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Blast performance of composite sandwich structures

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Abstract

A range of composite sandwich panels with different polymeric foam cores and face-sheets were subjected to full-scale air and underwater blast testing. The air blast panels had glass fiber reinforced polymer (GFRP) face-sheets with three different polymeric foam cores: styrene acrylonitrile (SAN), polyvinylchloride (PVC) and polymethacrylimide (PMI). The panels were subjected to 100 kg TNT equivalent charge from a stand-off of 15 m. The SAN panel had the lowest deflection and suffered from the least damage. The underwater blast panels had either a single density or graded density SAN foam core and either glass fiber reinforced polymer or carbon fiber reinforced polymer (CFRP) face-sheets. The research revealed that there is a trade-off between reduced panel deflection and damage. All the blast research that has been performed is part of a program sponsored by the Office of Naval Research (ONR).

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

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1. Introduction

Composite sandwich panels offer a number of advantages over traditional ship building materials including low radar signature, lightweight design, corrosion resistance and the combination of these factors to reduce fuel and maintenance costs. In naval applications the threat of an attack launched both at the surface and underwater is high, therefore the blast resistance of these composite sandwich panels is of high importance. Large scale composite

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sandwich panels with styrene acrylonitrile (SAN) foam cores were subjected to 30 kg C4 charges by Arora, Hooper and Dear [1]. Polyvinyl chloride (PVC) foam is a common choice for composite sandwich panel cores. Hoo Fatt and Palla used analytical solutions to predict the response of a PVC foam core sandwich panel when subjected to blast loading [2]. The low velocity impact behavior of composite sandwich panels with polymethacrylimide (PMI) foam cores was investigated by Shipsa and Zenkert along with the residual strength of the composite panels after impact [3]. SAN, PVC and PMI are common foam polymer types that are finding application in composite sandwich panels and this research will investigate the air blast performance of these three materials.

Underwater blast testing has been performed by Arora, Hooper and Dear on large composite sandwich panels [4]. The panels were subjected to a 1 kg C4 charge at distances of 1 m and 1.4 m. The same authors also investigated the relative air blast performance of composite sandwich panels with glass fiber reinforced polymer (GFRP) face-sheets against carbon fiber reinforced polymer (CFRP) face-sheets [5]. Additionally, the blast performance of graded density sandwich panels has been investigated by Gardner, Wang and Shukla [6]. The performance of graded density foam cores and of CFRP face-sheets when subjected to underwater blast will be investigated in this research.

This paper details the experimental procedures, results and post-blast damage assessment of the various composite sandwich panels tested. The suitability of the materials for blast applications are then analyzed.

2. Materials

These experiments investigated the performance of composite sandwich panels with differing foam cores under air and underwater blast. The air blast experiment was a comparative study of three different polymeric foam cores: PVC, SAN and PMI. The panels had 2 mm thick GFRP face-sheets and 40 mm thick foam cores, all cores had a density of 100 kg/m^3. The underwater blast experiment investigated the performance of a single density SAN foam core against a graded density SAN foam core along with the effect of GFRP versus CFRP face-sheets. The face-sheets were 2 mm thick and the foam cores were 30 mm thick.

3. Experimental procedure

This section details the experimental setups for air and underwater blast loading, including the instrumentation required to capture the panel response. All blast testing was performed at GL DNV, RAF Spadeadam in Cumbria, UK. The post-blast damage assessment techniques for both sets of blast experiments are also described.

3.1. Air blast setup

All blast testing was performed at GL DNV, RAF Spadeadam in Cumbria, UK. A 100 kg TNT equivalent charge (100 kg nitromethane) was placed at a stand-off distance of 15 m from the front of the composite sandwich panels. The test panels were bolted to a test cubicle with a reinforced steel front supported by concrete culverts. The panels were held in place by 20 x M16 bolts around the perimeter of the panel, with steel tubes inserted through the panel thickness to prevent crushing upon tightening of the bolts. A camera was placed 25 m away from the front of the panel to record the blast event, to ensure any unexpected events were recorded and could be accounted for in the results. A schematic of the test setup is shown in Fig. 1.

The full field displacement of the panels was recorded using a pair of high speed Photron SA1.1 cameras situated behind the test panel. The cameras recorded 5400 frames per second at a 1 megapixel resolution. The cameras were calibrated for 3D DIC and the sets of images were post-processed using Aramis DIC software to extract the back face-sheet displacement and strain. A reflected pressure gauge was placed on the center of the test cubicle below the panels and a side-on pressure gauge was placed 15 m from the charge at the same height as the center of the composite panels.

3.2. Post air blast damage assessment

Following air blast testing, the panels were sectioned into 112 pieces, and each edge was inspected for core cracks and face-sheet core debonds. The sections were different in size to enable edgewise, flatwise and flexural residual strength testing. The damage was quantified and mapped to enable comparison between the three panels.

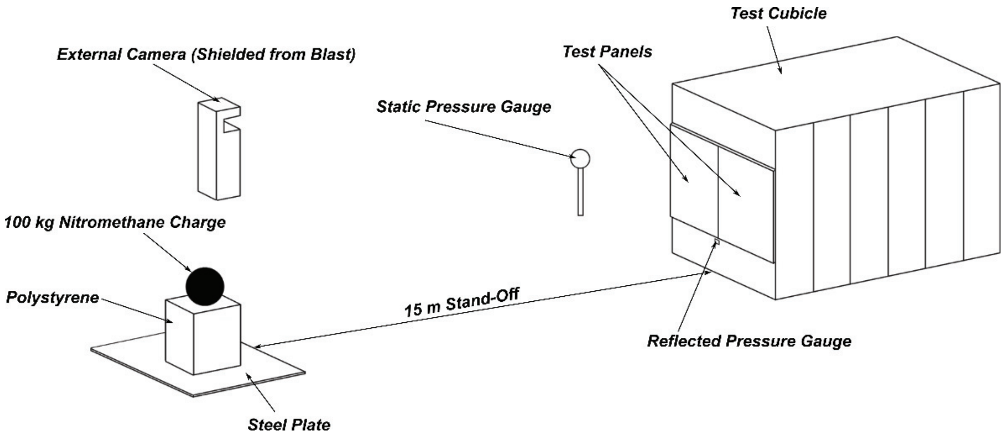

Fig. 1. Schematic of air blast setup.

3.3. Underwater blast setup

During the underwater blast experiment, the composite sandwich panels were bolted into a steel box using 20 x M16 bolts around the perimeter. Again, steel tubes were inserted to prevent the panel from crushing upon tightening the bolts. The steel box was designed such that a 0.65 x 0.65 m section of the panel was unsupported and air backed. A 1 kg Plastic Explosive 4 (PE4) charge was held 1 m from the center of the panel using a pine frame. This assembly was suspended from a crane and lowered into the test pond so the center of the panel was at a depth of 3.5 m. The underwater test setup is shown in Fig. 2.

One quarter of the panel was instrumented with 14 foil strain gauges on the front face-sheet and 16 foil strain gauges on the rear face-sheet. By instrumenting a quarter of the panel, it was assumed that the panel response was symmetric. A reflected pressure gauge was placed on the centerline of the steel box above the panel and a side-on pressure gauge was attached to the end of a curved steel rod such that it was at the same distance as the panel from the charge.

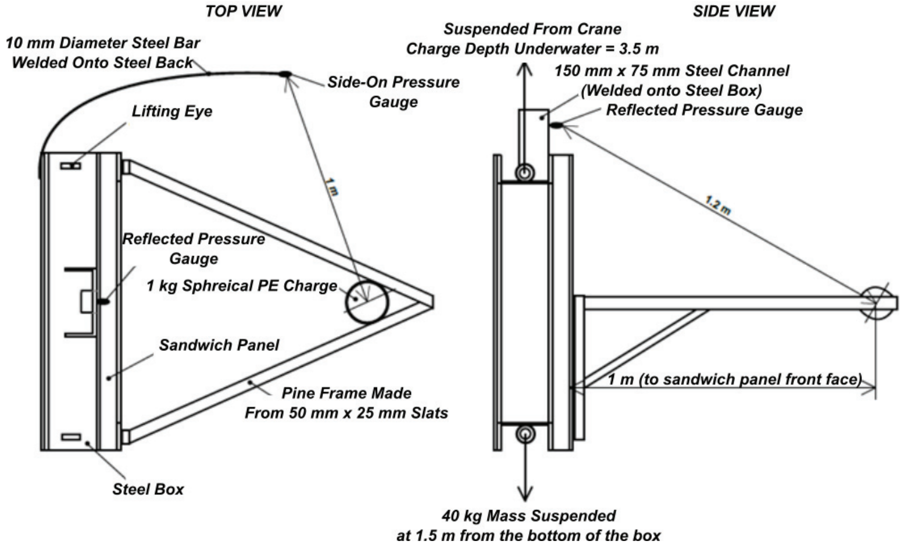

Fig. 2. Schematic of underwater blast steel box.

3.4. Post underwater blast damage assessment

After the blast the composite sandwich panels were sectioned into three pieces to enable X-ray CT scanning. The panel sections were scanned in the Nikon/Metris custom design machine at the University of Southampton. The machine has a flat panel detector with a resolution of 2000 x 2000 pixels. Three vertical detector positions were used to capture the length of the panels, and at each position the panels were rotated through 360°.

4. Test results

During the air blast experiment the out-of-plane displacement of the panels was recorded using DIC, whereas foil strain gauges were used to capture the panel response in the underwater blast experiment. In this section of the paper, key results from both blast experiments are presented along with the post-blast damage assessment.

4.1. Air blast results

Fig. 3 shows the displacement of the horizontal center line of the three panels, the positive displacements are shown in (a) and the panel rebounds are shown in (b). The initial displacement and pull-out of the PVC and PMI panels are greater than the SAN panel. This indicates that the SAN foam core is more resistant to the momentum of the blast and suffers less core damage which results in a lower pull-out displacement.

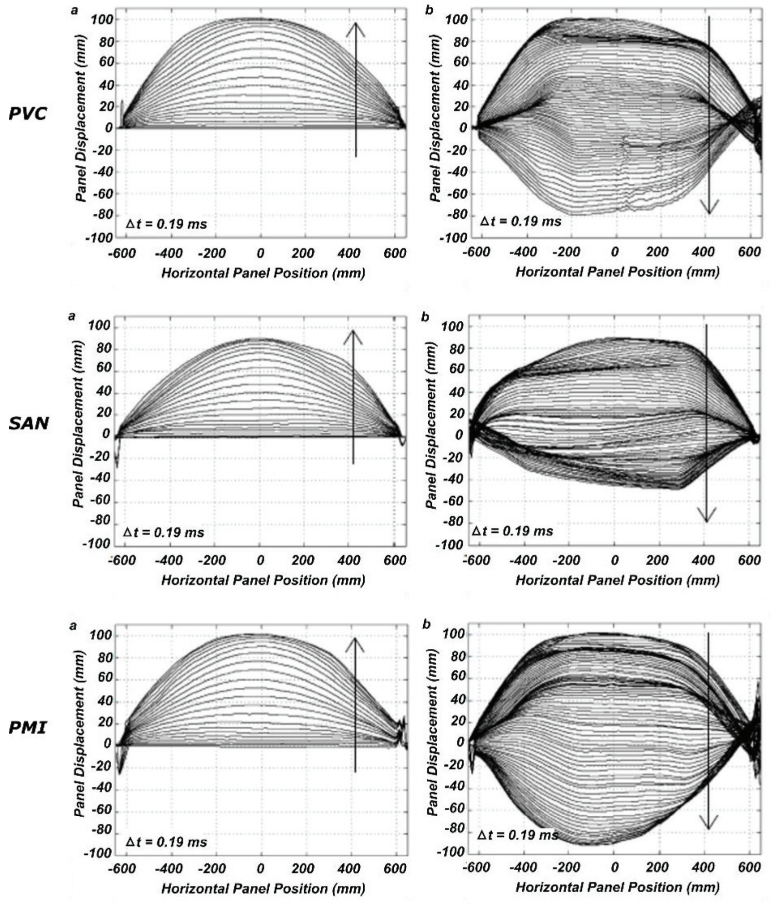

Fig. 3. The out-of-plane displacement of the three sandwich panels measured using DIC.

4.2. Air blast damage assessment

The three panels were sectioned and visually inspected for damage following the blast experiment. The location of damage was recorded and is shown for the PVC and SAN foam core sandwich panels in Fig. 4 and Fig. 5 respectively. It was not possible to section the PMI foam core sandwich panel due to extensive damage, around 75% of the panel was damaged with a mixture of debonding and cracking. It is clear from the inspection that the SAN panel suffered from the least damage.

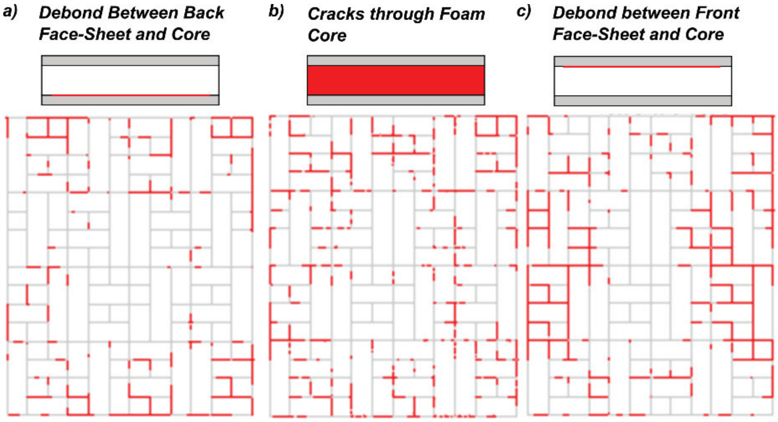

Fig. 4. Schematic of the locations of debonding and cracking (red lines) in the PVC foam core panel.

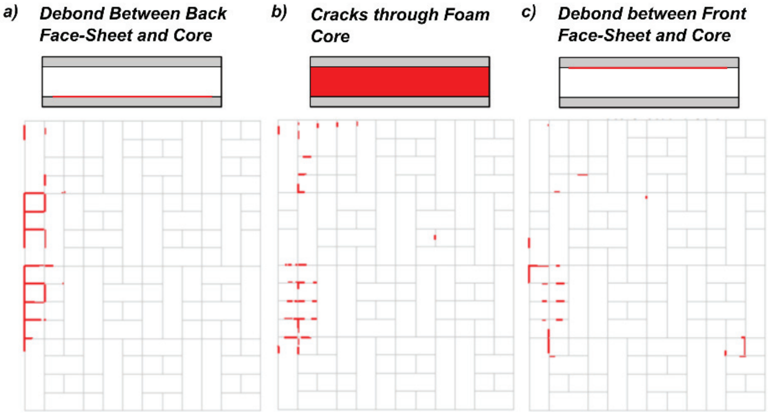

Fig. 5. Schematic of the locations of debonding and cracking (red lines) in the SAN foam core panel.

4.3. Underwater blast results

The out-of-plane displacement of the composite sandwich panels was calculated from the centerline strain using data from the strain gauges. The traces of central out-of-plane displacement are shown in Fig. 6 for the four panels (solid line) along with the recorded pressure trace (dashed line). The pressure plot in the graded CFRP graph (d) was calculated as a trace was not obtained during testing. It is clear that the graded density core reduces the out-of-plane displacement of the panels and the effect is more significant for a panel with CFRP face-sheets.

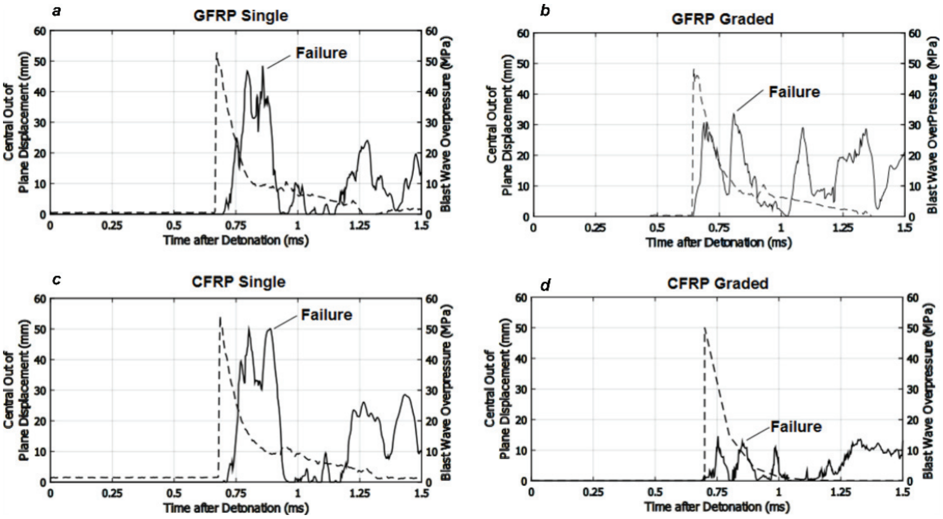

Fig. 6. Out-of-plane displacement (solid line) and pressure traces (dashed line) for the four composite sandwich panels subjected to an underwater explosion.

4.4. Underwater blast damage assessment

The regions of delamination, cracking and damage have been highlighted in the reconstructions of the panel from the X-ray CT data. These are shown in Fig. 7. The CFRP panel with a single foam core suffers from the greatest damage, the front face-sheet and almost completely debonded from the core. The single and graded core GFRP panels suffer a similar amount of damage, however, the graded panels suffers from debonding between layers in the core rather than through-thickness cracking.

5. Discussion

The air blast testing performed aimed to compare the resilience of three polymeric foam core materials. The panels were of the same thickness and contained cores with 100 kg/m^3 densities. DIC was used to record the out-of-plane displacement of the panels and visual inspection revealed the damage to the panel after the blast. The DIC data revealed the superior performance of the SAN foam core. The SAN panel deflected 10 mm less than the other panels and, although the discontinuities in the deflection reveal that core cracking did occur, the core cracking was the lowest of the three materials. This resulted in a lower pull-out displacement. The post blast damage assessment confirmed that SAN suffered from the least core cracking and debonding and the face-sheet core interfaces.

The underwater blast testing showed the relative performance of single density versus graded density SAN cores along with GFRP versus CFRP face-sheets. Strain gauges were mounted to the panels to record face-sheet strain and X-ray CT was used to assess the damage inflicted on the panels. The strain gauge results revealed a significant reduction in out-of-plane displacement is achieved by implementing graded density SAN foam cores. Post blast damage analysis, however, revealed that this reduced displacement results in greater panel damage. The graded GFRP panel suffered from less damage than the graded CFRP panel and there is, therefore, a trade-off between the reduced out-of-plane displacement from the high stiffness CFRP versus reduced damage from the more ductile GFRP.

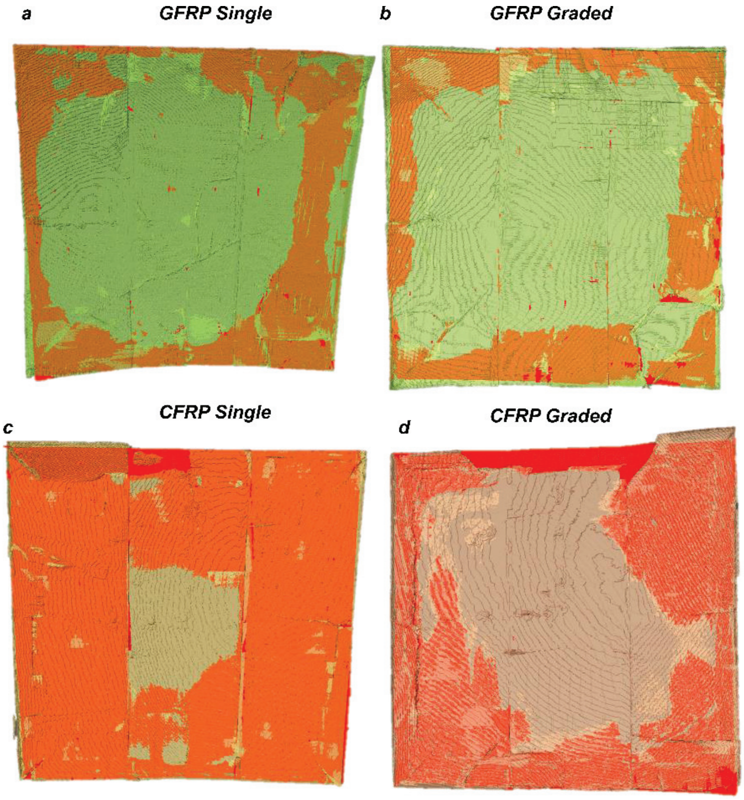

Fig. 7. 3D reconstructions of panels following underwater blast testing with damage highlighted in red.

6. Conclusion

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

- SAN foam polymer core has the lowest deflection and pull-out of the three polymer foams tested under air blast.
- The low deflection and pull-out of the SAN panel is a result of less damage as the stiffness of the panel is retained.
- Implementing a graded density SAN core reduces the panel deflection in underwater blast loading.
- There is a trade-off between reduced panel deflection and damage, an optimal combination needs to be identified.

Acknowledgements

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