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The experimental and numerical investigation of pistol bullet penetrating soft tissue simulant

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ABSTRACT

Gelatin, a representative simulant for soft tissue of the human body, was used to study the effects of 9 mm pistol bullet's penetration. The behavior of a bullet penetrating gelatin was quantified by the temporary cavity sizes in ballistic gelatin and the pressure values of bullet's impact. A numerical simulation model of a bullet penetrating the soft tissue simulant gelatin was built using the finite element method (FEM). The model was validated by the comparison between the numerical results and the experimental results. During a bullet penetrating ballistic gelatin, four stages were clearly observed in both the experiment and the numerical simulation: a smooth attenuation stage, a rolling stage, a full penetration stage, and a stage of expansion and contraction. The cavity evolution, equivalent stress field and the strain field in gelatin were analyzed by numerical simulation. Moreover, the effects of the bullet's impact velocities and angles of incidence on the temporary cavity in gelatin, its velocity attenuation, and its rolling angle were investigated, as well as the bullet's resistance and energy variation. The physical process and the interactive mechanism during a pistol bullet penetrating gelatin were comprehensively revealed. This may be significant for research in wound ballistics.

1. Introduction

Research on movement, energy absorption, wounding effects and acting mechanisms of a projectile such as a bullet or fragment after it enters the body of an organism provides very helpful information for forensic investigation and wound treatment. Such research has drawn wide attention in both the engineering and academic fields. Gelatin, with material and mechanical properties similar to that of human soft tissue such as muscle, has often been used widely to simulate human soft tissue in bullet's impact simulations in order to understand the acting mechanism between bullet and bionic material.

Research on a bullet penetrating gelatin has been primarily performed through experiments. Through these experiments, the temporary cavity effect and pressure wave effect during penetration was determined, and the values of the maximum temporary cavity and pressure were measured. The NATO standardized cylindrical Fragment Simulating Projectiles (FSPs) with different weights were fired at a range of velocities into four body areas of six pig cadavers as well as into 20% gelatin [1]. With a set of high speed movies and photographs, the expanding law was plotted to correlate the deceleration to the state of expansion and the size of the temporary cavity for different gelatin weight ratios and different gelatin block lengths [2], and the mechanical properties of tissue simulants were investigated [3,4]. Plate-impact experiments were employed to investigate the dynamic response of three readily available tissue simulants used for ballistic purposes: gelatin, ballistic soap and lard [5]. The Split Hopkinson Pressure Bar (SHPB) experimental method was adopted to study the stress–strain response of gelatin at different strain rates [6,7]. The correlation between the destruction in gelatin and the bullet's energy dissipation was analyzed with consecutive slices and scanning [8]. Those studies provided necessary material data support for further research.

In recent years, numerical computation has been applied to research on bullets penetrating a soft tissue simulant target. A 7.62 NATO bullet rolling in soap at high speed was simulated with Autodyn-3D software, and the numerical results were almost identical with the theoretical analysis [9]. The process of a bullet penetrating cuboid gelatin was simulated with

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LS-DYNA, and its effect was analyzed using a constitutive model of a different material [10]. The experimental method combined with numerical simulation was selected to analyze the process of a steel ball impacting gelatin at low speed [11,12]. Steel spheres at different velocities were used to investigate the penetration of a projectile into a surrogate human tissue numerically with Finite Element (FE) simulation [13]. In addition, the bullet's state of movement and the formation of a wound track was deduced theoretically, and certain factors (e.g. shape, construction and stability) influenced greatly the rate of energy transfer to the tissue along the wound track were analyzed [14].

At present, the study of the terminal effect of a bullet penetrating a soft tissue simulant is still in its infancy. The evolution of the gelatin temporary cavity, or the relationship between the bullet's energy loss and the velocity variation in gelatin, or the stress and strain field in a bullet penetrating soft tissue have not been studied, nor has the effect of the projection parameters on the penetration process. In this paper, the physical process and the mechanism of a bullet penetrating gelatin bionic material are more comprehensively revealed based on both the numerical and experimental study.

2. Material and methods

2.1. Material model of gelatin

As a kind of typical viscoelastic material, gelatin possesses both some properties of elastic solids and performance of viscous fluids. Such remarkable time-related mechanical properties like creep and stress relaxation phenomena are found in gelatin. When penetrated at high speed, gelatin is similar to a rubber material, with rapid cavity expansion and contraction. It has been found that a final crack is formed after oscillation. The material property of fluid elastic-plasticity of gelatin can be described with the material model of MAT_ELASTIC_PLASTIC_HYDRO in LS-DYNA [15], or with the bilinear stress–strain curve if the effective plasticity stress–strain data is not defined. Elastic modulus E represents the slope of the elastic section; yield stress σ_y represents the inflexion of material entering the plastic section. The stress–strain curve at the plastic section is simplified to a straight line with a slope equal to tangent modulus E_t. When the material is subjected to reverse load, the isotropic hardening model ($\beta = 1$) should be employed, and yield strength is computed with the following formula (based on isotropic hardening) [15]:

$$\sigma_y = \sigma_0 + E_h \cdot \bar{\epsilon}^p + (a_1 + Pa_2)\max[P, 0] \tag{1}$$

where σ_0 is initial yield stress; $\bar{\epsilon}^p$ the effective plastic strain; E_h the plastic hardening modulus, $E_h = E_t E/(E - E_t)$; and P is the pressure taken as positive in compression.

The pressure–volume relationship of gelatin under relatively high pressure should be defined with an equation of state. The internal energy in gelatin equation of state shows itself in linear distribution, and the pressure calculation formula is as following [15]:

$$P = C_0 + C_1 \cdot \mu + C_2 \cdot \mu^2 + C_3 \cdot \mu^3 \tag{2}$$

where $\mu = \rho/\rho_0 - 1$ (ρ and ρ_0 represent temporary and initial density respectively), and C_0, C_1, C_2, C_3 are material constants in Table 1.

2.2. Material model of the pistol bullet

The elastic–plastic material model MAT_JOHNSON_COOK governed by the GRUNEISEN equation of state is applied to simulate the jacket and the lead in the bullet. The flow stress is formulated as [15–17]:

Table 1
Values of material constants C_i ($i = 0, 1, 2, 3$).

Parameter	C_0	C_1	C_2	C_3
Value (GPa)	0	2.38	7.14	11.9

$$\sigma_y = (A + B(\bar{\epsilon}^p)^n) \cdot (1 + C\ln\dot{\epsilon}^*) \cdot (1 - (T^*)^m) \tag{3}$$

where A, B, C, m and n represent input constants; $\dot{\epsilon}^*$ represents effective plastic strain rate. Where $\epsilon^* = \bar{\epsilon}^p/\epsilon_0$ when $\varepsilon_0 = 1\ \mathrm{s}^{-1}$; $T^* = (T - T_{room})/(T_{melt} - T_{room})$; represents homologous temperature (where T_{melt} represents melting temperature and T_{room} represents room temperature).

When the plastic strain value reaches fracture strain value, the material will be damaged. The fracture strain is formulated as follows [15–17]:

$$\epsilon^f = [D_1 + D_2 \exp D_3 \sigma^*][1 + D_4 \ln\dot{\epsilon}^*][1 + D_5 T^*] \tag{4}$$

where $\sigma^* = P/\sigma_{eff}$, ($\sigma_{eff}$ represents effective stress), $D = \sum \frac{\Delta \bar{\epsilon}^p}{\epsilon^f}$. When the damage parameter D is equal to 1, the fracture happens.

The GRUNEISEN equation of state defines the pressure–volume relationship through three impact velocities–particle velocities ($\nu_s - \nu_p$). The pressure of compressed material is formulated as following [15,18,19]:

$$P = \frac{\rho_0 C^2 \mu \left[1 + (1 - \frac{\gamma_0}{2})\mu - \frac{a}{2}\mu^2\right]}{\left[1 - (S_1 - 1)\mu - S_2 \frac{\mu^2}{\mu+1} - S_3 \frac{\mu^3}{(\mu+1)^2}\right]^2} + (\gamma_0 + a\mu)E \tag{5}$$

The pressure of expandable material is formulated as following [15]:

$$P = \rho_0 C^{2\mu} + (\gamma_0 + a\mu)E \tag{6}$$

where C represents the intercept of the $\nu_s - \nu_p$ curve; S_1, S_2 and S_3 represent the slope coefficient of the $\nu_s - \nu_p$ curve; γ_0 represents the GRUNEISEN gamma; α represents the first-order volume correction of γ_0 (Table 2).

2.3. 3D model and meshing of bullet and gelatin

In finite element modeling, a scale of 1:1 is adopted for each part. A 9 mm × 19 mm Parabellum bullet (hollow point, copper-alloy, 7.45 g) is taken and the size of gelatin block is 240 mm × 200 mm × 340 mm. A right-handed Cartesian coordinate system is set with x and y axes in the incidence surface (240 mm × 200 mm) of the gelatin, the original point is located at the surface, and z axis coincident with the direction of the bullet's flight (340 mm).

The SOLID164 element is adopted to mesh the model. The model of the bullet was shown with 3692 elements, and the model of the gelatin was represented by 1,267,200 elements with free boundary conditions.

2.4. Experiment set-up

Gelatin is selected as a muscle simulant, with 10% formulation, the same amount as that in the simulation. A 9 mm ballistic gun (made by CJYM, China, barrel 180 mm, 6 right-hand rifling) and 9 mm Parabellum bullets (produced by Dynamit-Nobel AG, DE in Germany, hollow point, copper-alloy, 7.45 g) were used in the penetration experiment. The distance from muzzle to gelatin is 15 m. The bullet's flight is along positive Z direction. The comprehensive testing system is built according to the main testing physical parameters (speed of projectile before/after