.69      |
| Heart (kPa)           | 7.285  | 56   | 11.93      |
| Liver (kPa)           | 0.722  | 3.15 |            |
| Left lung (kPa)       | 3.821  | 231  | 13.36      |
| Right lung (kPa)      | 3.821  | 363  | 134.8      |

In Tang and Dong's research, the pressure data were obtained from experiment, but the simulation analysis was not compared with the experimental pressure data. In addition to the above analysis reasons, the selection of observation points had a great influence on the observation results. From the point of view of pressure, the peak pressure of fragment cloud on the heart can be compared with Dong and Tang, but the stress is greater than that. The thoracic acceleration is consistent with Robert and Dong in the order of magnitude. The liver pressure is comparable to that of Dong. The lung pressure is significantly higher than that of Dong and Tang, which may be caused by different material selection in numerical simulation.

Therefore, from the peak values of heart pressure, lung pressure, and sternum acceleration, the blunt trauma caused by the fragment cloud is equivalent to the speed of a 9 mm pistol bullet at 330–360 m/s. Regarding the finite element model of the human body, due to the lack of direct comparison of living prototypes, and the different mechanical properties of biological tissues, it is still necessary to further improved the FE model based on experimental data.

5. Conclusion

In this paper, the finite element model of the human torso suitable for Chinese people is applied, and the finite element simulation is carried out based on this model, and the after-effect fragments formed by armor-piercing projectiles are taken as the projectile body. The results are compared with the data in similar studies and it is partly comparable in some data. In order to lay the foundation for further establishing the quantity-effect relationship between human mechanics response and biological injury, the simulation results can provide the basis for the study of BABT. The research in this paper can provide a reference for the evaluation of the damage caused by the aftereffect fragments of the armor-piercing projectile and the optimization of the occupant's anti-ballistic measures in light armored vehicles.

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