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Energy dissipation of nanocomposite based helmets for blast-induced traumatic brain injury mitigation

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ABSTRACT

Injuries caused to the head by ballistic shock waves during blast impacts are not well understood. It has been postulated that traumatic brain injury (TBI) can be caused when the blast wave causes the kinetic energy and the pressure in the main blood vessels to oscillate rapidly and travel to the brain thereby damaging the axonal fibers and neurons or with the direct wave transmission to the head. In the direct wave transmission, the severity of blast wave impact can be reduced by ballistic helmets. The ballistic helmets currently used in the military have been designed to provide protection against penetrating ballistic projectiles and their effectiveness against blast shock wave has not been thoroughly understood. This research would focus on developing a multiscale computational model of blast impact response of high-performance nanocomposite materials for the helmet, followed by estimation of blast energy transfer to the tissues in the human head. Such a combined atomistic-computational model of ballistic response of nanocomposites, coupled with a human morphology-specific computational model is necessary to study the mechanics of blast impact on human head.

1. Introduction

The skull protects the brain, which is the most sensitive organ, from injuries during fall, stroke or blast wave impacts. Traumatic brain injury (TBI), or intra-cranial injury, is the damage caused to the brain by external mechanical forces, resulting in permanent or temporary impairment of the brain functions [1]. Blast injury is caused by a sudden increase in air pressure and causes injuries in spaces containing gas [2]. In a blast, shock wave travels at the speed of sound, and air is accelerated by this shock wave, forming a high-velocity blast wind. It has been found that during Operation Enduring Freedom and Operation Iraqi Freedom, improvised explosive devices (IEDs), and roadside car bombs caused about 60% of US casualties in Iraq and about 50% in Afghanistan [3]. Blast-induced TBIs have now become extremely significant as studies have shown that between January 2003–2005, out of the 450 soldiers admitted to Walter Reed Army Medical Center, 59% were diagnosed with TBI of which 56% were considered moderate to severe, and 44% were considered mild [4,5].

There are several causes of blast-induced TBI. Primary blast injury is caused by a high-pressure shock wave interacting with the body [3]. This shock wave produces high pressure, which can be amplified due to the impedance mismatch between the skull and air [6]. The direct impact of the shock wave causes acceleration of the head, and since the inertia of the brain is less than the inertia of the skull, the brain continues to vibrate after the skull has stopped moving. Cavitation bubbles are then formed from the intracranial pressure changes [3] and these bubbles cause injury to the brain as they collapse. In cases when the head is not directly subjected to the blast, the shock wave can be transferred through the abdomen to the blood vessels or other fluid pathways in the thoracic region. This compression effect can cause waves, which transmit kinetic energy to the brain [7]. Another cause of traumatic brain injury is due to shrapnel and debris from explosions. This is called secondary blast injury, and can often go further than the primary high pressure blast wave. The acceleration of the different body parts by the blast wind can cause tertiary blast injuries as well. Due to the difference in inertia between the skull and brain, higher shearing strains form in the intra-cranial region, causing shearing injuries [3]. Further, the high pressure gases following the explosion are at very high temperatures and these hot gasses can cause quaternary injuries, which include pulmonary injuries from the toxic gas and burns and the brain may also be damaged if the skull is heated excessively.

Various models have been created to simulate blast waves impacting a human head. A finite element (FE) study was initially carried out that could be parameterized to allow for various head

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sizes [8]. Grujicic et al. demonstrated the use of a Lagrangian-domain model for a human head to simulate blast-induced traumatic brain injury. They obtained results for pressure and stress measured at different points in the head model [9]. Experimental tests often demonstrated the need of helmets which can absorb blast pressure and thus mitigate the effects of blast impact on the human brain. At the same time, these helmets must protect the head from blunt trauma caused by shrapnel-induced wounds. Ganpule et al. performed finite element analysis on the role of the helmet in mitigating blast shock wave propagation [10]. They concluded that the highest reflected overpressure when a shock wave impacts a human head are in the regions of concavity, especially at the nasion, which is the nose–eye cavity. Kulkarni et al. carried out a comparative study on ballistic helmets [3]. This review included helmet materials such as Kevlar K29, K129 fibers, and thermoset resins, and possible future materials to be used for helmets, such as thermoplastic polymers and nano-composites.

The use of Kevlar-Carbon Nanotube based composites for use in helmets is hypothetical; however, there have been numerous studies on Kevlar-nanocomposites [11] for various applications like velocity impact studies and it was found that the energy absorption and impact response characteristics of the composite is increased due to the presence of nanotubes [12]. Similar trends were also observed by Randjbaran et al. [13] for the ballistic energy absorption of hybrid composite laminates reinforced with Kevlar and nanotubes.

Nanocomposite materials are often better alternatives to traditional composite materials because of their excellent mechanical properties: high stiffness-to-weight, strength-to-weight ratios, and excellent structural deformation characteristics. However, the major deterrent to experimental investigation of novel nanocomposites in the helmet design is the extreme cost and the lack of understanding of material response under extreme conditions. This handicap can only be overcome by developing multiscale computational models that consider the influence of materials at the nanoscales and macroscales. In this work, we develop a multiscale computational model of the helmet material with reinforced carbon nanotubes. The nanocomposite-based helmet material would be studied to understand the effect of energy transfer to the brain under blast loading conditions. The rest of the paper is as follows, Section 2 consists of the development of the computational model of the human head and the representation of the blast wave. This section is followed by the discussion of numerical results on the amount of energy transfer from the blast to the brain in a protected and unprotected head and also with a nanocomposite helmet. The paper concludes with a discussion of results.

2. Ideal-blast waves

There are many sources of blasts that occur in a battle-field that produce pressure waves by the rapid release of energy. Explosion sources also occur during the rapid vaporization of thin metal films or fine wires. However, more well-known blast sources are from chemical or nuclear reactions, when a sudden increase in air pressure causes a shock wave to form. This shock front is almost instantaneous and causes nearly discontinuous increases in temperature, density, and pressure [14]. A pressure wave can be approximated using a Friedlander equation, which can be used to describe the physical properties of an ideal blast shock wave as given by Eq. (1) [15,16] (see Fig. 1). The most efficient means of representing a blast impact is by the use of data from ConWep. ConWep is a collection of calculation routines that characterizes the effect of conventional weapons that includes air blast routines, breach, cratering, ground shock, and fragment and projectile penetrations etc. [17,18].

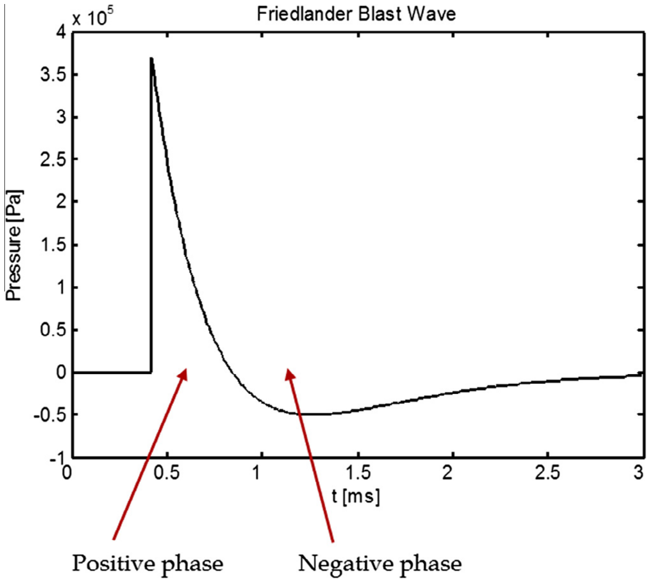

Fig. 1. Representation of Friedlander blast wave.

$$P = P_s e^{-\frac{t}{t^*}}\left(1 - \frac{t}{t^*}\right) \quad (1)$$

3. Computational model of human head and helmet

The 3D FE computational models are developed from the medical image data to create STereoLithography (.stl) files [19]. The FE model of the human head was obtained from the MR/CT data obtained from the Visible Human Female database from the National Library of Medicine [20]. This study partially follows the process outlined by Vonach et al. for creating the model of the human head [19]. Following the creation of the geometric model, tetrahedral or hexahedral meshing algorithms are used to generate the equivalent finite element mesh. The MR/CT images were then converted to a FE mesh using segmentation followed by smoothening of the resulting STL files and final conversion into an FE mesh. FE analysis was carried out using the general purpose FE code Abaqus (Abaqus Version 6.12, Dassault Systems) to study the effects of blast induced pressure differences in the human head with and without a helmet, using ConWep blast loading. The ConWep implementation in Abaqus is used for the simulations. The FE geometry of the human head model includes the brain, surrounding cerebral spinal fluid, and the skull. In the FE model, the head is fixed at the base of the neck with encastre boundary conditions. The model consists of the skull having 5998 elements, the cerebral spinal fluid with 5352 elements, and the brain model contains 6745 elements, for a total of 18,095 elements of type C3D4. In this study, the heterogeneity of the brain material and its non-isotropic behavior is not taken into account. A Mooney–Rivlin model is considered for the brain [21] and the strain energy function is given by [22,23]:

$$W = C_{10}(J_1 - 3) + C_{01}(J_2 - 3) + \frac{1}{D_1}(J_{el} - 1)^2 \quad (2)$$

where W is the strain energy potential, J_{el} is the elastic volume ratio, J_1 is the first invariant of the deviatoric strain, J_2 is the second invariant of the deviatoric strain, and C_{10}, C_{01}, and D_1 are material constants dependent on temperature. Linear viscoelasticity [24] is used to estimate the second Piola–Kirchhoff stress by the following convolution integral [21]: