Available online at www.sciencedirect.com

ScienceDirect

www.elsevier.com/locate/jmbbm

Research Paper

Analysis of behind the armor ballistic trauma

Yaoke Wen[a,*], *Cheng Xu*[a], *Shu Wang*[b], R.C. Batra[c]

[a]School of Mechanical Engineering, Nanjing University of Science and Technology, Nanjing 210094, China
[b]No. 208 Research Institute of China Ordnance Industries, Beijing 102202, China
[c]Department of Biomedical Engineering and Mechanics, Virginia Polytechnic Institute and State University, M/C 0219, Blacksburg, VA 24061, USA

ARTICLE INFO

Article history:
Received 2 September 2014
Received in revised form
6 January 2015
Accepted 12 January 2015
Available online 21 January 2015

Keywords:
Behind armor blunt trauma
Body armor
Ballistic gelatin
Ultrahigh molecular weight polyethylene (UHMWPE) composite

ABSTRACT

The impact response of body armor composed of a ceramic plate with an ultrahigh molecular weight polyethylene (UHMWPE) fiber-reinforced composite and layers of UHMWPE fibers shielding a block of ballistic gelatin has been experimentally and numerically analyzed. It is a surrogate model for studying injuries to human torso caused by a bullet striking body protection armor placed on a person. Photographs taken with a high speed camera are used to determine deformations of the armor and the gelatin. The maximum depth of the temporary cavity formed in the ballistic gelatin and the peak pressure 40 mm behind the center of the gelatin front face contacting the armor are found to be, respectively, ~34 mm and ~15 MPa. The Johnson–Holmquist material model has been used to simulate deformations and failure of the ceramic. The UHMWPE fiber–reinforced composite and the UHMWPE fiber layers are modeled as linear elastic orthotropic materials. The gelatin is modeled as a strain-rate dependent hyperelastic material. Values of material parameters are taken from the open literature. The computed evolution of the temporary cavity formed in the gelatin is found to qualitatively agree with that seen in experiments. Furthermore, the computed time histories of the average pressure at four points in the gelatin agree with the corresponding experimentally measured ones. The maximum pressure at a point and the depth of the temporary cavity formed in the gelatin can be taken as measures of the severity of the bodily injury caused by the impact; e.g. see the United States National Institute of Justice standard 0101.06-Ballistic Resistance of Body Armor.

1. Introduction

Behind armor blunt trauma (BABT) may occur when personal protective armor deforms dynamically to stop an incoming projectile. The impact by a fragment simulating projectile (FGP) causes local high rate loading of the thorax and subsequent trauma to the thoracic cage and internal organs (Cannon, 2001; Cannon and Tam, 2001). The relationships between injury mechanisms and human torso response to BABT are not well understood at present. For obvious reasons, effects of BABT on a

*Corresponding author. Tel.: +86 25 84315419; fax: +86 25 84303132.
E-mail address: wenyk2011@163.com (Y. Wen).

http://dx.doi.org/10.1016/j.jmbbm.2015.01.010
1751-6161/

human body cannot be experimentally studied and must be determined via proxies, the most common of which is ballistic gelatin because it's mechanical properties are believed to be close to those of a human tissue (Payne et al., 2013). Thus the response of ballistic gelatin to impact loading provides a good approximation of that of a human tissue.

The "rigid body armor" consisting of a ceramic plate facing the incoming projectile and a fiber–reinforced composite (FRC) backing is used to stop the projectile and protect a human torso. Generally, soft body armor is placed behind the FRC laminate to absorb the residual energy of the bullet and the fragments. A fiber of choice for the FRC and the soft body armor is the ultrahigh molecular weight polyethylene (UHMWPE) because of its high specific strength and modulus. Different experimental configurations including the punch-shear test can be used to find quasistatic tensile, compressive, inter-laminar shear and in-plane shear strengths of the UHMWPE FRC (Marissen et al., 2005; Umberger, 2010; Iannucci and Pope, 2011; Heru Utomo, 2011; Wen et al., 2013). However, there are very few results (Koh et al., 2010; Chocron et al., 1997) available in the open literature for dynamic loading of the composite and the BABT.

Numerical simulations provide details of deformations induced by ballistic impact (Gower et al., 2008). Using material parameters of Dyneema HB25 composite derived from their test data, Ong et al. (2011) have numerically studied the response of the composite to ballistic loading. Grujicic et al. (2008, 2009) have used the finite element method (FEM) to analyze deformations of a representative volume element and deduce material parameters of an UHMWPE FRC. Bürger et al. (2012) have developed a strain rate dependent constitutive relation for an UHMWPE FRC and implemented it in ABAQUS via a user defined subroutine, whereas the predicted energy absorbed during impact without considering delamination failure agreed well with the experimental value, the two values of the residual deformations were not close to each other. In the numerical study of Krishnan et al. (2010) the computed damage induced in a ceramic armor impacted by a M2AP bullet was found to agree well with that observed experimentally, however, the back face deformations were under-predicted.

A limited set of experimental investigations have been undertaken to provide insights into the BABT (Liu et al., 2012; Prat et al., 2012). van Bree and Fairlie (1999); van Bree and Gotts (2000) have studied the propagation of a compression wave in ballistic gelatin shielded by aluminum plates. They employed a "Twin Peak" theory and modeled 20% ballistic gelatin as a compressible elastic–plastic material. Cronin et al. (2001) used the Mooney-Rivlin material model for the gelatin to simulate the Twin Peak phenomenon in it, and subsequently analyzed the dynamic response of a surrogate torso covered by a Kevlar plate. Grimal et al. (2004) simplified the problem by assuming the thorax material to be linearly elastic, and approximated the impact load by a time-dependent pressure field of duration equal to that of the first pressure wave observed behind a ceramic armor impacted by a high-velocity projectile. Roberts et al. (2005, 2007) have developed a physical and a numerical model for a human surrogate torso with the tissue considered as a viscoelastic material. The study of the BABT is challenging due to geometric complexities and nonlinearities in the material response.

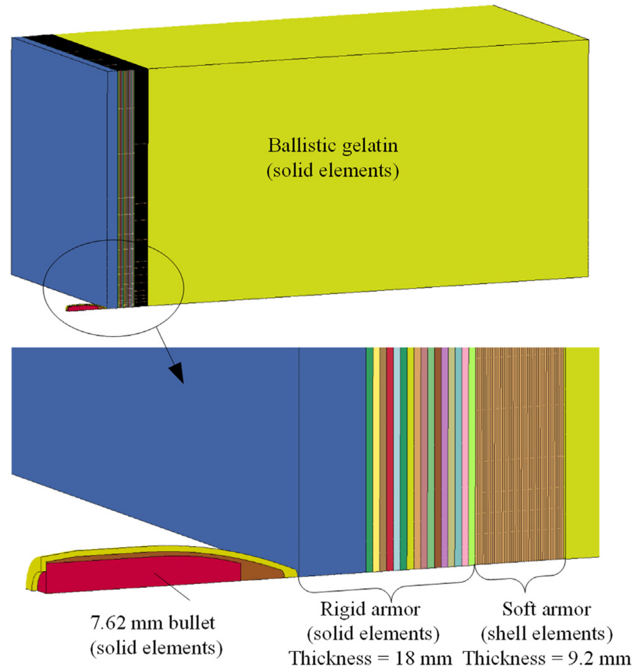

Fig. 1 – Schematic sketch of the system used for studying the BABT (sketch not to scale).

In this paper, transient deformations of the system shown in Fig. 1 have been experimentally and computationally analyzed to shed some light on the BABT. Experimental results for impact loading of the armor covered ballistic gelatin impacted by a 7.62 mm bullet are first presented. Subsequently, numerical results obtained by using the FEM and the commercial software, LS-DYNA, are compared with the corresponding experimental findings. Details of deformations during tests are captured using the high-speed photography. The maximum depth and diameter of the temporary cavity formed in the gelatin are found to equal, respectively, ~34 mm and 110 mm. The maximum pressure at a point 40 mm away from the gelatin surface contacing the protective armor equals ~15 MPa. The computed time histories of the pressure and the cavity dimensions are found to be close to the corresponding test values.

2. Experimental work

The rigid body armor studied here and schematically exhibited in Fig. 1 consists of 7 mm thick 99.5% Al_2O_3 ceramic tiles with 11 mm thick UHMWPE fiber–reinforced laminate backing. The combined thickness of the adhesive bonding the ceramic plate with the UHMWPE laminate and of the cover cloth equals 2 mm, and neither one is included in the sketch of Fig. 1. The armor shielding the 30 cm × 30 cm × 30 cm block of gelatin (10% mass fraction at 4 °C) resting on a table (e.g., see Fig. 2) was impacted by a 7.62 mm diameter bullet whose geometry and materials are given in Section 3. The gelatin was prepared by following the procedure proposed by Jussila (2004). The ceramic tiles either stop or slow down the bullet, and the UHMWPE soft body armor sheets placed behind the rigid armor absorb most, if not all, of the residual energy of the bullet and the fragments. Four