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Compressive response of sandwich plates to water-based impulsive loading

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ABSTRACT

The compressive response of sandwich plates with polyvinyl chloride (PVC) foam cores and aluminum facesheets to water-based impulsive loading is analyzed using an instrumented impulsive loading apparatus called the underwater shock loading simulator (USLS) and a fully-dynamic 3-D computational framework. The loading conditions analyzed are similar to those in underwater blasts. The study focuses on the overall deformation, strain recovery and impulse transmission which are quantified as functions of structural attributes such as core density, front and backface masses, and incident impulsive load intensity. Measurements obtained using high-speed digital imaging and pressure and force sensors allow the computational models to be calibrated and verified. Quantitative loading–structure–performance maps are developed between the response variables and structural and load attributes. The results reveal that core density has the most pronounced influence on core compressive strain and impulse transmission. Specifically, for severe impulse intensities, a 100% increase in core density leads to a 200% decrease in compressive strain and a 500% increase in normalized transmitted impulse. On the other hand, structures with low density cores are susceptible to collapse at high impulse intensities. Additionally, the compressive strains and transmitted impulses increase monotonically as the mass of the frontface increases, but are unaffected by backface mass. For the same core density, a 100% increase in facesheet thickness leads to a 25% and 50% increase in the core strain and normalized transmitted impulse, respectively. The results and performance maps are useful for designing marine structures with restricts, such as hull sections and pipelines backed by water or machinery.

1. Introduction

Marine vessels operate in severe environments with temperature extremes, transient loads and corrosive sea water. In addition to operational loads, the structures are required to withstand accidental hydrodynamic impulsive loads due to surface and sub-surface blasts and weapons impact. Sandwich composites can provide good blast mitigation due to their high strength-to-weight ratios and high shear and bending resistances. Previous research on the dynamic behavior of sandwich composites has focused on low velocity, contact-based loads such as drop weight and projectile impact [1–8]. It is found that the overall deflection experienced by sandwich plates is significantly lower than monolithic plates of equivalent mass. Additionally, the forces and impulses transmitted by sandwich structures are significantly smaller than those transmitted by monolithic structures [9–11]. Recent assessments of blast-loaded marine structures show that fluid structure interaction (FSI) effects play an important role in response and can be exploited to improve the blast mitigation capability [12–21]. The deformation and failure of sandwich structures subjected to underwater impulsive loads are complicated due to competing damage mechanisms, complex failure modes, interfacial effects and material heterogeneity. The facesheets have a dominant effect on the rigidity of the sandwich structure and provide protection from environmental conditions while the core governs the energy absorption by, and impulse transmission, through the structure. In addition, load intensities, boundary conditions, and operating environments all influence deformation and failure. Despite recent advances in understanding, several key issues remain unresolved.

The objective of the present combined experimental and numerical study is to characterize the behavior of structural foams subjected to underwater impulsive loads and delineate the role of core compressibility and facesheet thickness on the response of sandwich plates. The focus is on quantifying the compression and impulse transmission characteristics of PVC foams with a range of densities under loading of water-based, high-intensity impulses generated using a recently developed experimental setup called the underwater shock loading simulator (USLS). The loads mimic the high-pressure, exponentially-decaying impulses that are generated during

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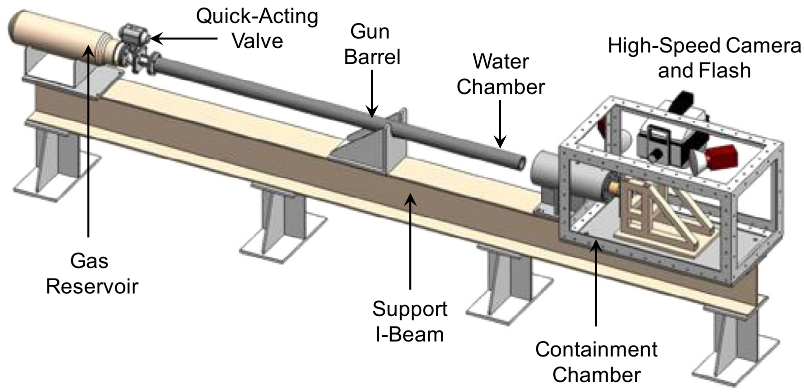

Fig. 1. A schematic illustration of the underwater shock loading simulator (USLS) and a photograph of the facility.

underwater explosions. As shown in Fig. 1, the USLS consists of a projectile-impact-based impulsive loading system, a water chamber, a target holder and a safety enclosure. In-situ measurements of the material response are obtained using high-speed digital imaging and force transducers, providing an opportunity to assess the role of core density and strength on blast resistance during events mimicking an underwater detonation.

2. Instrumented underwater impulsive loading apparatus

Gas gun impact has been successfully used to generate impulsive loading through water [12–15,22]. To obtain controlled loading and simulate different water-structure contact conditions, the underwater shock loading simulator (USLS) in Fig. 1 is designed to provide a variety of load configurations with quantitative diagnostics [12,13,22]. Important features of this facility include the ability to generate water-based impulsive loading of a wide range of intensity, the ability to simulate the loading of submerged structures, and integrated high-speed photographic and laser interferometric diagnostics. Fig. 2 shows a schematic illustration of the cross-section of the USLS.

The shock tube is an 800 mm long cylinder which is horizontally mounted and filled with water. It is made of steel and has an inside diameter of 80 mm. A thin piston plate is mounted at the front end and the specimen is located at the rear end. A projectile is accelerated by the gas gun and strikes the piston plate, generating a planar pressure pulse in the shock tube. The impulsive load that impinges on the target induces deformation in the specimen at strain rates up to 10^4 s^{-1}. Projectile impact velocities in the range of 15–150 ms^{-1} are used to delineate the effect of loading rate on the deformation and failure behavior of the structures analyzed. This velocity range corresponds to peak pressures between 15 and 200 MPa, which are comparable to pressures observed in underwater explosions [16–18]. The metal platens have a thickness of 10 mm and a diameter of 100 mm; while the foam specimens have a thickness of 50 mm and a diameter of 70 mm.

The uniaxial compressive loading setup developed for this analysis is referred to as the "Dynacomp" setup. Here, an aluminum platen is held in contact with water on one side of the platen and a deformable core on the opposite side of the platen. This deformable core is supported by another aluminum platen which rests on a force transducer embedded in a 25 mm thick steel plate. A flange is designed to ensure that the foam core is always in contact with the aluminum platens on both the impulse side and the opposite side and is held normal to the platens. Care is taken to ensure that there is no slippage between the platens and the core. The compressive strain of the foam core is obtained via high-speed digital imaging and the transmitted impulse is measured using a high dynamic range force transducer. These two parameters provide a description of the compressive response and help quantify the blast mitigation capability of each core configuration. Additionally, the front and backface thicknesses can be varied to evaluate the effect of both variables on the foam core.

According to Taylor's analysis of one dimensional blast waves [19] impinging on a light, rigid, free standing plate, the pressure in the fluid at a distance r from an explosive source follows the relation $p(t)=p_0\exp(-t/t_0)$, where p_0 is the peak pressure, t is time and t_0 is the pulse time on the order of milliseconds. The area under the pressure–time curve is the impulse carried by

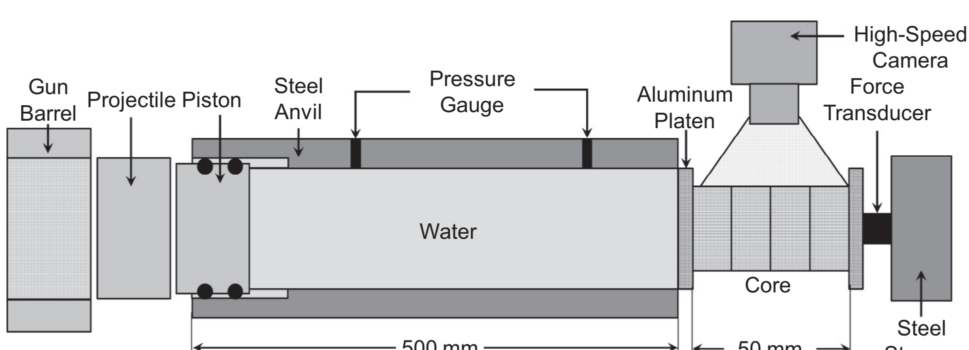

Fig. 2. A schematic illustration of the dynamic compression "Dynacomp" test setup within the underwater shock loading simulator (USLS).