Numerical Simulation of Human Torso Dynamics under Non-penetrating Ballistic Impact on Soft Armor

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Abstract

The dynamics response of human torso with body armor to non-penetrating ballistic impact is necessary for predicting the injury severity resulting from behind armor blunt trauma and evaluating the effectiveness of personal protection equipment against ballistic impact. This investigation developed a computational model for non-penetrating ballistic impact on human torso with soft armor by combining the three-dimensional finite element models of human torso, soft armor and pistol bullet. The loading and solution were conducted using the finite element software Ls-Dyna. The stress field distribution in the armor and the stress responses in the skin, skeleton and organs to non-penetrating ballistic impact were obtained after numerical calculation. The simulation results of human torso dynamics corresponded well with the biological injuries resulting from non-penetrating ballistic impact.

Keywords: Human Torso, Dynamics, Non-penetrating Ballistic Impact, Finite Element Model, Numerical Simulation

1. Introduction

Projectile is one of the lethal threats that the soldiers or policemen have to face in regional and local wars or anti-terrorist activities. The body armor can effectively prevent the penetration of ballistic projectiles. However, the non-penetrating ballistic impact at high velocity result in intense acceleration and overpressure wave, which do harm to human body to a certain degree. Some researches show that the injury severity of behind armor blunt trauma (BABT) depend on the propagation of stress wave and the body response at the time when projectile impacts the armor [1]. So far, the mechanical response and injury mechanism of human organ remain the major challenge for the studies on behind armor blunt injury. Compared to the tests on animals or human cadavers, the finite element method is characterized with good repeatability, high efficiency and other features. Thus, it is widely applied in the analysis of dynamic response of human body to mechanical loading.

Cooper and Taylor [2] have done some experiments on blunt trauma caused by projectile. When a projectile with weight of 140 g and diameter of 3.7 cm impacted the chest of pig at velocities of 30-64 m/s, a high-speed camera was used to measure the displacement and the compression velocity of chest wall. According to the test results, Cooper suggested that impact of a light projectile at velocity over 30 m/s may result in short duration and slight offset of the chest. Under this condition, the stress wave plays a leading role in injury mechanism, for example, the wave can cause injury at the interface between the air and tissue for lung, stomach and intestine. Roberts [3] have carried out a comparative study on a finite element model of human body protected by different armors and a physical human torso model by using a 7.62 mm bullet to shoot at the armors. When the impact point was at the sternum, the peak overpressure in the heart is 0.85 Mpa, which is higher than that in other organs under the same condition. The results demonstrated that the differences between overpressure values of two models is within 10% under the same impact condition. Shen [4] used a combined experimental and modeling method to characterize the interaction among bullet, body armor, and human surrogate targets. The results exhibited three distinct loading phases during the interaction. In the first phase, the bullet was significantly slowed as it transferred a major portion of its energy.
into the body armor. In the second phase, the armor were pulled toward the point of impact and kept on absorbing energy until energy absorption reached its peak. In the third phase, the deformation on the armor’s back face continued to grow and energies inside both armor and targets redistributed through wave propagation.

The previous studies mainly focused on the injury characteristics of blunt trauma by means of animal tests. However, the mechanical mechanism of behind armor blunt trauma has been poorly elucidated. Therefore, the aim of this study was to develop a computational finite element model for non-penetrating ballistic impact on human torso with body armor and conduct numerical simulation for the whole process in which a pistol bullet penetrates the armor. As a result, the stress field distribution in the armor and the stress responses of the skin, skeleton and organs to non-penetrating ballistic impact were obtained from the numerical calculation.

2. Principles and methods

2.1. Development of the finite element models

2.1.1. Human torso finite element model

The CT scanning of human torso is carried out using a healthy adult male (height 170 cm, weight 65 kg and age 35), with a scanning interval of 0.625 mm. Resolution of gray image is 512×512×8 bit. Then the raw data of human torso is imported into the Mimics software for three-dimensional reconstruction of geometric model of human torso. The model includes skin/muscle, internal organs (heart, lungs, liver, stomach) and thoracic skeleton (sternum, ribs, spine).

Afterwards, the geometric model in stl format generated by Mimics is imported into Hypermesh software. Geometric processing and simplification are conducted for three-dimensional meshing of all tissues [5][6]. Consequently, the human torso finite element model consisting of 685,362 tetrahedral elements is developed as shown in Figure1(a) and (b).

![Finite element model of human torso with soft body armor](a)

![Internal organs in the finite element model of human torso](b)

**Figure 1. Human torso finite element model**

2.1.2. Pistol bullet finite element model

The geometric model of 9 mm pistol bullet consisting of steel jacket and lead core is created in Solidworks soft with format of IGES. The model is imported into Hypermesh software for geometric pre-processing and meshing. The steel jacket and lead core of the model have 3,108 and 12,628 hexahedron elements respectively.
2.1.3. Armor finite element model

The soft body armor is made of high molecular weight polyethylene with a thickness of 9.2 mm and a total of 46 layers. Each layer is meshed with Belytschko-Tsay thin-shell elements, as shown in Figure 1(a). There is 150,144 units for the total 46 layers. The dense and homogeneous meshes are applied in the target region which is five times the size of the bullet head, while the converged mapping meshes are used in the rest regions. However, such division contributes to a reduction in the mesh amount and calculation time without loss of the calculation accuracy [7][8].

2.2. Material models

2.2.1. Material model for human body

The material property is a key factor for finite element analysis and calculation. In this paper, the material models and parameters of human torso finite element model are defined by reference to the relevant studies on the material characteristics of human tissues. The material model of MAT_ELASTIC is applied for skeleton of human torso. This simplified model ignores the heat effect and the state equation is not required for description. The skin, muscle, and internal organs are set as viscoelastic materials. The linear viscoelastic material model MAT_VISCOELASTIC put forward by Herrmann and Peterson [9] is applied for viscoelastic materials in LS-DYNA. Accordingly, the stress variables apply linear viscoelasticity assumption, which can be seen in equation (1).

$$\sigma_y = 2 \int_0^\infty \phi(t-\tau) \left( \frac{\partial \varepsilon(t)}{\partial \tau} \right) d\tau$$  \hspace{1cm} (1)

Where, shear relaxation modulus can be seen in equation (2).

$$\phi(t) = G_\omega + (G_0 - G_\omega) e^{-\beta t}$$  \hspace{1cm} (2)

In the model, the elastic bulk modulus $K$ and volume $V$ are used to calculate pressure $P$, as shown in equation (3).

$$P = K \ln V$$  \hspace{1cm} (3)

Based on the elastic modulus and tangent modulus, plastic hardening modulus $E_h$ can be calculated, as shown in equation (4).

$$E_h = \frac{E_i E}{E - E_i}$$  \hspace{1cm} (4)

For linear distribution of internal energy for state equation, the pressure $P$ is denoted in equation (5).

$$P = C_0 + C_1 \cdot \mu + C_2 \cdot \mu^2 + C_3 \cdot \mu^3 \text{, and } \mu = \rho / \rho_0$$  \hspace{1cm} (5)

In the above equation, $C_0$, $C_i$, $C_j$ and $C_3$ are material constants and $C_0$ is set as zero. $\rho$ and $\rho_0$ are current density and initial density, respectively. The material characteristic parameters of internal organs are obtained from Saraf’s test [10] which was carried out at a strain rate of 1500 1/s by using a improved split Hopkinson bar. The elastic material parameters of sternum and rib are determined by reference to Caruso’s data [11].
The material property of spine is determined by mean of the tests carried out by Wang [12] and Duck [13].

**2.2.2. Material models for bullet and armor**

The elastoplastic material mode MAT_JOHNSON_COOK 1 is applies for the pistol bullet under state equation of GRUNEISEN. Describing constitutive models for materials under large deformation, high strain rate and high temperature, Johnson-Cook material model is applicable to many types of materials. The model is still equivalent under lower strain rate and even within quasi-static scope. The typical application of this model includes explosion forming of metal, ballistic penetration and impact.

Through analysis on the structure of armor, it can be seen that this soft armor belongs to laminated structure with layers bonding together. Thus, the composite material model with damage is applied for the armor. The destruction intensity of composite material mainly depend on the inherent material property and the stress and strain state under loading. In this study, chang-chang principle [14] is used as failure criterion for composite material.

**2.3. Contact type**

The contact of bullet and armor is set to be surface-to-surface erosion contact. The automatic single surface contact is assigned to any two neighboring layers of the armor. The contact between the armor and human torso is defined as surface-to-surface contact type. The contact of organs and skeletons are constrained to be automatic single surface contacts. The boundary condition is to constraint the degree of freedom for human torso model in vertical direction.

**2.4. Calculation model**

The finite element models of pistol bullet and armor are assembled to the human torso finite element model. The pistol bullet is used to shoot at the armor with a horizontal velocity of 360 m/s, aiming at the middle part of sternum. The complete computational finite element model developed in Hypermesh is exported as K file and then imported into LS-DYNA for numerical solution. The time step for calculation is 0.6 us. After calculations, analysis is conducted on the results.

**3. Results and analysis**

**3.1. The equivalent stress field in the armor**

When t=4 us (Figure 2(a)), the moment pistol bullet impacting the armor), it presents a circular equivalent stress field with diameter slightly higher than that of pistol bullet. After the pistol bullet begins to penetrate the armor, the equivalent stress becomes larger and the equivalent stress field tends to diffuse in the pattern of circle. In this way, the diameter of equivalent stress field increases gradually. When t=88 us (Figure 2(b)), the diameter of equivalent stress circle is about 9.5 cm with sectional area of about 283.39 cm². When penetration time is long enough and t>104 us, the stress reduces and disappears gradually.
3.2. The equivalent stress field in the skin

When \( t=8 \) us (Figure 3(a)), obvious variation happens to the equivalent stress in the skin, the time of which is later than that of occurrence of equivalent stress when \( t=4 \) us. The reason is that it takes some time for the equivalent stress generated by the impact of pistol bullet on the armor to transfer to the skin. It can be seen that the equivalent stress on the skin is the largest at the center of impacted area. With the lapse of time, the equivalent stress field extends and the value of equivalent stress at the center part firstly increase and then reduce. When \( t=88 \) us (Figure 3(b)), the diameter of circular area for high equivalent stress in skin is 5.8 cm, which is less than 9.5 cm, the diameter of equivalent stress circle in the armor. It shows that under the condition of \( t \leq 88 \) us, the armor plays a protective role by absorbing a great amount of energy generated from the impact of the pistol bullet.

3.3. The equivalent stress field in the skeleton

When \( t=8 \) us (Figure 4(a)), the equivalent stress occurs in the sternum. Since sternum is stiff, the stress field begins to diffuse and weaken. The high equivalent stress concentrates mainly on the sternum and extends outward with the lapse of time. When \( t=88 \) us (Figure 4(b)), the equivalent stress field diffuse throughout the sternum. With the finish of penetration process, the equivalent stress gradually reduces. When \( t=120 \) us, the equivalent stress completes the first cycle of propagation.
3.4. The equivalent stress field in the major organs

When $t=16$ us (Figure 5(a)), the stress variation happens to the heart, the time of which is later than that of initial equivalent stress variation in the skin and skeleton at $t=4$ us and $t=8$ us respectively. It shows that with the lapse of time, the energy converts to the form of equivalent stress and transfers into the internal location of human torso. In the earlier stage, it mainly diffuse in heart area which aligns with the impact point on the armor. When $t=88$ us (Figure 5(b)), the equivalent stress reaches the lung. When $t=156$ us, the equivalent stress finishes a cycle of propagation.

As shown in Figure 6 and 7, the equivalent stress value on the measuring position of each organ increases gradually with the lapse of time. Within the duration of 50 us to 500 us, a slight variation happens to the equivalent stress values for measuring positions of liver and stomach. At the same time, the equivalent stress value for heart is the maximum, followed by the values of lung, liver and stomach. It can be seen that the equivalent stress in various organs diminishes as the distance from the impact point increases, whereas the equivalent stress increases with the lapse of time. The maximum equivalent stress appears during the period from 430 us to 500 us. The maximum equivalent stress values are 7285 pa, 3820 pa, 722 pa and 777 pa respectively at the measuring positions of the heart, lung, liver and stomach.
3.5. The peak overpressure in the major organs

As shown in Figure 8, the overpressure at the measuring position of the heart firstly reaches its peak value at $t=120$ us, followed by that of lung at $t=124$ us, liver at $t=188$ us and stomach at $t=196$ us. The peak overpressure in the heart is 4.02 Mpa, which is greater than those of 1.251 Mpa, 1.096 Mpa and 0.597 Mpa respectively in the lung, liver and stomach. Thus, the time for organs to reach its peak overpressure and the amplitude of the peak overpressure depend on the distance between the measuring position and the impact point. The closer the measuring position is to the impact point, the earlier the peak overpressure occurs with larger amplitude.

4. Conclusions

When a pistol bullet impacted a human torso with body armor, the stress wave transferred to the body through the armor. The stress wave propagated from the impact point to the heart, lung, liver and stomach, resulting in damages to the tissues and organs.

Despite the disparities in the material models and the mesh amount of finite element models for the human body, the armor and pistol bullet, our study was comparable to the previous investigations. As reported by Robert’s tests, the impact of a 9 mm pistol bullet at a velocity of
358 m/s produced a peak overpressure of 0.78 MPa in the heart. The calculated value of the peak overpressure under similar impact condition was 2.723 MPa in our study. The differences of the finite element model and calculation condition may contributed to the discrepancy of the overpressure. According to the criterion suggested by Greer [15], the threshold of overpressure for lung injury was 240 kPa. In our study, the simulated values of peak overpressure in the left and right lung were 571 kPa and 583 kPa, respectively. Therefore, it can be predicted that the impact of a 9 mm pistol bullet on the armor still resulted in lung injury. The experimental studies of behind armor bunt trauma targeting animals exhibited extensive cardiopulmonary injuries, such as diffuse lung hemorrhage and epicardium hemorrhage. However, the simulated result corresponded well to the experimental evidences.

The computational finite element model for non-penetrating ballistic impact on human torso with body armor developed in this paper is available for the prediction of injury severity resulting from behind armor blunt trauma, as well as the evaluation and improvement of the effectiveness of personal protection equipment.

5. References