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A fluid structure interaction study of a viscous mechanism for energy absorption in protective structural panels

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ABSTRACT

Sandwich panels designed to resist blasts and high-velocity impacts usually dissipate most of the delivered energy through inelastic deformation of solids. A concept is explored in this study to improve the energy absorption of such structures by the addition of a viscous mechanism. The mechanism relies on the fact that when a viscous liquid is forced through narrow passages at high speeds, it undergoes high shear rates that cause viscous energy dissipation. A simple test specimen in the form of a steel tube with capillaries attached at both ends was chosen for study. Both empty and liquid-filled test specimens were subjected to experimental and simulated drop-weight impact tests and simulated blast load tests. Fluid structure interaction analyses in the form of Coupled-Eulerian–Lagrangian simulations were performed to assess the energy dissipated both by solid plastic deformation and liquid viscous dissipation in the drop-weight and blast simulations. The liquid flow speeds generated by the applied loads were found to be a critical factor in determining the contribution of the viscous mechanism. The moderate liquid flow speeds generated by the drop-weight impacts resulted in negligible viscous energy dissipation. The simulated blast loads generated much higher liquid flow speeds and as a result the viscous energy contribution to the total absorbed energy in the test specimens approached 30%. The viscosity of the liquid has a major effect on the fraction of energy absorbed in the form of viscous dissipation. Results of this study support the viability of the concept of viscous-assist for improving the ability of protective panels and structures to withstand high-speed impact and blast loads.

1. Introduction

Panels designed for impact or blast energy absorption are usually either monolithic plates or sandwich constructions. Depending on the blast and impact intensities that are anticipated, these energy-absorbing panels can be constructed of metals such as steel or aluminum or of polymer matrix composites. Sandwich constructions can have cores that could be honeycombs, foams, and other such lightweight, energy-absorbing geometries [1,2]. For high intensity blasts and impacts, metals are still the material of choice for constructing energy absorbing panels [3]. Metals such as steel, when used in panels, are capable of absorbing a significant amount of energy from blasts and impacts thereby providing protection to the target. This energy is absorbed primarily by plastic deformation [4].

A blast or high velocity impact event can cause damage to energy-absorbing panels in multiple ways. Severe penetration and perforation of the panel can result. Even without perforation, there could be extensive deformation causing harm to the target. Shock and stress waves can propagate through the panel and be transmitted onto the target. Deformation and stress wave mitigation can be accomplished by absorbing and redirecting the energy as it works its way through the panel. An example of utilizing this concept is the use of sacrificial cladding in the form of a ductile metal layer over a steel plate [5].

The concept explored in this investigation involves the use of a viscous assist to the plastic energy absorption in protective structures. While this concept can be implemented in numerous ways, a simple sandwich structure is used as an illustrative model. Consider an array of metallic tubes bonded between two metal face plates, thus forming a sandwich panel. The tubes, filled with a viscous liquid, taper into capillaries at the ends (Fig. 1(a)). When a blast wave or high velocity impact event strikes this viscous-assist sandwich panel (Fig. 1(b)), the panel deforms with a significant amount of the energy absorbed in the plastic deformation of the face plates of the panel and the metal tubes. An additional energy dissipation mechanism that will be triggered is viscous in nature, as the liquid in the tubes is forced out through the capillaries. If a sizeable fraction of the energy absorbed is in the form of viscous dissipation, the resulting lower deformation in the panel will mean reduced penetration into the target.

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Several examples exist of the use of liquids for impact and blast energy absorption and stress wave mitigation. Su et al. [6] describe the analysis of a piston-cylinder device that mitigates propagating shock waves by repeated reflections, thereby reducing the peak pressure transmitted. Zakrajsek et al. [7] explored the use of water sheets to reduce the peak overpressure and impulse of a shock wave. They were able to experimentally demonstrate a reduction in the overpressure and impulse transmitted by a shock wave through the water sheet. Liquids containing nanoporous particles have recently been explored as energy absorbing media [8–10]. When such liquid suspensions are subject to a quasi-static or dynamic pressure, the liquid infiltrates into the pores and energy is absorbed and stored as interfacial surface energy at newly created liquid–solid interfaces in the nanopores [9]. Using liquids to absorb impacts in helmets has also been recently explored [11]. Stewart et al. [11] studied the use of fluid filled channels in helmet liners. Testing revealed that the presence of fluid filled channels within a helmet liner improves the helmet performance under impact loads, by decreasing the peak acceleration of the impact and increasing the duration of the impact. Deshmukh and McKinley [12] loaded a cellular solid with a magnetorheological fluid, thus creating a composite medium whose energy absorbing capability can be tuned using applied magnetic fields. Lee et al. [13] used shear thickening fluids to soak a Kevlar fabric to examine the ballistic impact resistance. They demonstrated an increase in ballistic resistance because of the presence of the shear thickening fluid.

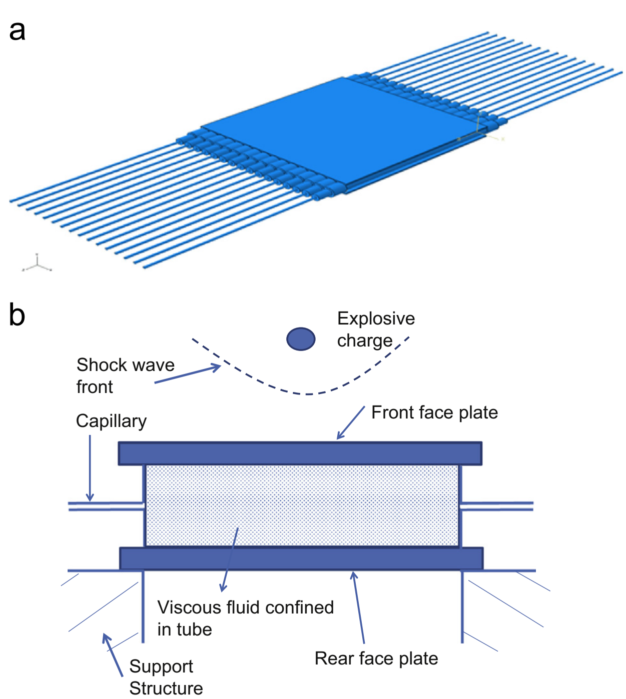

Fig. 1. Conceptual model of a viscous-assist sandwich panel for blast/impact protection. (a) An array of viscous liquid filled tubes sandwiched between two face plates. The tubes end in thin capillaries. (b) A sectional view of the viscous-assist panel; the panel is resting on structural supports and is being subject to a blast load.

There has also been a lot of interest in investigating how liquid-filled tubes and pipes respond to impact loads [14,15]. This is very relevant for applications in the power generation and petrochemical industries. Nishida et al. [14] examined aluminum pipes filled with water and impacted by steel spheres. They found a strong dependence of the pressure generated in the liquid on the impact velocity. In a similar fashion, Lu et al. [15] found that the pressure of the water in water-filled pipes significantly affects the critical perforation energy of the pipes when impacted by projectiles.

In this work, we explore the concept of a viscous-assist mechanism as a means of energy dissipation in a protective panel for blast and impact loads. The feasibility of the concept is explored by numerical fluid–structure-interaction simulations, and experimental testing. In Section 2, a preliminary assessment is performed to explore the viability of the viscous-assist mechanism to cause energy dissipation when viscous liquids are moved rapidly through narrow orifices. In Section 3, we assess the response of a simple viscous-assist test specimen to drop-weight tests. This is done through experiments and finite element simulations. In Section 4, finite element fluid–structure interaction simulations are conducted to assess the response of viscous-assist test specimens to simulated blast loads. Our conclusions are outlined in Section 5.

2. Preliminary assessment of viscous-assist concept

The preliminary assessment involved idealized, conceptual models on paper. The aim was to establish order-of-magnitude estimates of viscous dissipation energy when a simplified geometry of a viscous-assist panel is subject to blast loads. A second goal was to confirm the conjecture that in the time scales associated with blast pressure pulses, viscous liquids can be moved at high speeds to dissipate energy.

An order-of-magnitude estimate of the viscous dissipation energy was produced by considering a simplified, conceptual model of a viscous-assist sandwich panel. The conceptual panel consisted of two square, rigid flat plates of side length 30 cm (12 in.), sandwiching a viscous-liquid core. Capillaries of inside diameter 3 mm (0.12 in.) and length 2.5 cm (1 in.), spaced 2.5 cm (1.0 in.) apart, were arrayed around the periphery of the square sandwich panel. A side view of the concept sandwich panel is shown in Fig. 2(a). The effect of a blast pressure pulse acting on the upper square plate of the sandwich is simulated by the rapid downward motion of the plate with an effective downward

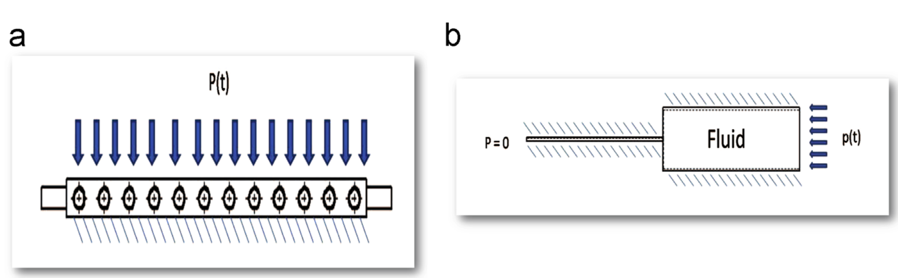

Fig. 2. Proof of concept models for preliminary assessment of the viscous-assist concept. (a) Two square plates sandwiching a viscous liquid core. A pressure pulse drives the top plate downward at high speeds, thus squeezing the plates together and forcing the liquid out through capillaries at the edges. (b) A pressure pulse driving a viscous liquid through a tube-capillary arrangement. A cross-section of the tube-capillary is shown.