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Research Paper

Viscoelastic shock wave in ballistic gelatin behind soft body armor

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ABSTRACT

Ballistic gelatins are widely used as a surrogate of biological tissue in blunt trauma tests. Non-penetration impact tests of handgun bullets on the 10 wt% ballistic gelatin block behind soft armor were carried out in which a high-speed camera recorded the crater's movement and pressure sensors imbedded in the gelatin block recorded the pressure waves at different locations. The observed shock wave attenuation indicates the necessity of considering the gelatin's viscoelasticity. A three-element viscoelastic constitutive model was adopted, in which the relevant parameters were obtained via fitting the damping free oscillations at the beginning of the creep-mode of rheological measurement, and by examining the data of published split Hopkinson pressure bar (SHPB) experiments. The viscoelastic model is determined by a retardation time of 5.5×10^{-5} s for high oscillation frequencies and a stress relaxation time of $2.0\text{–}4.5\times10^{-7}$ s for shock wave attenuation. Using the characteristic-line method and the spherical wave assumption, the propagation of impact pressure wave front and the subsequent unloading profile can be simulated using the experimental velocity boundary condition. The established viscoelastic model considerably improves the prediction of shock wave attenuation in the ballistic gelatin.

1. Introduction

The Behind Armor Blunt Trauma (BABT) has received considerable researches in the field of biomechanics (Roberts and Biermann et al., 2005; Roberts and Merkle et al., 2007) and the pressure wave induced by non-penetration impacts is acknowledged as one of the most important factors that cause blunt trauma (Stuhmiller and Ho et al., 1996; Long and Bentley et al., 2009; Grujicic and Bell et al., 2010; Chavko and Watanabe et al., 2011). Non-penetration pressure waves are usually produced by impacts of bullets on body armor generating high-speed movement and deformation of the armor and inducing short-duration stress wave in biologic targets. For hard armors, the so-called two-strike ("twin peak") phenomenon was observed in experiments (van Bree and Fairlie, 1999; Cronin and Worswick et al., 2001) and it attracted endeavors of numerical simulation exploring its mechanism (Cronin and Worswick et al., 2001; Grimal and Gama et al., 2004). It is generally accepted that the second pressure peak is due to the relatively large deformation of the armor at the later stage of impact. It should be pointed out that the time-profile of a pressure wave behind the pressure

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front is complicated by various reflection waves from the free and rigid boundaries of the gelatin block. Also from the viewpoint of momentum transfer, if the sound resistance (ρC, the density multiplied by the speed of sound) of a bullet is considerably larger than that of the armor, there will be an instant of contact lost between the bullet and armor, and a second or even third impact is possible (Wang, 2007, Cronin and Worswick et al., 2001). The difficulty in full numerical simulation lies in the lack of reliable rate-sensitive constitutive equations for the target (biological tissues or gelatin) and the armor (usually a composite consisting of ceramics and layered polymeric fabrics), as well as of appropriate boundary conditions. In the experiments of Bax (2001), the target material was silicon gel and the body armor was made of ceramic-composite; numerical simulations were carried out with properly defined boundary conditions on the front side of the target, and the silicon gel was modeled as a simple elastic material. Comparison of the experimental and numerical results shows that the trajectory attenuation of the pressure wave front in the experiments is considerably larger than that in the numerical simulations and the disagreement was attributed by the author to the actual viscoelastic behavior of silicon gel. Bree and Fairlie's (1999) experiments consisted of a ballistic gelatin block protected by a thin or thick aluminum plate, and the other sides were restricted by glass plates; a high-speed camera caught an approximately semi-spherical crater that appeared at the front of the gelatin block just behind the point of impact, increasing to a maximum size and then shrinking. Bree and Fairlie also carried out corresponding numerical simulations in which the bullet, aluminum armor and glass side-wall were modeled with appropriate constitutive equations from the database of DYNA and allowed to interact with the gelatin block. They found that with fixed failure models of the boundary materials, modeling the gelatin as a liquid, or a perfectly elastic solid or an elastic–plastic solid did not significantly affect the calculated pressure history, which was rather poor in comparison with the experiment due to the lack of an appropriate constitutive model and parameters for ballistic gelatin, according to the authors.

The present study focuses on establishing an appropriate viscoelastic model for ballistic gelatin to describe the shock wave attenuation of blunt impact behind soft armor. The schematic diagram of our impact experiment is shown in Fig. 1. Five pressure sensors were implanted in a gelatin block to measure pressure profiles at different positions; meanwhile a high-speed camera recorded the deformation of the target front face. The pressure profile measured was a discontinuous uploading to a peak value, followed by a rapid unloading for several hundreds of microseconds. Considerable attenuations of the pressure-wave front with its travel distance were observed and we aim to study the mechanism of attenuation. Non-penetrating impact generates highly localized dynamic loading on biological targets protected by soft armors. In our experiment approximate semi-spherical craters were observed on the front face of the gelatin block, so the pressure wave may be treated as semi-spherical. It is well known that in an elastic medium a spherical wave front will attenuate inversely with its travel distance, which is sometimes called "geometrical attenuation". Polymer materials like ballistic gelatin and silicone gel are known to be quite rate-sensitive (Ottone and Deiber, 2005; Ottone and Peirotti et al., 2005), that is, they are viscoelastic. It is anticipated that shock waves transmitted in polymer medium will also be attenuated by stress relaxation. Since the sizes of gelatin blocks in impact experiments are limited, waves reflected from various boundaries make the analysis of the time-profile of pressure wave a formidable task. But if we consider the wave front attenuation, the frontal travel distance is the shortest among various incident–reflected waves, that is, the shock wave front will not be affected by any wave reflections.

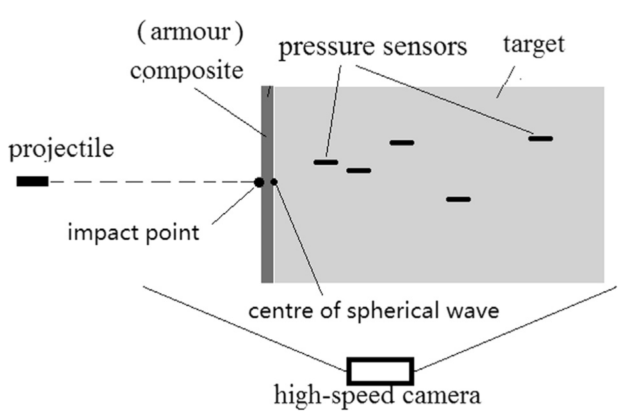

Fig. 1 – Schematic of blunt impact experiments.

In Section 2, a three-element viscoelastic model is established for 10 wt% ballistic gelatin, based on rheological measurement and the published split Hopkinson pressure bar (SHPB) experiments. In Section 3 the solution of spherical shock wave propagating in the viscoelastic medium is presented using the characteristic-line method. Section 4 details the results of our non-penetrating experiments and the comparisons with the predictions of the spherical viscoelastic shock wave model. The conclusions and discussions are given in Section 5.

2. Viscoelastic model for ballistic gelatin

10 wt% ballistic gelatin is generally accepted as a muscle surrogate. In the literature, viscoelastic behavior of ballistic gelatins has been investigated by a number of experiments including uniaxial compression and extension, shearing and the split Hopkinson pressure bar (SHPB) with high strain-rates (Normand and Muller et al., 2000; Ottone and Peirotti et al., 2005; Salisbury and Cronin, 2009; Cronin and Falzon, 2011; Moy and Foster et al., 2011; Subhash and Kwon et al., 2012). What happens in shock wave propagation is small strain and high frequency deformation; thus establishing a linear viscoelastic model is adequate.

The rotational rheometer Gemini 200 (Bolin) was used by us to study the dynamic behavior of gelatin. With the standard forced small-stain oscillation experiment one can obtain the elastic modulus G' and loss modulus G'' as the functions of frequency. However, the measurement is reliable only in relatively low frequencies. We adopted the creep-ringing method, that is, to utilize the coupling of the instrument's inertia and the specimen's viscoelasticity to obtain