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Bio-inspired armor protective material systems for ballistic shock mitigation

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ABSTRACT

Severe transient ballistic shocks from projectile impacts, mine blasts, or overhead artillery attacks can incapacitate an occupant at low frequencies, or sensitive equipment at high frequencies, if they are not properly attenuated by armor protective systems. Unique challenges exist in developing armor protective systems for mitigating both low and high frequency ballistic shocks due to the lack of robust design methodology, the severe dynamic loading conditions, and the uncertainties in predicting ballistic shock responses.

Nature offers engineers a blueprint of highly effective, efficient, and adaptive material designs to protect certain regions from external threats. This paper presents the modeling, analysis, design, optimization, fabrication, and experimental validation of bone-inspired armor protective material systems for reducing projectile penetrations and alleviating ballistic shocks at both low and high frequencies. The optimized bone-inspired armor protective material system has a soft–stiff–soft–stiff material distribution pattern based on bone-foramen and osteonal-bone material systems. Analysis and experimental results demonstrated that the bone-inspired armor protective material systems have excellent capabilities for drastic ballistic shock mitigation, weight savings, and significant reductions in penetration and load transmission under ballistic loading conditions.

1. Introduction

The necessity of considering ballistic shock effects in new vehicle designs has been well recognized in the combat vehicle community during the past two decades [1]. A ballistic shock results from a significant amount of concentrated energy deposited from caliber projectile impacts, mine blasts, or overhead artillery attacks onto a small area of a military vehicle [2]. This energy may be transmitted throughout the vehicle including areas far away from and not exposed to the incident agent. At low frequencies (up to 1 kHz), the ballistic shock response is dominated by high load transmissions and large-magnitude flexural vibrations, which can be fatal to humans in a demanding high-g environment. A shock of 100 g for 3 ms or 40 g for 50 ms will cause severe injury [3]. At high frequencies (above 1 kHz), the ballistic shock response is dominated by the propagation of the stress waves in the vehicle materials, which will damage the light, intricate, frequency-sensitive components such as electronics and optics. Despite the recognized increasing demand for innovative lightweight armor protective systems capable of mitigating both low and high frequency ballistic shocks, the development of the enabling techniques to support such armor protective system analysis and design has been slow. This is due to the severe dynamic loading conditions, the uncertainties in predicting ballistic shock responses, the difficulty in selecting proper constituent materials, and difficulties in determining critical material and geometry design variables.

In ballistic shock analysis, finite element based commercial software, especially LS-Dyna, has been predominately utilized to calculate the target shock responses including acceleration histories, shock response spectra, deformation, penetration, velocities, and severity indices [4–6]. Due to the high frequency range of ballistic shock, the finite element based methods can become intractable for large structures. A statistical energy analysis (SEA) method was investigated for the prediction of ballistic shock in combat vehicles [1]. Compared to conventional analysis methods, the SEA method results in faster model construction, smaller model sizes, shorter running time, and a reduced set of input parameters. However, the SEA predictions at some locations within the test component might disagree significantly from the experimental measurements [1].

Many efforts have been made to mitigate ballistic shocks. Trabia et al., employed side and bottom *L*-shape panel joints for a combat vehicle to mitigate ballistic shocks from projectile and blast attacks [5,6]. The optimization results showed that the average of the mean of accelerations at critical locations in commander and driver seats and instrumentation panels could be reduced considerably by extending the joint and reducing its thickness. One drawback of the panel joint approach is its strong dependence on applied

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