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High-speed digital imaging and computational modeling of dynamic failure in composite structures subjected to underwater impulsive loads

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ABSTRACT

The load-carrying capacity of composite structures under water-based impulsive loads is evaluated in relation to different core materials and load intensity. The analysis focuses on the role of core density and the effect of varying structural attributes and environmental conditions on deformation and failure mechanisms in monolithic as well as sandwich composites. The structures analyzed are simply supported planar composites with PVC foam cores and E-glass/vinylester facesheets. For the analysis carried out, the material properties of the sandwich cores are varied while the total mass is kept constant. The structures are subjected to impulsive loads of different intensities using a novel new projectile-impact-based facility called the Underwater Shock Loading Simulator (USLS). In-situ high-speed digital imaging and postmortem analysis are used to study the deformation and failure of individual components, focusing on the effects of loading intensities, failure modes and material heterogeneity. Depending on the loading rate, shear cracking and/or collapse are the primary failure modes of the polymeric foam cores. Core density and height also significantly influence the response and failure modes. On a per unit weight basis, structures with low density cores consistently outperform structures with high density cores because the former undergo smaller deflections, acquire lower velocities and transmit a smaller fraction of incident impulses. Scaling relations in the form of deflection and impulse transmitted as functions of core density and load intensity are obtained to provide guidance for structural design.

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1. Introduction

Marine vessels operate in hostile environments which include high and low temperature extremes, transient dynamic loads like hull slamming, and corrosive sea water. Additionally, the structures are expected to withstand hydrodynamic loads resulting from surface and underwater explosions and weapons impact. Sandwich composites can provide good blast mitigation due to their high strength-to-weight ratios and high shear and bending resistances. The lightweight of sandwich composites can also improve speed and fuel economy. Compared with metal, composites are also more corrosion-resistant and have lower repair costs. These attributes make composite sandwich structures attractive materials for marine vessels. However, before such materials can be used, the relationships between their performance, constituent materials and geometric design must be well-understood and quantified.

Investigations have been out on the dynamic deformation and failure of layered materials. Results showed that key damage mechanisms include matrix cracking, fiber breakage and interlaminar delamination. The primary driving forces for the damage processes are transverse shear stresses [1–3]. Interlaminar delamination is the most detrimental to stiffness and strength and, therefore, is a major concern because delamination is not visible on the surface. Chang and co-workers [4–6] have studied the damage behavior of composite laminates under low velocity impact loading, concluding that in-ply matrix cracking precedes delamination growth and shear and bending crack initiation. The damage behavior of composite laminates is significantly influenced by matrix material, composite layup and geometric aspects such as size, thickness and loading area [7–9]. Minnaar and Zhou [10] used a novel interferometric experimental setup to show that interlaminar crack speeds are significantly higher under shear loading, and that crack speeds are strongly influenced by loading rate in mode II.

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However, only limited study has been reported [11,12] on the dynamic response of composites to water-based impulsive loads. The compressive response and fracture behavior of core material are of primary importance in the structural response of sandwich structures. The stress–strain behavior of cellular foams at high strain rates has been investigated using Split Hopkinson Pressure Bar apparatuses [13–17]. These experiments reveal that PVC foams have mild strain rate sensitivity in the strain rate range of $\dot{\varepsilon} = 10^{-2}$ to $10^{3}\ s^{-1}$ and negligible strain rate sensitivity in the strain rate range of $\dot{\varepsilon} = 10^{-4}$ to $10^{-2}\ s^{-1}$. The primary mechanism for energy absorption in foam cores is local wall collapse and volumetric, stress-saturated compression. Constitutive models for foams often rely on homogenized continuum descriptions of the cellular materials [18,19].

Through the combination of a thick, low-density core and thin facesheets, sandwich structures achieve considerably high shear and bending stiffness to weight ratios than homogenous plates of equivalent mass made exclusively of either the core or the facesheet material. The primary factors that influence the structural response of a sandwich structure are (1) facesheet thickness, (2) core thickness, and (3) core density. Previous research on the dynamic behavior of sandwich composites has focused on low velocity contact-based loads such as drop weight and projectile impact [13,14,20–24]. It is found that the overall deflection experienced by sandwich plates is significantly lower than monolithic plates of equivalent mass [25–33]. Additionally, the forces and impulses transmitted by sandwich structures are also smaller than those by monolithic structures [25,28,29]. Recent assessments of blast-loaded structures show that FSI (fluid–structure interaction) effects play an important role in dynamic response and can be exploited to improve the blast mitigation capability of marine structures [29,34–37]. Experiments focusing on different core topologies and specimen sizes have been carried out by Espinosa and co-workers [38–40] and McShane et al. [41] using underwater pressure impulses generated by gas gun impact and by Dharmasena et al. [42] using planar pressure impulses generated by explosive sheets. Shukla and co-workers [43–47] examined the dynamic response of sandwich structures consisting of woven E-glass composite facesheets and stitched core to air-based shock loading and concluded that stitched cores exhibit superior mechanical performance.

The deformation and failure of composite sandwich structures subjected to underwater impulsive loads are complicated due to competing damage mechanisms, failure modes, interfacial effects and material heterogeneity. The material properties of the different components significantly affect the blast resistance of the structures. In addition, loading (intensity, boundary conditions, and environments) influences the failure modes. Despite recent advances in understanding the dynamic response of sandwich composites, several issues remain. One is the lack of design relations that quantify the response as functions of both materials and geometric parameters. To obtain such relations, experiments that account for proper loading conditions are required. Diagnostics that provide in-situ, time-resolved response measurements are also required. Until recently, such experiments remained unavailable. Full scale underwater blast experiments have been carried out by Dear and co-workers using C4 explosives to generate the impulsive loads and high-speed photography with Digital Image Correlation (DIC) to evaluate the dynamic response of composite structures [48,49]. Nurick and co-workers have conducted air-blast experiments using PE4 plastic explosive and a ballistic pendulum apparatus to analyze the damage and energy dissipation in monolithic composite laminates and fiberglass/PVC foam sandwich structures [50,51].

The objective of the present study is to characterize the damage response of sandwich composites with different core densities but similar total masses. The focus of this analysis is on understanding the deformation and failure mechanisms, and quantifying the damage in composite structures as a function of structural attributes, material properties, loading conditions and loading rates. The loading of interest is high intensity water-based impulsive loads. Planar impulses resembling those resulting from underwater explosions are generated using the Underwater Shock Loading Simulator (USLS), a novel experimental setup developed recently. The USLS consists of a projectile-impact-based impulsive loading system, a water chamber, a target holder, and a safety enclosure. The target holder allows clamped and simply-supported boundary conditions. The experiments are designed to quantify the resistance of each structural configuration to underwater impulsive loads The response and failure mechanisms studied include overall deflection, face wrinkling, core–face debonding, core compression, core shear cracking and rupture. Of particular interest is the influence of load intensity and sandwich core characteristics on deformation and failure.

This is a combined experimental and computational study. Finite element simulations are carried out, accounting for the experimental conditions and material properties which are measured independently. The simulations also account for the fluid–structure interaction (FSI) effect at the water–composite interface. Failure mechanisms considered include shear cracking and fragmentation in the core, cracking in the facesheets, and core–face interfacial debonding. The simulations focus on damage initiation and evolution in the early stage of deformation (~1000 μs) since the load-carrying capacity is most critically reflected then. This combined experimental and numerical approach enables the identification of factors that play important roles in determining the dynamic response of the materials. The analysis uses metrics such as deflection, energy absorbed and impulse transmitted to quantify blast resistance. The results are presented in normalized forms to identify underlying trends in material and structural response.

2. Water-based impulsive loading experiments

Gas gun impact has been successfully used to generate impulsive loading through water [39,52–55]. To obtain controlled loading and simulate different water–structure contact conditions, the Underwater Shock Loading Simulator (USLS) was designed to provide a variety of load configurations with quantitative diagnostics. 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. 1 shows a photograph of the USLS. The shock tube is an

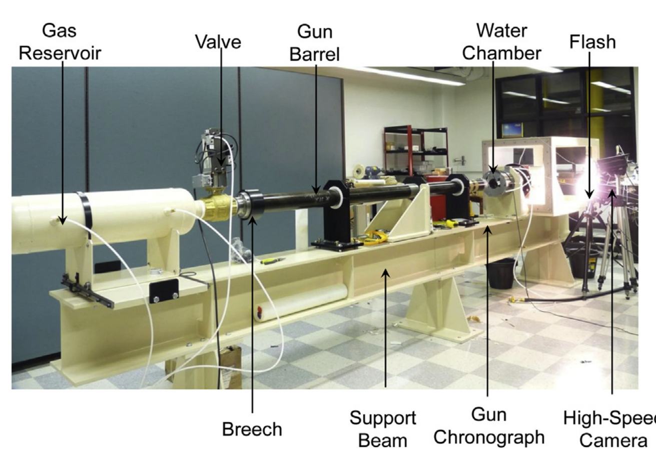

Fig. 1. Photograph of the Underwater Shock Loading Simulator (USLS). Pictured are the gas reservoir, gun barrel, water chamber and the Imacon 200D high-speed camera.

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