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Failure analysis using X-ray computed tomography of composite sandwich panels subjected to full-scale blast loading☆

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ABSTRACT

The tailorable mechanical properties and high strength-to-weight ratios of composite sandwich panels make them of interest to the commercial marine and naval sector, however, further investigation into their blast resilience is required. The experiments performed in this study aimed to identify whether alterations to the composite skins or core of a sandwich panel can yield improved blast resilience both in air and underwater. Underwater blast loads using 1.28 kg TNT equivalent charge at a stand-off distance of 1 m were performed on four different composite sandwich panels. Results revealed that implementing a stepwise graded density foam core, with increasing density away from the blast, reduces the deflection of the panel and damage sustained. Furthermore, the skin material affects the extent of panel deflection and damage, the lower strain to failure of carbon-fibre reinforced polymer (CFRP) skins reduces deflection but increases skin debonding. A further two panels were subjected to a 100 kg TNT air blast loading at a 15 m stand-off to compare the effect of a graded density core and the results support the underwater blast results. Future modelling of these experiments will aid the design process and should aim to include material damage mechanisms to identify the most suitable skins.

1. Introduction

Composite sandwich panels with polymeric foam cores are becoming more prevalent in marine applications due to their high strength-to-weight ratios and adaptable properties. In naval applications it is important to understand the resilience against blast of these sandwich panels. Such dynamic loading is challenging to predict, therefore, it is necessary to test these composite structures against representative charges.

Arora et al. [1] performed full-scale underwater blast experiments on glass-fibre reinforced polymer (GFRP) skinned composite sandwich panels and GFRP tubular laminates. These experiments demonstrated the ability of simple sandwich constructions to resist blast loads and for strain gauges to monitor the dynamic response of the structures. A similar experimental setup was used in the research presented in this paper. Underwater blast experiments on composites have been carried out by a number of other authors; Mouritz subjected stitched composite laminates to 30 g and 50 g plastic explosive charges underwater and investigated the subsequent delamination [2].

Latourte et al. [3] subjected scaled samples to underwater impulse loading using a water column and water piston setup to identify failure modes and damage mechanisms of the panels. Furthermore, Le Blanc et al. [4] used a conical shock tube to determine the effects that a polyurea coating has on a composite sandwich panel with GFRP skins during underwater shock loading. The authors found, that for a given polyurea thickness, the panel responded best when it was applied to the back skin. The authors went on to test the effects of plate curvature and plate thickness during underwater blast loading using a conical shock tube [5]. The results showed an improvement in plate performance was achieved when the core thickness was increased.

Deshpande and Fleck simulated a one-dimensional underwater impulsive wave interacting with a composite sandwich panel using finite element simulation and a lumped parameter model [6]. The results show that greater core strength increases the momentum

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transferred to the panel and a weaker core may improve the underwater shock resilience of composite sandwich panels. Huang et al. [7] used an underwater explosive simulator to test sandwich panels with PVC cores and metallic skins. The setup consisted of a projectile fired from a gas gun at a water column to create the pressure loading with DIC implemented to record the panel response. The authors concluded that core density influences failure modes, response rates and significantly affects panel deflection. These investigations provided motivation for experiments into further effects of the core and skins during underwater blast and hence different core densities and skin materials were tested.

Arora et al. [1] also performed experiments investigating the effect of core thickness during air blast. A 40 mm thick panel with GFRP skins and SAN foam core and an identical panel with a 30 mm core were subjected to a 30 kg C4 charge at a stand-off distance of 14 m. The response of the panels to the blast load was recorded using digital image correlation (DIC). A larger charge size was used in the experiments presented in this paper but a similar test setup, using DIC, was adopted. The effect of the core thickness in cylindrical composite sandwich shells under air blast loading was also investigated by Hoo Fatt and Surabhi through an analytical model [8]. The authors found that increasing core thickness lead to an increase in the energy absorbed by the shell and a decrease in the failure load. The effect of whether a core is filled with polymer foam or not has been investigated by Zhang et al. [9]. The authors subjected sandwich panels with steel skins to explosive blast loads. The cores were either empty of foam with just a steel core web, had foam throughout or had foam positioned at the front or rear of the panel. It was clear that the foam increased the energy absorbing capability of the panels and reduced front skin deflection.

Since full-scale blast testing is expensive, laboratory methods that simulate blast waves are often used. Further investigations into the role of the core have been carried out by Wang et al. [10]. A stepwise graded density foam core with the foam placed in increasing order of density (low/medium/high), the lowest density foam on the blast side, was subjected to shock loading using a shock tube. By using this core arrangement, the core was found to absorb blast energy in the front layers early in deformation, reducing back face-sheet damage. An alternative configuration (medium/low/high) suffered from face-sheet cracking and severe core damage.

Further shock tube experiments were carried out by the same group on sandwich panels with three to five core density gradations [11]. By increasing the number of core layers, hence decreasing the difference between the acoustic wave impedance of successive layers, the structural integrity of the sandwich panel is retained. These experiments on stepwise graded cores directly motivated the research into graded cores presented in this paper. Porfiri et al. have extended this work to look into functionally graded composite cores which have hollow particles dispersed within a matrix as these offer improved damage tolerance [12]. The authors successfully developed a processing method whereby the resins are co-cured, eliminating the need for adhesive bonds, and tested the potential cores under compression.

Non-linear density gradients have been studied by Liu et al. [13]. The authors evaluated a foam rod with a density varying with a power law in the longitudinal direction being impacted by a projectile. The theoretical results were compared to a finite element model. The results indicated that the energy absorption and impact resilience of foam could be increased using non-linear density profiles. Chen et al. evaluated the underwater shock response of one-dimensional sacrificial coating with Density Graded Polymer Foam (DGPF) and Continuous Density Graded Foam (CFGF) cores [14,15]. The authors concluded that the CDGF coating with a lower density facing the blast reduces the first pressure peak but not the total impulse. Total impulse can be reduced by using a large density gradient but the lower densities may enter densification much earlier reducing the total energy absorption capability. The results show the optimal density gradient varies depending on the type of load.

The effect of CFRP versus GFRP skins on composite sandwich panels during a 100 kg TNT air blast load at 14 m stand-off distance was studied by Arora et al. [16]. Although the two panels had an equivalent mass per unit area of ~17 kg/m^2, the CFRP-skinned panel experienced less out-of-plane deflection, lower surface strains and less damage. This experiment led to the investigation of CFRP versus GFRP skins during underwater blast in this study. Tekalur et al. [17] subjected GFRP and CFRP composites to shock tube and controlled explosion tube testing to understand their dynamic behaviour. The laminates were of equal thickness and similar areal density. The results revealed that CFRP laminates exhibit sudden failure whilst GFRP laminates are able to sustain more damage. Shock tube experiments investigating the effect of altering the sandwich panel skins to include a polyurea layer between GFRP layers during air blast found that the incorporation of this layer reduced the central deflection by 25% [18].

Radford, Fleck and Deshpande have developed another laboratory technique where the pressure versus time profile created by blast loads can be simulated by firing an aluminium foam projectile at composite specimen [19]. The authors used this technique to compare the response and damage of composite sandwich panels to monolithic composite panels [20]. This technique has also been adopted by Schneider et al. to test the performance of self-reinforced poly(ethylene terephthalate) (SrPET) beams [21]. The fibres and matrix are made from the same base polymer. Based on experiment and finite element analyses, the authors concluded that the SrPET beams have a comparable impact performance to aerospace grade aluminium and carbon fibre sandwich composites with equal mass and geometry.

In service, sandwich panels are likely to be subjected to more than one type of loading or an adverse environment. Shukla and Wang performed experiments where a composite sandwich panel underwent edgewise compression prior to shock tube loading [22]. Buckling and front skin failure was promoted by the compressive loading. Jackson and Shukla [23] subjected sandwich composites to sequential impact and shock tube loading. The authors found that a low velocity drop weight impact had a more severe effect on the blast performance of the panels than a high velocity projectile penetration due to the type of damage caused by this loading, debonding between front skin and core. Gupta and Shukla identified that the failure mechanisms of composite sandwich panels change when subjected to blast loading at different temperatures [24]. At 80 °C fibre breakage and fibre delamination occurs whereas at −40 °C the sandwich panel is brittle and core cracking and face/core delamination dominates.

The performance of composite sandwich panels subjected to low velocity impact has been investigated by Wu et al. [25]. The authors evaluated the response of panels with CFRP skins and aluminium honeycomb cores and found they had a higher impact resistance than the honeycomb cores or the CFRP skins alone. Lopresto et al. [26] used non-destructive and destructive techniques to evaluate the damage to CFRP laminates subjected to low velocity impact. The laminates were either air-backed or water-backed and this had an effect on their residual compressive strength. The non-destructive evaluation technique was ultrasonic scanning. The same research group has used ultrasonic scanning to evaluate the damage to jute/poly(lactic acid) composites after low velocity impact [27]. In the investigation presented in this paper, X-ray computed tomography (CT) scanning was used as a non-destructive damage evaluation technique.