Defence Technology xxx (2017) 1–7

Contents lists available at ScienceDirect

Defence Technology

journal homepage: www.elsevier.com/locate/dt

An experimental study on shock wave mitigation capability of polyurea and shear thickening fluid based suspension pads

Andi Haris, Heow Pueh Lee, Vincent Beng Chye Tan*

Department of Mechanical Engineering, National University of Singapore, 9 Engineering Drive 1, Singapore 117576, Singapore

ARTICLE INFO

Article history:
Received 7 June 2017
Received in revised form
24 August 2017
Accepted 29 August 2017
Available online xxx

Keywords:
Shock wave mitigation
Polyurea
Shear thickening fluid
Suspension pad
Ballistic fabric
Primary blast injuries

ABSTRACT

The present experimental study investigates shock wave mitigation capability of potentially new personal protective equipment (PPE) suspension pads made from polyurea and shear thickening fluid (STF). The shock tube test results show that when placed behind Twaron fabric systems with thickness ranging from 2 mm to 18 mm, the replacement of conventional flexible foam pad with STF and STF-infused foam pads with the same thickness of 20 mm greatly reduces the normalized peak pressure (by about 72% for each pad). However, this benefit is partially offset by a large increase in the normalized impulse (by about 78% for the STF pad and 131% for the STF-infused foam pad) which may cause the shock wave mitigation performance of these two pads to become less effective. Interestingly, the use of 4 mm thick polyurea pad can greatly reduce the normalized peak pressure and impulse as well (by about 74% and 49%, respectively). These results reveal that among the potentially new suspension pads tested, the polyurea pad displays the best shock wave mitigation performance. Therefore, polyurea has potential for use as a suspension pad in personal protective equipment requiring shock wave mitigation capability such as fabric ballistic vests, bomb suits and combat helmets.

1. Introduction

Improvised explosive devices (IEDs) are mainly homemade bombs that are usually hidden in signboards, guardrails, roadside structures, debris, animal carcasses, containers, briefcases or back packs carried by suicide bombers, and vehicles driven by suicide bombers. These explosive devices can be detonated manually or remotely by a variety of triggering mechanisms or devices such as hand phones, satellite phones, radio, remote controllers, or garage door openers [1]. The threat of IED hinders troop mobility as well as security forces and moving vehicles. Although their targets are primarily military personnel, IED attacks also routinely cause unintentional civilian injuries.

Besides high velocity shrapnel, injuries from IEDs could be due to shock waves. Despite improvements in combat helmets, propagation and reflection of shock waves (within the intracranial cavity) [2] produced by IEDs have caused traumatic brain injury (TBI) – the signature wound of the US armed forces in Iraq and Afghanistan. This type of TBI is referred to as primary TBI and has often no externally visible signs of trauma. As the design parameters for ballistic protection and shock wave mitigation are different, improved impact resistance has not led to improved pressure wave attenuation. Although improved ballistic protection by helmets has saved lives, many military survivors from Iraq and Afghanistan suffer irreversible traumatic brain injuries [3–6].

The commonly used combat helmets are the personnel armor system ground troops (PASGT), modular integrated communications helmet (MICH), lightweight helmet (LWH), advanced combat helmet (ACH), and enhanced combat helmet (ECH). In general, the helmets consist of a protective shell and a pad suspension system. The shell is usually made from multiple layers of anti-ballistic fabrics such as Kevlar, Twaron, Spectra and Dynemaa due to their excellent properties in defeating bullets and fragments [7–9]. The suspension pad is often made from conventional foam materials [10]. While current combat helmets have been successful in terms of providing an effective protection against penetrating ballistic injury, their protective performance against shock wave has yet to be established [3,12]. Preliminary studies by Mott et al. [13] and Moss et al. [14] showed that the helmets tend to enhance local blast overpressure on the head by focused interactions of the blast waves. Ganpule et al. [11] computationally investigated the role of helmets in mitigating the effect of primary shock waves. In their

---

* Corresponding author.
E-mail address: mpetanbc@nus.edu.sg (V.B.C. Tan).
Peer review under responsibility of China Ordnance Society.

http://dx.doi.org/10.1016/j.dt.2017.08.004

Please cite this article in press as: Haris A, et al., An experimental study on shock wave mitigation capability of polyurea and shear thickening fluid based suspension pads, Defence Technology (2017), http://dx.doi.org/10.1016/j.dt.2017.08.004

work, the primary shock wave interactions for various helmet head configurations were evaluated, and the pressure and impulse intensification effects were elucidated as a function of geometry, head-helmet gap and surface curvature. Grujicic et al. [10] developed a simple “core-sample” finite element model of the helmet/head assembly to investigate computationally the potential of polyurea as a shock wave impact mitigating helmet suspension-pad material. Lately, they have extended the simple “core-sample” finite element model to a fully three dimensional (3D) finite element model [15]. The simulation results of both simple and 3D models showed that the use of polyurea suspension pads is associated with a substantially greater decrease in the peak pressure experienced by the brain relative to that observed in the case of the conventional foam. Other computational studies by Radovitzky's group [16] and Karami's group [17] reported that wearing an advanced combat helmet (ACH) can reduce level of the blast-induced traumatic brain injury.

Shock waves from IEDs can also interact with other body organs such as lungs and gastrointestinal tract causing primary blast injury [18]. Used together with anti-trauma (suspension) pads which can reduce injury due to dynamic deformation of the armor into the wearer, ballistic vests and bomb suits made from multiple layers of anti-ballistic fabrics have been successful in providing an effective protection against the resulting high velocity shrapnel produced by IEDs. However, their protective performance is highly questionable when they are subjected to shock waves [19]. Previous studies showed that the severity of primary blast injury (i.e. caused by the impact of a shock or blast wave generated by an explosion) is increased when protective fabrics are used since the transmitted overpressures are significantly amplified through the fabrics [19–23]. Besides polyurea and conventional foams, shear thickening fluid (STF) may be used as suspension pad material. STF has huge potential for many industrial applications ranging from devices with adaptive stiffness and damping to body armour [24]. In body armour, the application of STF has received substantial attention. Particularly, STF has been used in combination with high strength ballistic fabrics to enhance their stab, puncture and ballistic resistance properties with little or no increase in thickness or stiffness of the fabrics. A recent study by Haris et al. [25] found that STF treated fabrics have potential applications not only for ballistic protection but also for shock wave mitigation. The STF treated fabrics can provide lower peak pressure and lower maximum rate of pressure rise as compared to (untreated) neat fabric and fabric impregnated with PEG only revealing that STF contributes to the increase in performance.

As outlined above, research on this area is still limited and minimal. More studies are needed to improve the performance of current fabric ballistic vests and combat helmets for optimal protection; not only for protecting from projectiles, but also from shock waves. Most of the earlier studies are computational works which need experimental validation. In the present study, shock wave mitigation capabilities of potentially new suspension pads made of polyurea, shear thickening fluid (STF), and STF-infused foam is experimentally investigated and compared with conventional foam pad.

2. Materials and method

2.1. Flexible polyurethane foam

The foam pad used in this study is made of a flexible open cell polyurethane foam. The polyurethane foam has the following specifications: density of 22 kg/m^3 and an average pore diameter of 715 μm. Fig. 1 shows a photograph of the foam taken with a digital microscope. The thickness of the foam pad and other pads used in this study is limited to at most 20 mm as systems thicker than this are deemed to be too bulky for personnel protection purposes and may affect soldier performance like visual awareness, aiming of weapons and mobility. The foam pads of current combat helmets have thicknesses of approximately 0.75 in or ~19.05 mm.

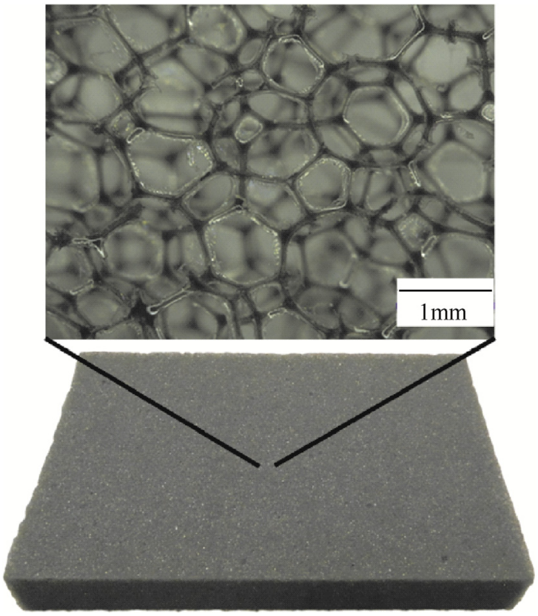

Fig. 1. Conventional foam pad (20 mm thick).

2.2. Polyurea

Polyurea is a multiblock polymer with alternating soft (linear hydrocarbon chain) and hard (aromatic moiety) segments along its backbone. At room temperature, the soft domains are above their T_g and impart polyurea its elastomeric properties, whereas the hard domains are below their T_g and impart polyurea its mechanical toughness and compressive stiffness, allowing polyurea to be used in a wide range of coating applications [26,27]. In recent years, polyurea has attracted much attention due to its excellent dissipative properties and thus has been used as external and internal wall-slidings and foundation coating for buildings aimed at minimizing the degree of structure fragmentation and minimizing the extent of the associated collateral damage in the case of a bomb blast. Besides, it has been used as ballistic resistant and blast mitigating coating for military vehicles and structures [26]. As mentioned earlier, the feasibility of using polyurea as a combat helmet pad was recently explored computationally in three studies [10,15,28].

The polyurea used in the present study is Dragonshield-HT ERC with an elongation percentage of 619% and density of 1000 kg/m^3. It was purchased from Specialty Products Incorporated (SPI). The manufacturer's specifications for the polyurea are presented in Table 1. Due to its high density, the thickness of the polyurea pad was set at 4 mm. Fig. 2 shows the polyurea pad specimen.

2.3. Shear thickening fluid and STF-infused foam

An STF is a non-Newtonian fluid and is often termed as a dilatant fluid. It is characterized by significant, and sometimes discontinuous, increase in viscosity when the applied shear rate reaches a critical value [29]. The fluid has low viscosity at shear rates lower than a critical value and high viscosity when the shear rate exceeds the critical value. There are two main mechanisms of shear

Please cite this article in press as: Haris A, et al., An experimental study on shock wave mitigation capability of polyurea and shear thickening fluid based suspension pads, Defence Technology (2017), http://dx.doi.org/10.1016/j.dt.2017.08.004