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X-ray CT analysis after blast of composite sandwich panels

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Abstract

Four composite sandwich panels with either single density or graded density foam cores and different face-sheet materials were subjected to full-scale underwater blast testing. The panels were subjected to 1 kg PE4 charge at a stand-off distance of 1 m. The panel with graded density core and carbon fiber face-sheets had the lowest deflection. Post-blast damage assessment was carried out using X-ray CT scanning. The damage assessment revealed that there is a trade-off between reduced panel deflection and panel damage. This research has been performed as part of a program sponsored by the Office of Naval Research (ONR).

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Keywords: air blast; underwater blast; sandwich structures; composites

1. Introduction

Composite sandwich panels offer many advantages over traditional ship building materials and are hence becoming increasingly commonplace. There is a wide variety of choice for the constituent materials and research into the optimal combinations are ongoing. Styrene acrylonitrile (SAN) foam is commonly used as the sandwich panel core material and Gardener, Wang and Shukla have investigated the air blast performance of stepwise graded density SAN foam cores [1]. The graded density panels were shown to absorb more blast energy in the front, lower density layers leaving the back face-sheet intact. Additionally, the performance of glass fiber reinforce polymer

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(GFRP) face-sheets against carbon fiber reinforced polymer (CFRP) face-sheets, both with SAN foam cores, against air blast loading has been investigated by Arora et al [2]. The CFRP face-sheets were shown to suffer from less damage.

Underwater blast performance of composite sandwich panels is important for naval structures. Arora et al investigated the performance of GFRP sandwich panels and GFRP tubes during underwater blast loading [3]. Due to the expensive nature of blast testing, alternative testing methods have been developed including the water filled conical shock tube (CST). LeBlanc and Shukla have used a CST to research into the effect of plate curvature and poly-urea coatings on composite sandwich panels under shock loading [4].

Air blast testing into different constituent materials has revealed the advantages of employing a graded density foam core into a sandwich panel along with the benefits of using CFRP face-sheets. The research reported in this paper investigates whether these materials perform as well when subjected to underwater blast loading.

2. Materials

Four composite sandwich panels were selected for underwater blast testing to compare the relative performance of their materials. Two of the panels had 30 mm foam cores consisting of a single density SAN foam, one panel employed GFRP face-sheets and the other CFRP face-sheets. The other two panels had 30 mm graded density foam cores. This consisted of 10 mm layers of three SAN foams with different densities. The foams were arranged such that the lowest density foam was facing the blast, the highest density foam was furthest from the blast and an intermediate density foam was between the two. Again one panel employed GFRP face-sheets whilst the other had CFRP face-sheets. Table 1 details the four panels tested.

Table 1. Summary of panel types.

Face-sheet fiber type	Core material	Core density (kg/m^3)
Glass	SAN M130	140[1]
Carbon	SAN M130	140[1]
Glass	Graded SAN (M100/M130/M200)	108/140/200[1]
Carbon	Graded SAN (M100/M130/M200)	108/140/200[1]

3. Experimental Procedure

This section details the experimental setup and instrumentation of the underwater blast experiment along with the post-blast damage assessment that was carried out using X-ray CT scanning. The blast testing was performed at GL DNV, RAF Spadeadam in Cumbria, UK and the X-ray CT scanning was carried out at the University of Southampton.

3.1. Underwater blast setup

The 0.8 m x 0.8 m panels were bolted in a welded steel channel box which had an enclosed volume of air behind the panel leaving an unsupported area of 0.65 m x 0.65 m. The charge was a 1 kg plastic explosive 4 (PE4) that was held 1 m from the center of the panel using a pine frame, this charge has an equivalent TNT weight of 1.28 kg. This load was chosen as it would cause full compressive failure of the foam cores and failure of the face-sheets. A reflected pressure gauge was adhered to the top of the steel box and a side-on pressure gauge was held at the same height and distance from the charge as the center point of the panel using a steel rod. The response of the panel was measured using electronic foil strain gauges; 14 were adhered to the front face-sheet and 16 to the rear face-sheet. These were situated along the horizontal, vertical and leading diagonal axes. Since the sandwich panels were square, only one quarter of each panel had strain gauges attached. The whole assembly was suspended from a crane and the center point was lowered into the test pond to a depth of 3.5 m. The setup of the blast test is shown in Fig. 1.

[1] As stated in the manufacturer data sheet [5].

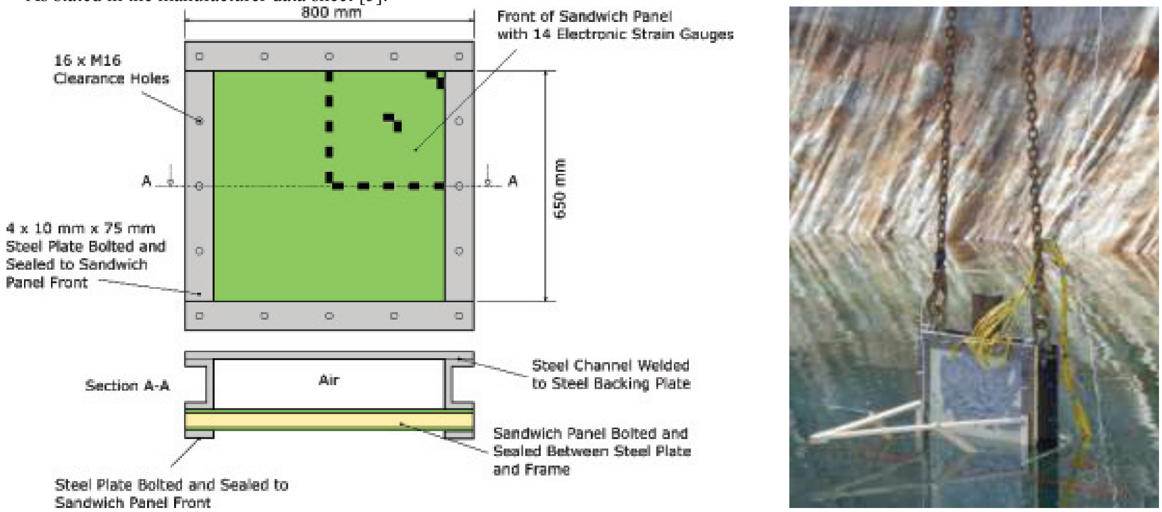

Fig. 1. (a) diagram of panel setup for underwater blast test; (b) photograph of panel being lowered into the water from crane without charge on pine frame.

3.2. Post blast damage assessment method

Following blast testing the damage suffered by each panel was analyzed using X-ray CT scanning. The large length to thickness ratio of the panels causes a large disparity in the power required to penetrate the panel at different angles and the panels would require 16 scans to fully capture them due to their size. For these reasons and to optimize the scanning efficiency whilst capturing the required level of detail, the panels were reduced from their original size. The outer 75 mm perimeter of the panels were removed and each panel was cut into three strips 271 mm x 650 mm in size. This reduction in size was minimized to prevent damaging the panels any further. The three strips from each panel were stacked within a clear PMMA (polymethyl methacrylate) tube creating a cuboidal structure, the panels were padded and held firmly in place within the tube using foam with a very low attenuation.

The panels were scanned in the Nikon 'hutch' μCT scanner at the University of Southampton. This custom machine has two X-ray sources: 225 W (225 kV, 1000 μA) and 450 W (450 kV, 1000 μA) and a 2000 x 2000 pixel flat panel detector [6]. Data was acquired in these scans using an accelerating potential of 200 kV and tube current of 390 μA. Three vertical detector positions were used to capture the length of the panels, at each position the panel assembly was rotated through 360°. A total of 3142 equiangular projections were acquired in each scan. The back projection resulted in an isometric voxel resolution of 0.1482 mm. A reconstruction of each panel was created by fusing the section scans using FEI Avizo software.

4. Results

In this section the key results from both the blast test that were recorded using foil strain gauges are reported, including a calculation for the out-of-plane displacement of the panels. Additionally, the and post blast damage assessment are reported.

4.1. Underwater blast results

The strain gauge readings for the GFRP panels show the core crushing phase, where the front face-sheet is in tension and back face-sheet in compression. This is followed by the expected 'bath tub' deflection, the back face-

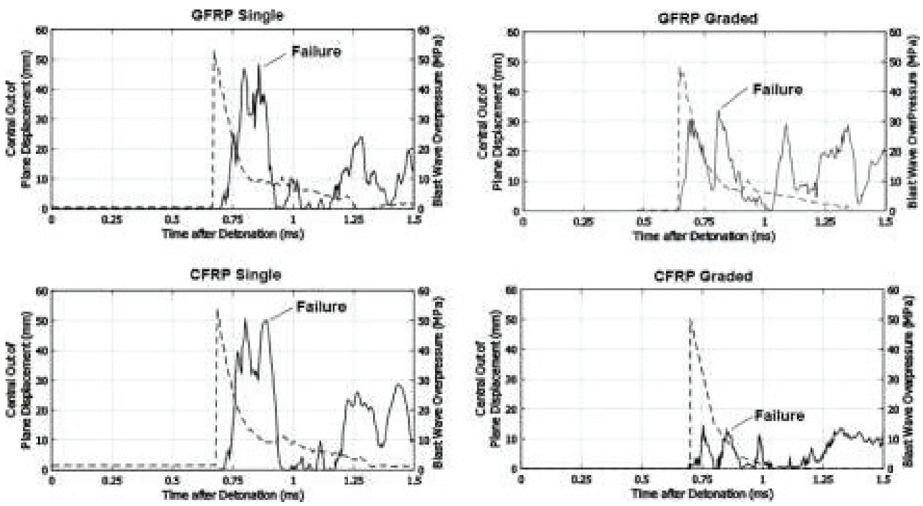

Fig. 2. Solid line: centre point out-of-plane displacement against time; dashed line: blast pressure profile.

sheet goes into tension and remains in tension until failure whilst the outer corners of both face-sheets are in compression. The strain in the graded GFRP panel builds up later than that of the single GFRP panel. The response of the single density core CFRP panel is similar to that of the GFRP panels. The graded CFRP panel, however, has a much flatter deflection shape which results in high strain at the boundaries. It is the boundaries that ultimately fail in tension.

The out-of-plane displacement of the panels could be calculated from the strain gauge results at their discreet locations then linearly interpolated to generate a displacement profile and to calculate the central out-of-plane displacement. The panel centerline strain was calculated by assuming no crushing occurs in the foam cores, which is not strictly true, and this centerline strain was used to calculate panel displacement. Despite the simplification, the values can be used to compare the relative displacement of the four panels tested and this displacement against time is shown in Fig. 2. The displacement is relative to the edge of the sandwich panel and, therefore, takes into account the deflection of the steel box. The blast pressure plot for the CFRP graded panel is calculated because a trace was not obtained during testing.

The results clearly show the reduction in panel displacement when a graded core is implemented. The GFRP panel with graded core deflected to 34 mm compared to the single core GFRP deflection of 48 mm. The reduction is even more significant for the panel with CFRP face-sheets. The out-of-plane displacement for the single and graded core CFRP panels was 50 mm and 13 mm respectively.

4.2. Damage assessment results

The majority of the damage to the sandwich panels was in the form of debonding between the front face-sheet and core and between the front core layers. In the graded core panels, the interfaces between the core layers arrested debonds and prevented them from propagating through the entire thickness of the panel. Fig. 3 and Fig. 4 shows regions where this is occurring in the CFRP and GFRP panel respectively.

The single core CFRP panel suffers from almost complete debonding between the front face-sheet and core, the panel is no longer able to transfer shear stresses between the face-sheets. The graded density core CFRP panel suffers from 10.3% less damage and experiences less core crushing. The single and graded core GFRP panels suffer from a similar amount of damage and core crushing. A summary of the damage is detailed in Table 2.

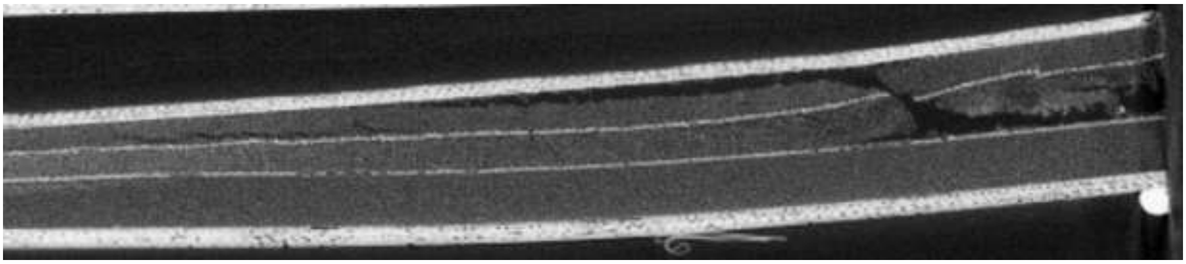

Fig. 3. X-ray CT scan showing region of debonding between front face-sheet and core on graded CFRP panel.

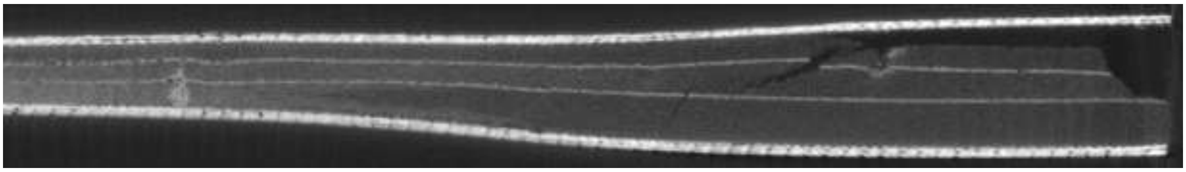

Fig. 4. X-ray CT scan showing region of debonding between front face-sheet and core on graded GFRP panel.

Table 2. Summary of damage to panels.

	GFRP		CFRP	
	Single	Graded	Single	Graded
Fraction of panel containing damage (%)	7.2	4.4	20.6	10.3
Fraction of panel with front face-sheet and core debond (%)	26.9	32.5	76.0	58.1
Fraction of panel with rear face-sheet and core debond (%)	18.2	9.3	15.2	31.8
Central point foam thickness (mm)	4.0	6.0	9.6	13.4

5. Discussion

Underwater blast testing aimed to reveal the relative performance of single density versus graded density SAN foam cores and GFRP versus CFRP face-sheets. The strain gauge results from the blast testing revealed the significant reduction in out-of-plane displacement that is achieved by implementing a graded density core. The post blast damage assessment revealed that the panels with graded density cores also suffer from less overall damage. However, the different face-sheets lead to different types of damage. The GFRP panels suffer from less debonding but more core crushing, whereas the higher stiffness of the CFRP face-sheets causes significant front face-sheet debonding. In the absence of a graded core, the single GFRP panel suffered from extensive core crushing and a large displacement whilst the single CFRP panel suffered from almost complete front face-sheet debonding. The choice of face-sheet material, therefore, results in a trade-off between out-of-plane displacement against panel damage, particularly debonding.

6. Conclusion

The main conclusions drawn from this research are summarized in the following points:

- The blast method and damage assessment method adopted successfully give a qualitative comparison of the performance of different composite sandwich panels.
- Employing a graded density SAN foam core reduces the panel deflection in underwater blast loading.

- A trade-off exists between reduced panel deflection and damage when selecting the face-sheet materials, an optimal combination should be identified.

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