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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.

The research presented in this paper investigates the effect of two different types of composite skin material and two different core constructions against air and underwater blast loading. The different composite skins tested were glass-fibre reinforced polymer (GFRP) and carbon-fibre reinforced polymer (CFRP). These panels had a styrene acrylonitrile (SAN) foam core and were subjected to an equal underwater blast. Further underwater blast testing was performed on a second GFRP panel and a second CFRP panel with stepwise graded cores. The graded cores consisted of three layers of SAN foam with different densities arranged so that the lowest density sheet was on the blast side and the highest density furthest away from the blast. Finally, a GFRP panel with a single density core and a GFRP panel with a graded density core were subjected to an air blast load.

The experiments performed 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. This investigation intended to determine whether the progressive absorption of blast energy by composite panels with graded foam cores, demonstrated under shock tube loading, occurs under loading against explosive charges. Additionally, whether this graded core configuration is advantageous against both air and underwater explosive loads. Furthermore, in field experiments, there are more environmental effects that can alter the panel response. The direct comparison of GFRP versus CFRP skins underwater has not previously been investigated. The performance was analysed to determine the effect of increased strength but reduced strain to failure of the CFRP skins compared to GFRP skins in underwater blast. Although the increased strength of CFRP skins proved beneficial in air blast [16], this may not be the case in a denser medium.

2. Materials and methods

2.1. Sandwich panel materials

The performance of composite sandwich panels with graded density foam cores was evaluated in both air and underwater blast experiments. Four composite sandwich panels were subjected to a 1 kg plastic explosive charge at 1 m stand-off underwater. Two of the panels had GFRP skins constructed from two Gurit QE1200 quadriaxial plies infused with SR8500/SD8601 Sicomin epoxy. The remaining two panels used four plies of Gurit biaxial XC411 carbon fibre as skins and the same epoxy system. The panels had either a 30 mm thick single density foam core of Gurit M130 SAN foam or a graded density foam core. The graded density foam core consisted of 10 mm layers of Gurit M100, M130 and M200 SAN foam arranged so the lowest density was closest to the blast and the highest density furthest from the blast. The panels were 800 mm square. In order to manufacture the panels, they were drawn to vacuum and held at room temperature for 24 h. The panel temperature was then elevated to 85 °C at a rate of 1 °C/min and held for 12 h before being allowed to return back to room temperature. A further two panels were subjected to 100 kg TNT equivalent charge at a stand-off distance of 15 m in air. The panels both had Gurit QE1200 quadriaxial GFRP face skins, one with a 40 mm single density M100 SAN foam core and the second with a 30 mm graded density SAN foam core. The air blast panels were manufactured using the same process but adopting a ST 94 film epoxy resin. The air blast panels were larger in size: 1.4 × 1.7 m. The details of the six panels tested are summarised in Table 1.

Table 1
Summary of the panel types.

Blast type	Face-sheet fibre type	Core foam material	Core density (kg/m^3)
Air	Glass	SAN M130	140[a]
Air	Glass	Graded SAN (M100/M130/M200)	108/140/200[a]
Underwater	Glass	SAN M130	140[a]
Underwater	Carbon	SAN M130	140[a]
Underwater	Glass	Graded SAN (M100/M130/M200)	108/140/200[a]
Underwater	Carbon	Graded SAN (M100/M130/M200)	108/140/200[a]

[a] Values stated in the manufacturer data sheet [33].

2.2. Underwater blast experiment design and instrumentation

The blast experiments were performed at the DNV GL site at RAF Spadeadam, Cumbria, UK. In order to contain the sandwich panel, a steel channel box was assembled by butt welding steel channels together with the flanges outwards. To create an enclosed volume of air behind the panel, a 10 mm thick steel plate was sealed and bolted to the back of the box. 10 mm thick steel strips were sealed around the perimeter of the front of the panel using Sikaflex 291i marine sealing adhesive and the panel was bolted to the front of the steel box. Crushing of the sandwich panel by the bolts was prevented by inserting steel tubes into the panel bolt holes. The steel box assembly left an unsupported area of the panel 0.65 × 0.65 m in size.

The 1 kg explosive source was a spherical plastic explosive 4 (PE4) charge and was placed 1 m from the front of the sandwich panel. The equivalent weight in TNT of this charge is 1.28 kg. The charge was held in place by attaching it to a pine frame bolted to the front of the steel box. The whole assembly was suspended from a crane and was lowered to a charge depth of 3.5 m. A 40 kg weight was suspended from the bottom of the steel box to keep it vertical underwater. The reflected and side-on pressure during the blast were measured using two Neptune Sonar T11 gauges. The side-on pressure gauge was attached to a 10 mm diameter steel bar and was located 1 m away from the charge, this measured the peak overpressure created by the blast. The reflected pressure gauge recorded the loading on the structure which is greater than the incident overpressure as the blast wave is brought to rest and further compressed to cause a reflection. Both pressure gauges measure the change in pressure so total pressure inflicted upon the panel is the pressure recorded plus hydrostatic pressure. Although the steel frame is able to translate forwards, backwards and laterally, and this movement may differ between experiments, the reflected pressure gauge will record the loading on the frame and indicate whether there is a large disparity between experiments. The response of the composite sandwich panels were recorded using 30 electronic foil strain gauges. One quarter of each panel was instrumented, due to symmetry of the panel, with 14 gauges on the front face-sheet and 16 on the rear. The strain gauges were TML FLA-2-350-11 350 Ω [28], adhered with TML CN adhesive [29]. The experimental set up is shown in Fig. 1 along with a sequence of photographs taken during the blast event, a schematic showing the location of the strain gauges is shown in Fig. 2.

2.3. Air blast experiment design and instrumentation

The sandwich panels were bolted to the front of a test cubicle which was a reinforced steel frontage attached to concrete culverts. Steel strips were adhered to the front of the panel using Sikaflex 291i marine sealing adhesive and steel tubes were placed in the panel bolt holes to prevent crushing of the panel. The charge was raised to the centre height of the panel by placing it on polystyrene foam with a thick steel plate underneath to create an elastic foundation for the initial blast wave upon detonation.

To record the blast pressure a PCB 102A06 gauge was placed on the front of the test cubicle between the two panels to record the

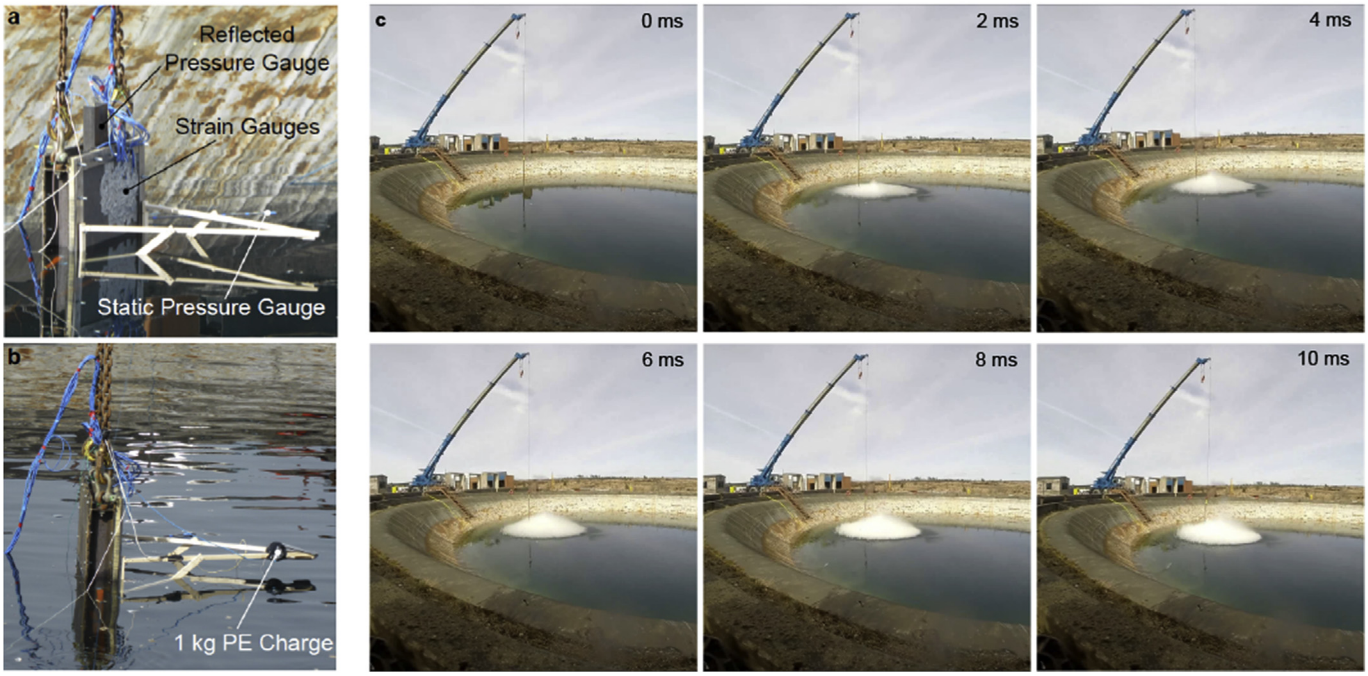

Fig. 1. Photographs showing the underwater blast experiment; a) the single core CFRP assembly before the charge was assembled; b) the single core CFRP assembly with the charge; c) sequential photographs during underwater blast loading [32].

reflected pressure and a second PCB 102A06 gauge was placed 15 m from the blast at the same height as the centre of the panels to record the side-on pressure. The out-of-plane displacement of the panels was recorded using digital image correlation (DIC). A pair of high-speed cameras was placed behind each panel, four cameras in total, and the rear face of the panel was speckled with paint to enable displacement tracking. The high speed cameras were Photron SA1.1's and Photron SA5's, which sampled at 5400 fps and 7000 fps respectively at full resolution (1024 × 1024 pixels). A photograph of the test cubicle and diagram of the high speed camera setup is shown in Fig. 3.

2.4. Post-blast damage assessment

Following blast loading, the damage sustained by the underwater panels was evaluated using X-ray computed tomography (CT). In order to capture the required level of detail and optimise scanning efficiency, the panels were reduced from their original size. The outer 75 mm perimeter was removed and the panels were divided into three strips 217 mm × 650 mm in size. The three parts of each panel were then stacked in a Perspex tube and padded with foam to create a cuboidal structure. A photograph of one of the panels after it has been cut into strips and a schematic diagram of the X-ray scan setup is shown in Fig. 4. The Nikon 'hutch' μCT scanner at the University of Southampton was used to scan the panels. The accelerating potential used was 200 kV and the tube current was 390 μA. The scanner had a flat panel detector with 2000 × 2000 isometric elements. The length of the sandwich panels were captured using three vertical positions. An isometric voxel resolution of 148 μm was achieved. The panels that underwent air blast testing were analysed for damage through visual inspection. The full-size panels were cut into 112 pieces and the cracks and debonds along each edge was recorded and used to estimate the crack density and area of debonding of each piece.

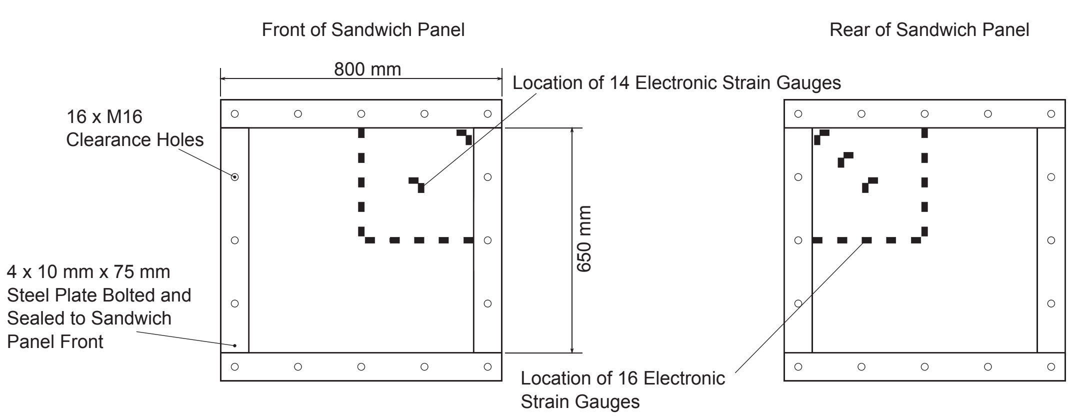

Fig. 2. The location of the adhered strain gauges on the front and rear of the sandwich panel.

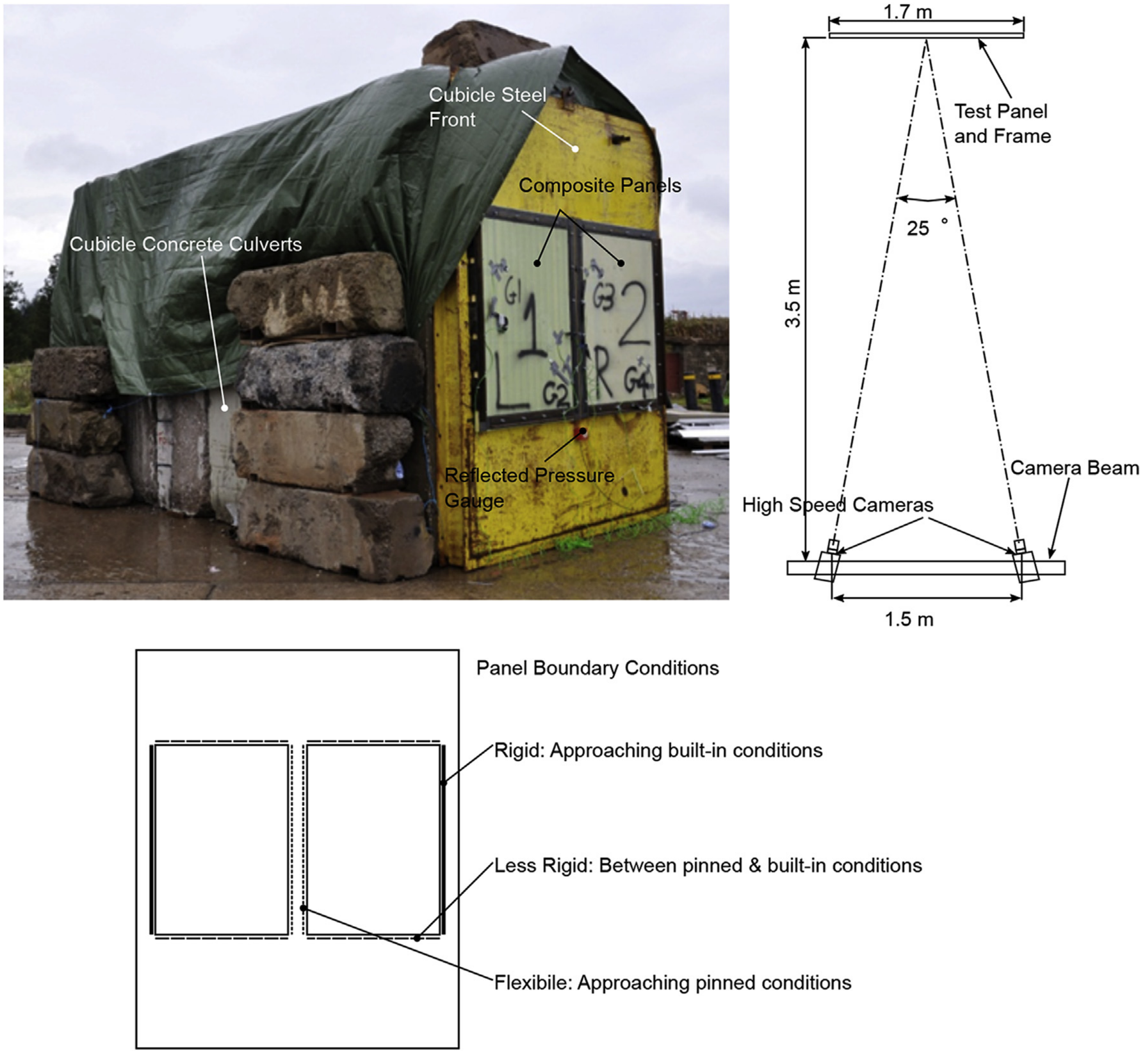

Fig. 3. Photograph showing the sandwich panels bolted into the test cubicle, a diagram of camera setup inside test cubicle for digital image correlation and a schematic of the boundary conditions along each panel edge [32].

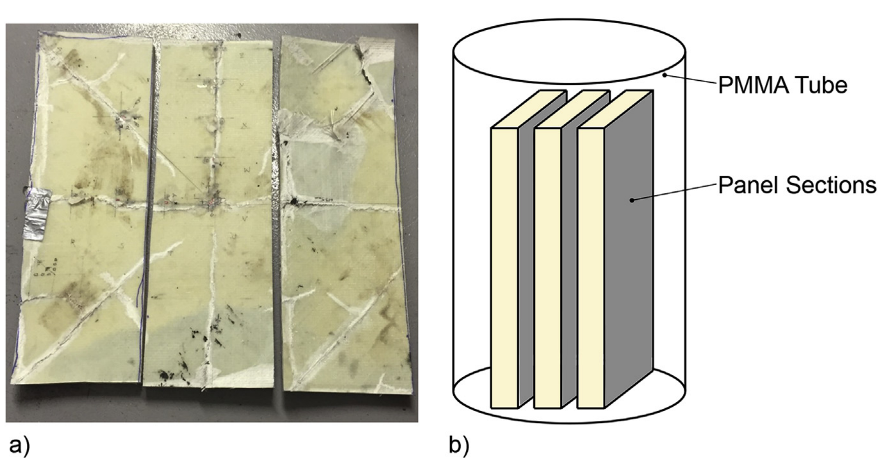

Fig. 4. a) A photograph showing the single density GFRP panel after it had been reduced in size for X-ray CT scanning; b) a schematic of the X-ray CT scanning setup.

3. Results

3.1. Underwater blast loading of GFRP-skinned single and graded density core panels

The high frequency noise was eliminated from the raw strain gauge data by applying a low-pass moving average filter. Filtered strain gauge traces for the panel with GFRP face-sheets and a single density core are shown in Fig. 5. The location of the strain gauge on the panel is shown on the left hand side of the figure and the corresponding traces are on the right hand side. The blast overpressure against time is shown below the strain gauge traces. To aid visualisation of the strain data, the strain values were interpolated between the discrete strain gauge locations along each leading direction and assigned colours to create strain contour plots. The contour plots have revealed that higher levels of strain (shown in red) were recorded on the back face-sheet of all panels. The contour plots for the single and graded density GFRP panels are shown in Figs. 6 and 7 respectively.

The effect of the blast wave is felt by the single density core GFRP panel approximately 0.7 ms after charge detonation. Initially, the front face goes into tension and the rear into compression as the foam core is crushed. Subsequently, the rear face switches into tension and remains in tension until failure. A combination of bending and membrane loading on the front skin results in approximately zero strain. The panel deflects into the characteristic 'bath tub' shape which is apparent from the data as compression occurs at the outer edges of the panel. The panel fails at 0.9 ms when it becomes debonded from the steel box on all sides and both faces. The graded core GFRP panel response differs from the single core panel in that the critical failure strain on the rear face builds up at a later time. The graded panel also fails due to sealant debonding from the steel box and this occurs at 0.85 ms.

3.2. Underwater blast loading of CFRP-skinned single and graded density core panels

The contour plots for the single and graded density CFRP panels are shown in Figs. 8 and 9 respectively. The CFRP panel with a single density core responds in a similar manner to the two GFRP panels. The blast wave reaches the panel approximately 0.6 ms after detonation and the panel fails at 0.93 ms. Compression at the outer corners due to 'bath tub' deflection is evident. Greater strain is experienced on the rear face of the panel and lesser on the front, as is the case with the GFRP panels. This CFRP panel fails due to fracture of the back skin. The graded core CFRP panels shows a significantly different response. Due to the high stiffness of the carbon-fibre skins and graded core, the panel deflection is much flatter in shape which causes high strain at the boundary. The panel ultimately fails due to fracturing of the back skin.

3.3. Out-of-plane displacement of the underwater blast panels

The out-of-plane displacement of the central point of each panel can be calculated by linearly interpolating the strains measured at the strain gauge locations. The calculation assumes that no

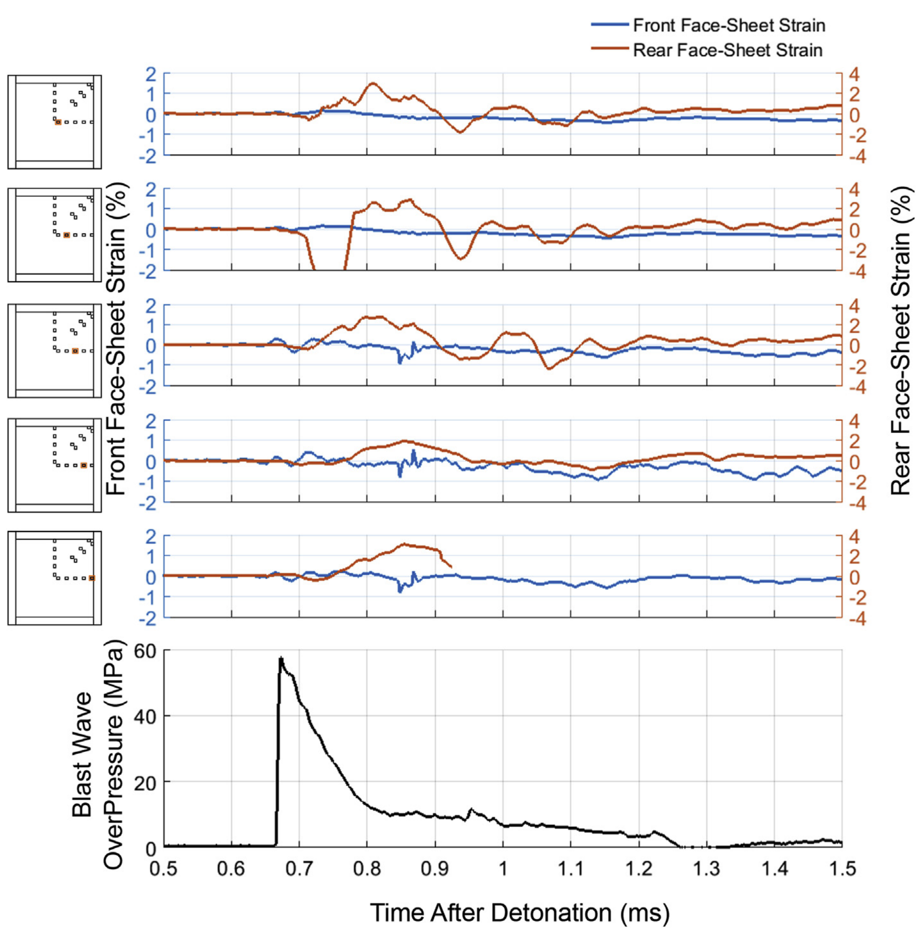

Fig. 5. Filtered variation of strain with time for the single core GFRP sandwich panel; the location of the strain gauges are shown on the left hand side and corresponding strain on the right hand side and blast wave overpressure against time.

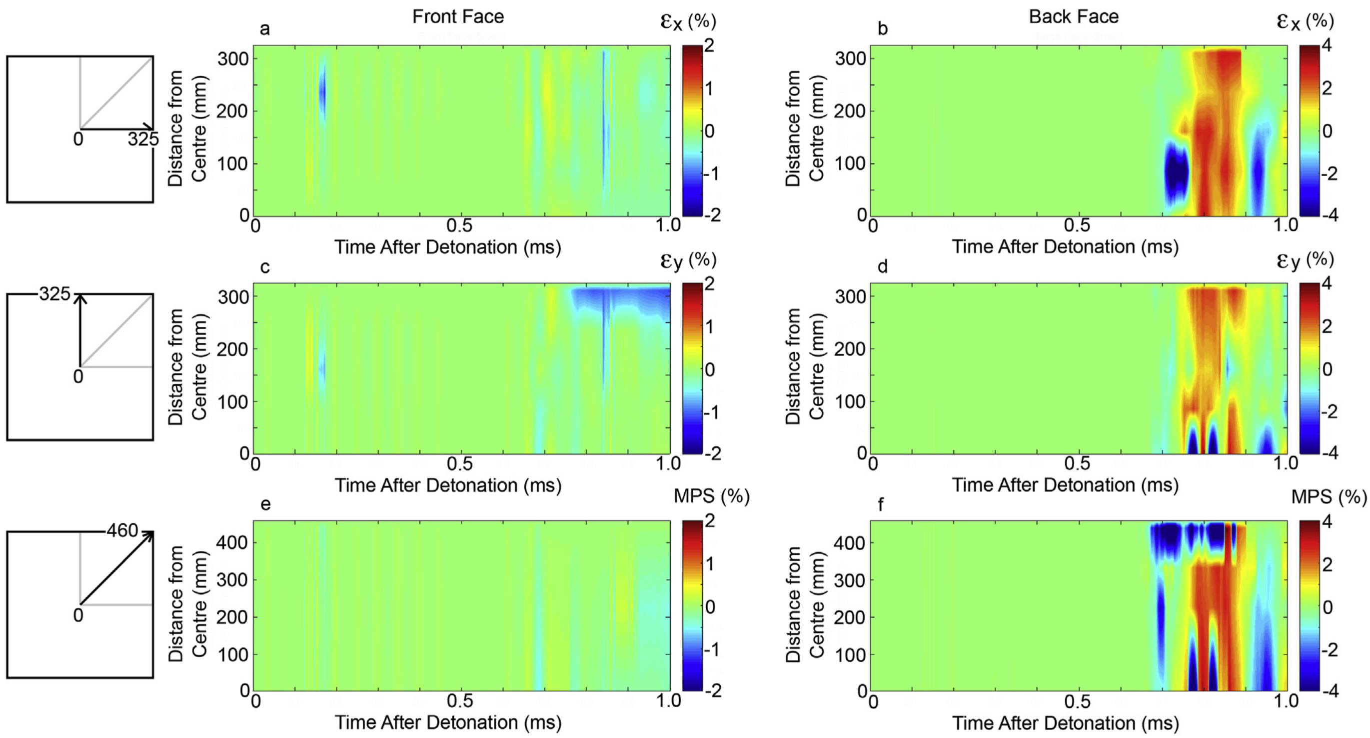

Fig. 6. Variation of strain with time for a) the horizontal section of the front face; b) the horizontal section of the back face; c) the vertical section of the front face; d) the vertical section of the back face; e) the diagonal section of the front face; and f) the diagonal section of the back face, for the single core GFRP sandwich panel [32].

crushing of the panels occurs as a result of the blast which is a simplification. Nevertheless, the values can still be used as an indicator to compare the performance of the different panel configurations. The deflection calculated is relative to the edge of the sandwich panel, therefore taking into account the deflection of the steel box. These calculated displacements are shown in Fig. 10. It can clearly be seen that implementing a graded core significantly reduces the out-of-plane displacement of the panels. The graded

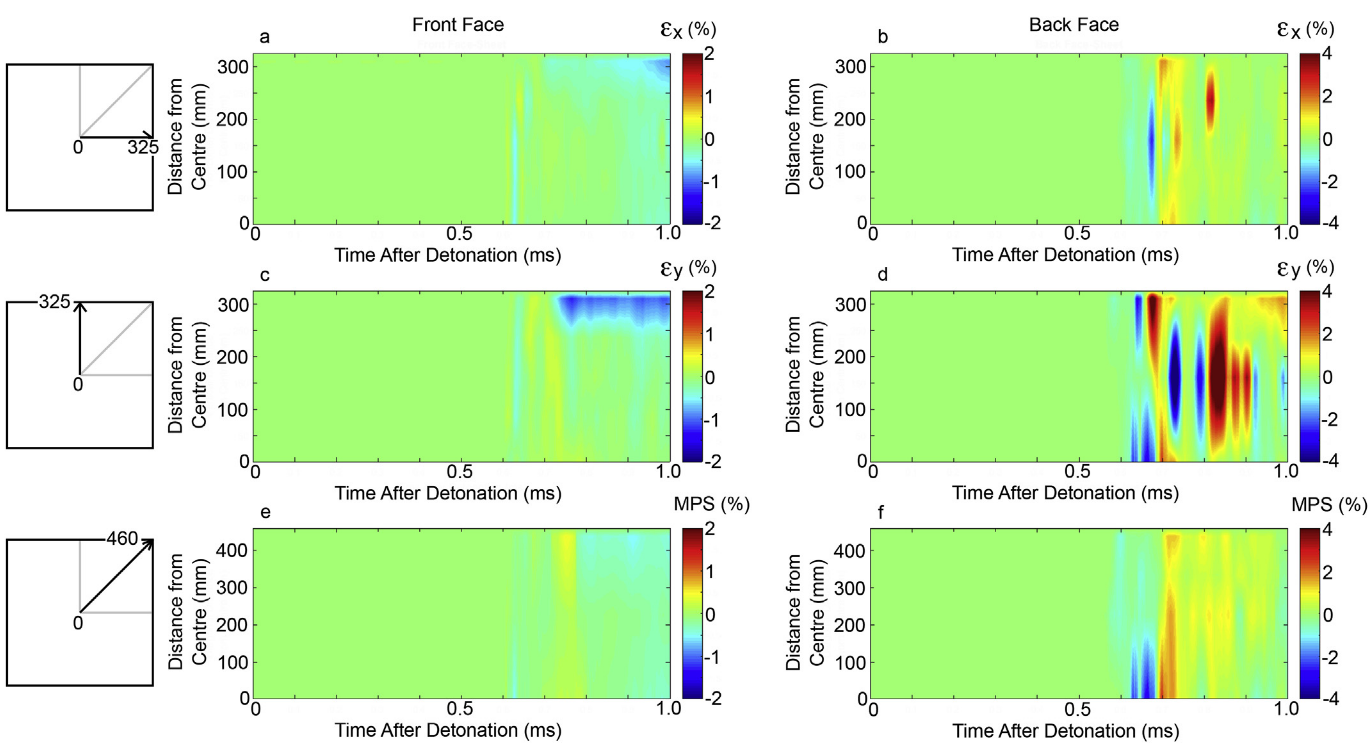

Fig. 7. Variation of strain with time for a) the horizontal section of the front face; b) the horizontal section of the back face; c) the vertical section of the front face; d) the vertical section of the back face; e) the diagonal section of the front face; and f) the diagonal section of the back face, for the graded core GFRP sandwich panel [32].

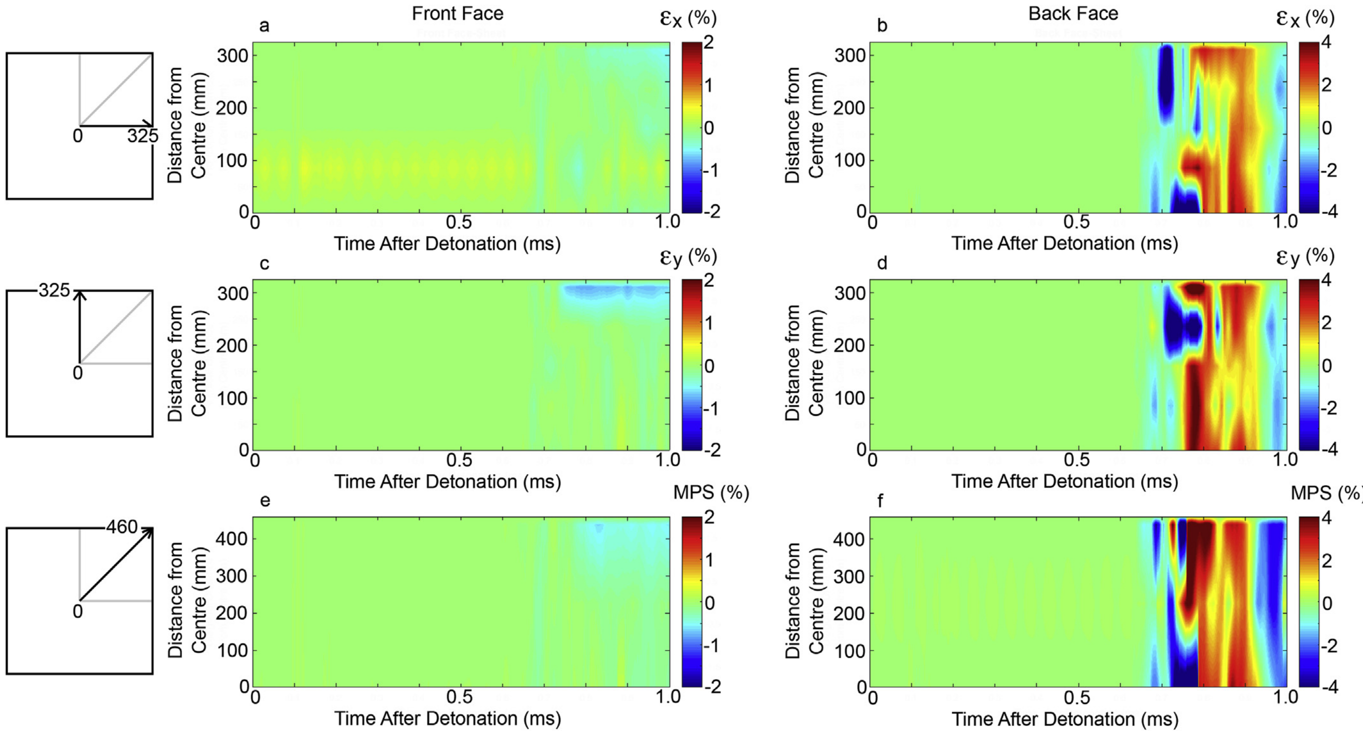

Fig. 8. Variation of strain with time for a) the horizontal section of the front face; b) the horizontal section of the back face; c) the vertical section of the front face; d) the vertical section of the back face; e) the diagonal section of the front face; and f) the diagonal section of the back face, for the single core CFRP sandwich panel [32].

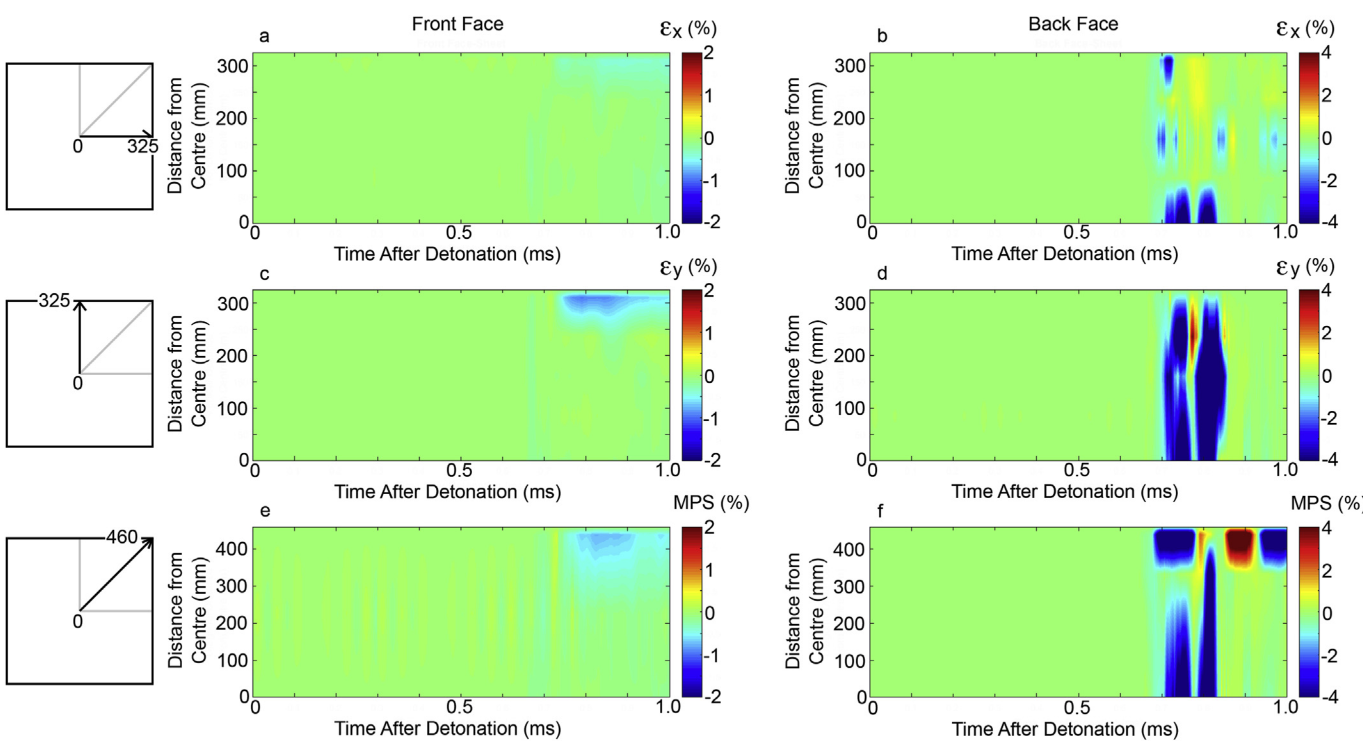

Fig. 9. Variation of strain with time for a) the horizontal section of the front face; b) the horizontal section of the back face; c) the vertical section of the front face; d) the vertical section of the back face; e) the diagonal section of the front face; and f) the diagonal section of the back face, for the graded core GFRP sandwich panel [32].

GFRP displacement at failure was 34 mm compared to 48 mm for the single core panel. The reduction for the CFRP panels was even more significant, reducing from 50 mm to 13 mm. These displacements have been verified from the X-ray scans of the panels. The permanent deflection of the panels away from the horizontal plane was calculated from the scans and the severity of the permanent deflection correlates with the deflection during blast loading calculated from the strain gauge data.

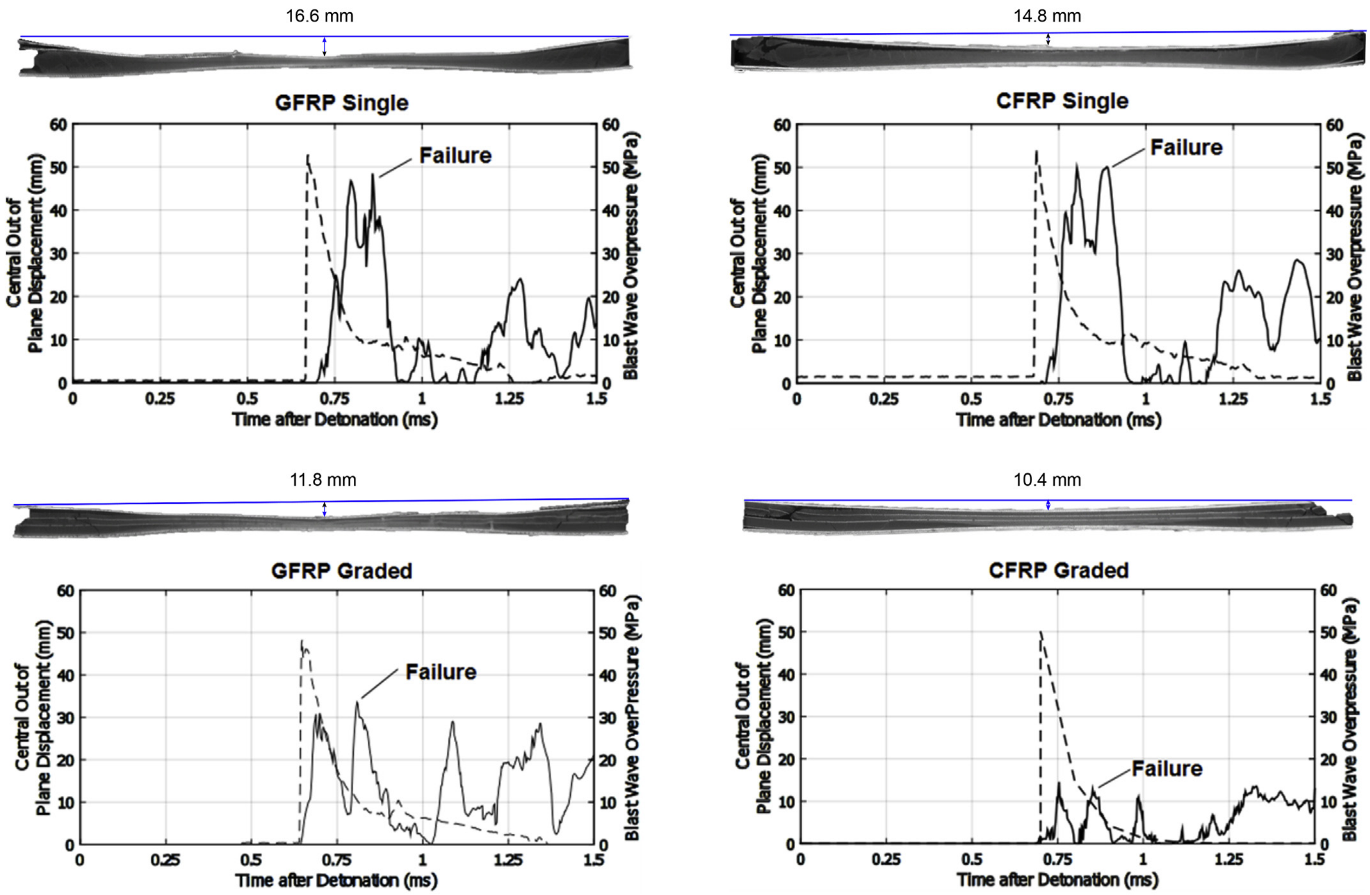

Fig. 10. The central deflection and the side-on blast pressure (calculated for the graded CFRP) for the four composite sandwich panels and X-ray CT scan images showing the permanent panel deflection [32].

3.4. Air blast loading of GFRP-skinned single and graded density core panels

Comparison of the DIC results revealed that the out-of-plane displacement of the graded core panel is very smooth. This arises as the lower density foam layers crack first, due to their lower elastic moduli and proximity to the blast, resulting in less cracking of the rear-most layer and hence protecting the rear skin. The 30 mm thick graded panel deflected more than the 40 mm single density panel but this can be attributed to its reduced thickness. Arora [30] compared the performance of composite sandwich panels with varying core thicknesses and found that the reduction of a SAN foam core from 40 mm to 30 mm results in an out-of-plane displacement 1.3 times greater when subjected to the same charge at 14 m stand-off distance. The materials, core thicknesses and stand-off distance investigated by Arora are similar to those used in this research. Therefore, based on this observation, if the 40 mm single core panel in this experiment were to be reduced to 30 mm, the out-of-plane displacement observed would have been 117 mm. This is greater than the out-of-plane displacement of the graded core panel. Additionally, the graded core panel had a shorter rebound time than the single density panel indicating that it suffered from less core damage. A sequence of photographs taken during air blast loading along with the out-of-plane displacement of the horizontal centre section of the graded panel and the 40 mm thick single core panel are shown in Fig. 11. Following air blast loading, the panels were visually inspected for damage. This revealed that through thickness cracking in the graded core panel is reduced. Core cracks are arrested at the interfaces between the core layers and propagate as debonds between the core layers before continuing through the core or being halted. Although the overall number of cracks in the graded and single core panels are similar, the graded core reduces critical skin to skin cracks which result in the panel losing the ability to transfer shear loads. Fig. 11 (c) shows the crack paths and delamination found in the graded core panel after blast loading and Fig. 11 (d) shows the pressure time trace for the graded panel blast.

3.5. Post-blast damage assessment

Following the underwater blast experiment, the damage inflicted upon the four panels was evaluated using X-ray CT scanning. The 3D reconstruction of the single core GFRP panel from the X-ray data is shown in Fig. 12 along with CT scans showing cross-sectional views of the panel and hence the damage. 1–2 mm of material was removed from the panels when they were cut into three sections, hence the separate scans do not align exactly. The scans revealed that the single core GFRP panel suffers from more damage (debonding, core crushing and core cracking) than its equivalent graded core GFRP panel. The X-ray data for the graded core GFRP panel is shown in Fig. 13. Both panels experienced a similar level of core crushing, the single and graded cores crushed to 4 mm and 6 mm at their centre points respectively. The crushing of the panels is non-uniform, as shown in the figures, with the degree of crushing increasing towards the panel centre. The single core CFRP panel reconstruction and scans are shown in

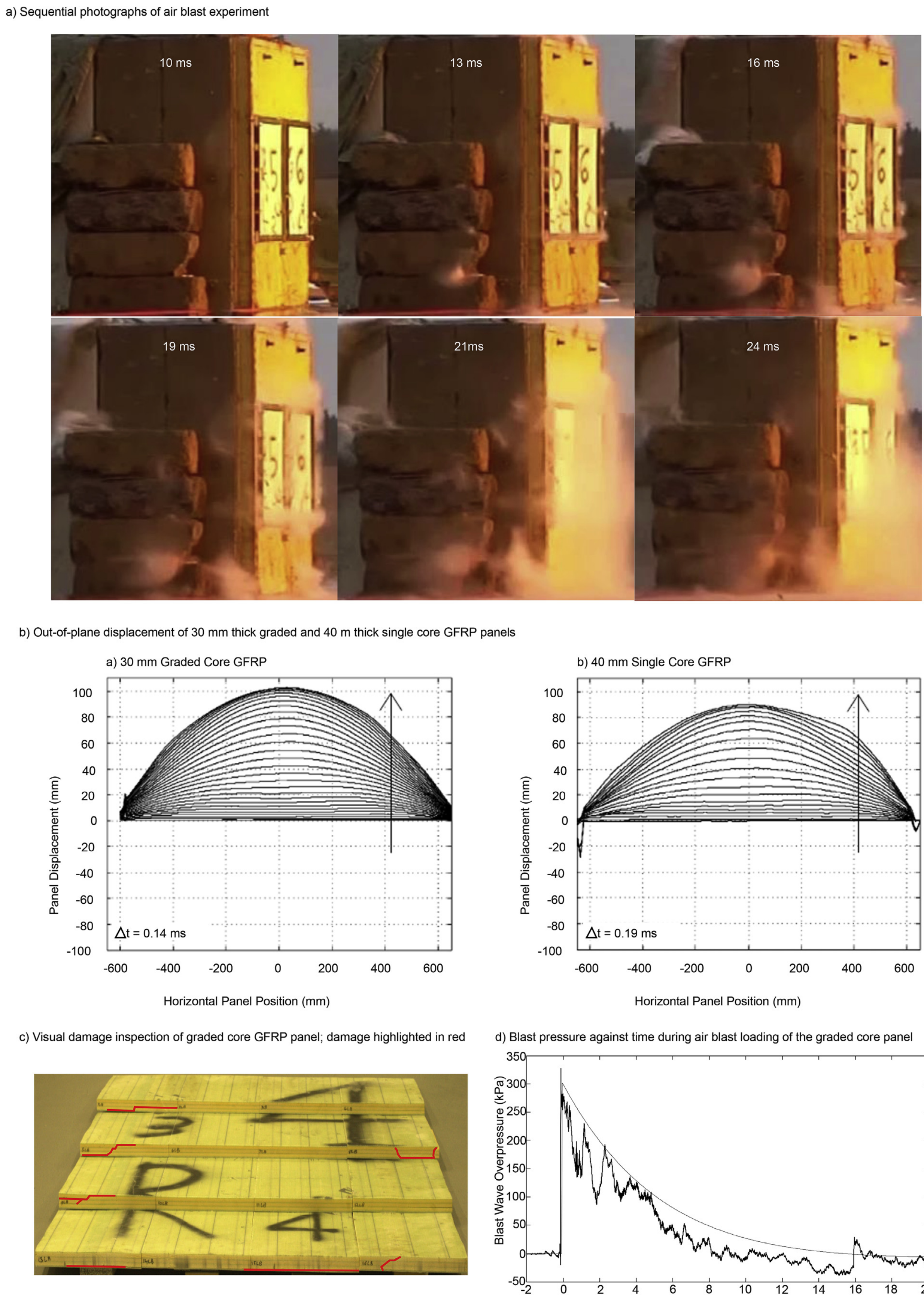

Fig. 11. a) Sequential photographs during the air blast loading of two panels; b) out-of-plane displacement of the horizontal centre section of the 30 mm thick graded core GFRP sandwich panel and the 40 mm thick single core GFRP sandwich panel; c) photograph of the graded density panel showing the visual damage inspection following blast testing; d) trace of blast pressure against time for the charge used during air blast loading of the graded core panel [32].

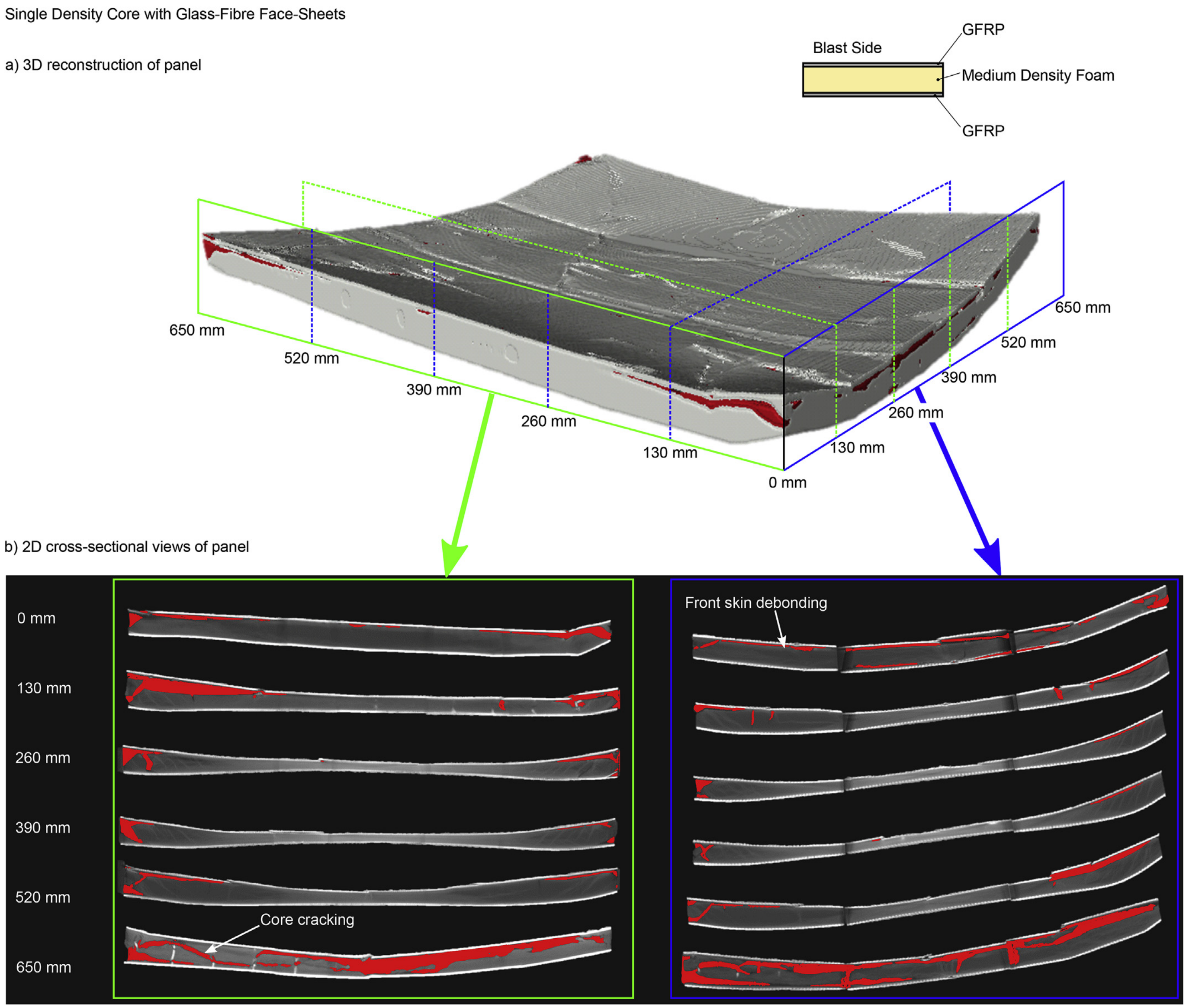

Fig. 12. a) 3D reconstruction of single core GFRP panel from X-ray CT scans; b) 2D cross-sectional views from original scans showing extent of damage through panel.

Fig. 14, this panel suffers from almost complete debonding between the front skin and core. The graded panel X-ray CT scans are shown in Fig. 15. The centre point of the single and graded core panels crush to 9.6 mm and 13.4 mm respectively, the crushing of these panels is more uniform. Additionally, the graded core panel suffers from less damage. The X-ray CT scans have revealed that the panels with GFRP face-sheets suffer from less damage but more core crushing. The panels with graded density cores still suffer from significant damage but to a lesser extent than the single core panels. Details of the extent of damage to all six panels are listed in Table 2.

4. Discussion

Sample data from these experiments is limited (no repeat experiments) due to the large-scale and complex nature of the experiments. However, these studies build upon years of composites research both within the group and worldwide. Findings between groups are being confirmed and analytical and numerical models are being compared and benchmarked against field experiments. Repeat experiments are a key aspect that will be addressed in future experimental testing.

4.1. Graded versus single density

It is evident from both the air and underwater blast results that implementing a graded core reduces the out-of-plane displacement of the panels, for panels with the same core thickness. This was found to be true for both glass- and carbon-fibre face-sheets during underwater blast. The X-ray CT damage analysis revealed that the out-of-plane displacement of the graded panels is reduced due to their ability to absorb more energy via debonding between the core layers. Without a graded core, the single core GFRP panel suffered from severe core crushing (87%) and the front face-sheet of

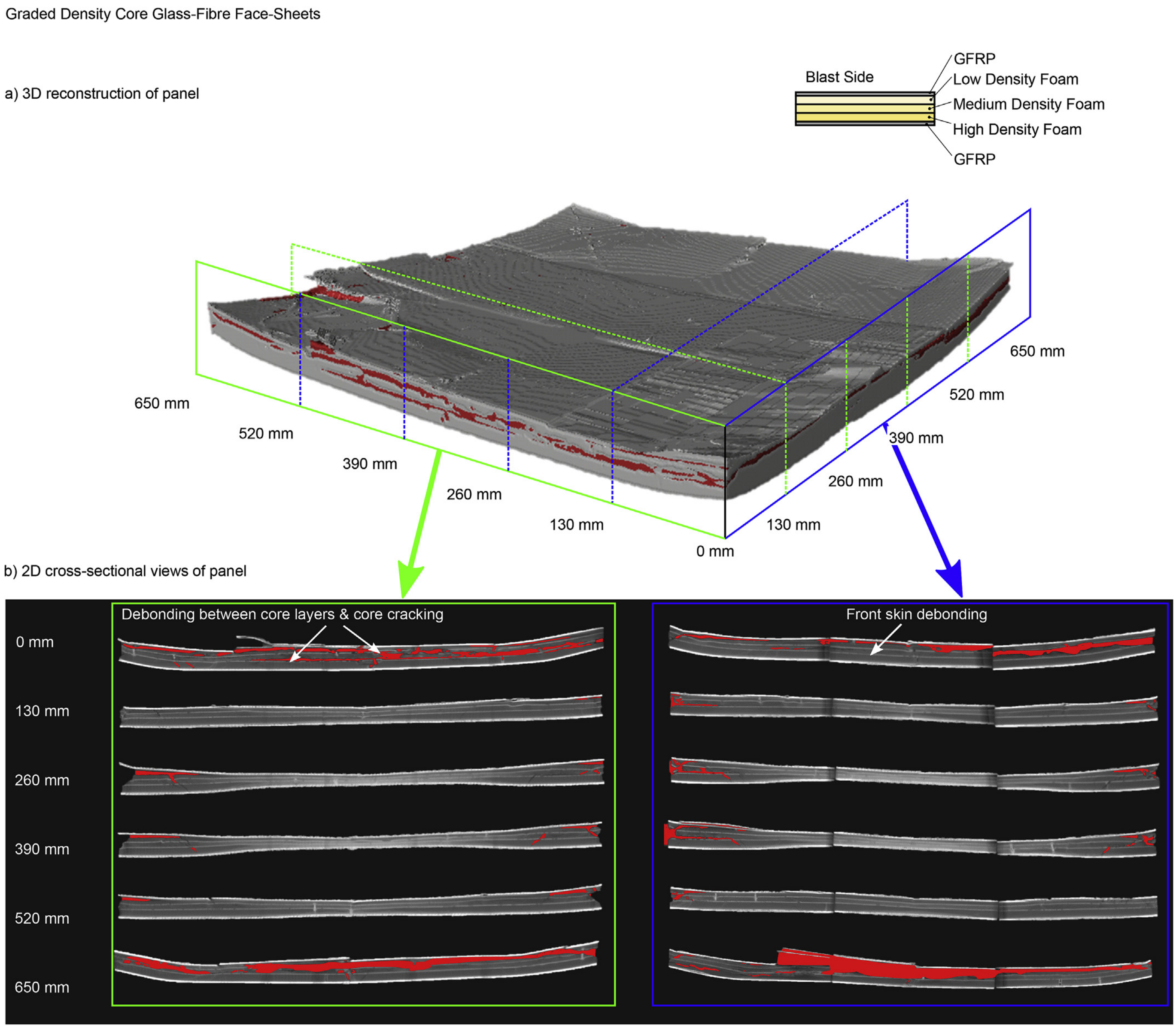

Fig. 13. a) 3D reconstruction of graded core GFRP panel from X-ray CT scans; b) 2D cross-sectional views from original scans showing extent of damage through panel.

the single core CFRP panel was almost completely debonded from the rest of the panel. Following air blast, through thickness cracking is found in the single density panels but not in the graded panels as the core interfaces inhibit the cracks and the damage propagates as debonding between core layers instead.

4.2. Air versus underwater blast

The panels demonstrated different energy absorbing and failure mechanisms in the air and underwater blast experiments due to the different densities of the test mediums. The pressure of the blast in the underwater experiment was two hundred times greater than the air blast. Additionally, the time period of the impulse underwater was less than one tenth of that for the air impulse. For these reasons, the underwater blast panels suffered from core crushing (up to 87%) and large strains in the skins (>3%) leading to fibre breakage on both the front and rear face-sheets. Due to the increased load and shorter time period, greater levels of plastic collapse were observed in the foam core during the underwater blast experiment. Additionally, the time available for the skins to respond is shortened so the skins are unable to activate their flexural response. Hence compression of the core dominated as the failure mechanism for underwater blast whereas flexure dominated for air blast.

During air blast testing, the size of charge was beyond the control of the authors due to a simultaneous experiment being performed at the test site. Therefore, the air blast experiments were far-field to ensure expensive camera equipment situated behind the panels, for DIC, was not damaged. The underwater blast panels, however, could be tested against a greater explosive pressure as the data acquisition equipment used was sacrificial. The size of the test pond meant that reflections from the pond edges were a concern and the stand-off distance was limited. It was, therefore, decided that a near-field test would be most appropriate as the load from the charge would reach the panel far before any pressure reflections and the response of the panel to the charge loading could be analysed. This further accounts for the shift in damage mechanisms between the air and underwater blast panels.

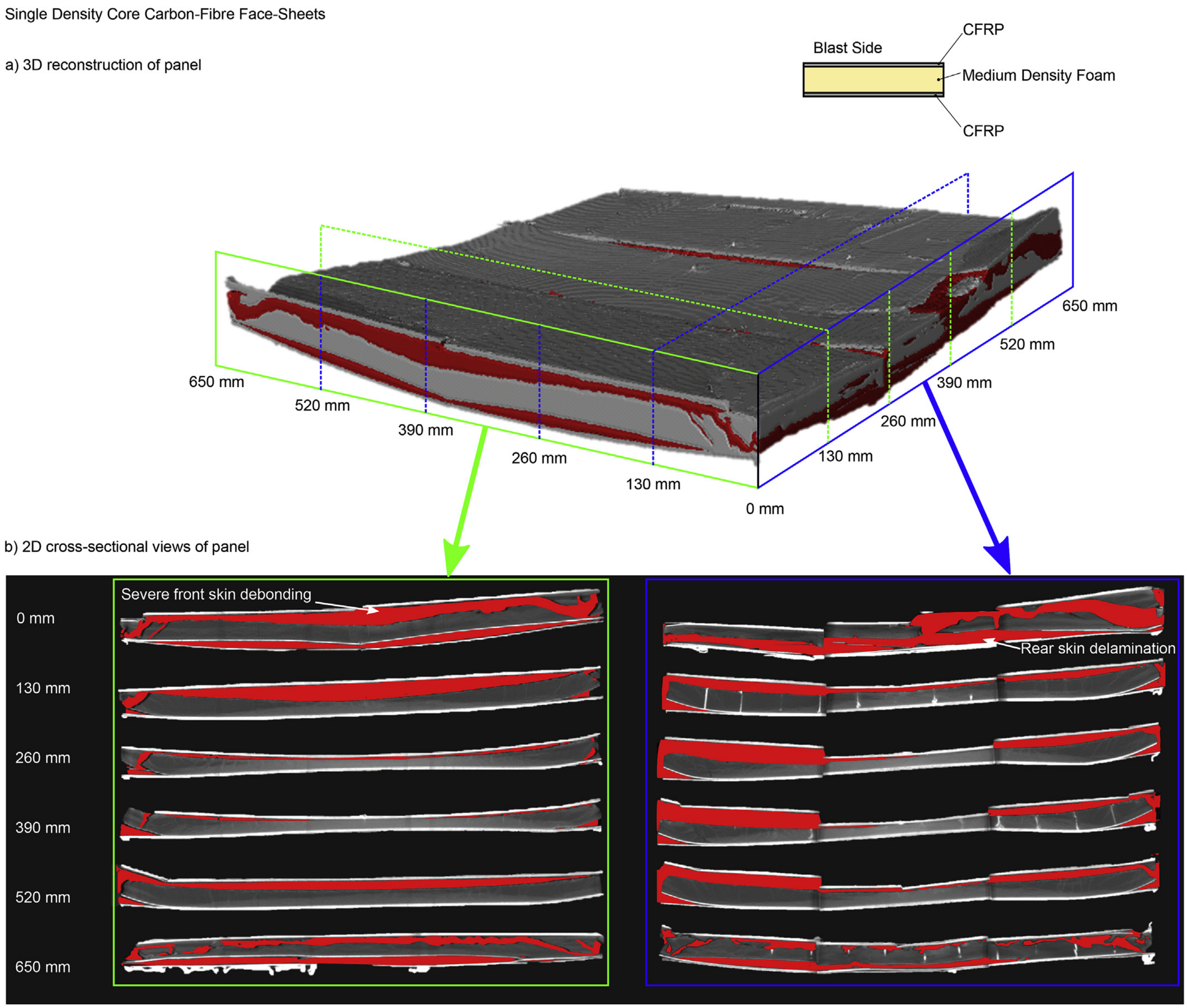

Fig. 14. a) 3D reconstruction of single core CFRP panel from X-ray CT scans; b) 2D cross-sectional views from original scans showing extent of damage through panel.

4.3. Post-blast damage assessment

The visual inspection technique adopted for the air blast panels was carried out on the three sections of each underwater blast panel prior to X-ray CT scanning to validate the accuracy of this technique. Identical calculations for estimating the total area of debonding were used for both the air and underwater inspection. The percentage of debonding along each section edge was found and this provided an overall percentage debond for the section. The calculated visual debonding was then compared to that determined from X-ray CT analysis. Due to the large size of the underwater blast panel sections (217 mm × 650 mm) the errors of visual inspection were very high, up to 132%. However, the air blast panels were sectioned into 112 pieces, and since the error simply scales linearly with the section length, the predicted error drops dramatically. The largest error is predicted to be 1.2%. Confidence in the accuracy of the estimated percentages of debonding for the air blast panels is high. In order to achieve this accuracy, however, the panel is required to be sectioned into 112 pieces which may not always be possible and can introduce damage. X-ray CT damage analysis results in accurate results with minimal alterations to the full-size panels.

4.4. Future modelling

The development of predictive models that are able to validate, repeat and extend experiments are key for creating marine vessel designs, especially since sample data from field experiments, such as these, is limited. Previous investigations have shown that boundary conditions are not constant from the start to finish of blast loading and any structure used during blast experiments or marine structures will have a degree of elasticity [31]. During both the air blast and the underwater blast experiments, the panels were bolted to their respective fixtures. This gives the panels boundary conditions that lie between built-in and pinned due to the flexibility of the fixtures. The response of the fixtures, however, differs significantly, the air blast test cubicle will offer significantly more resistance to the blast wave than the underwater fixture. However, not all sides of the air blast cubicle have equal rigidity as shown in Fig. 3. The boundary conditions of the underwater blast structure

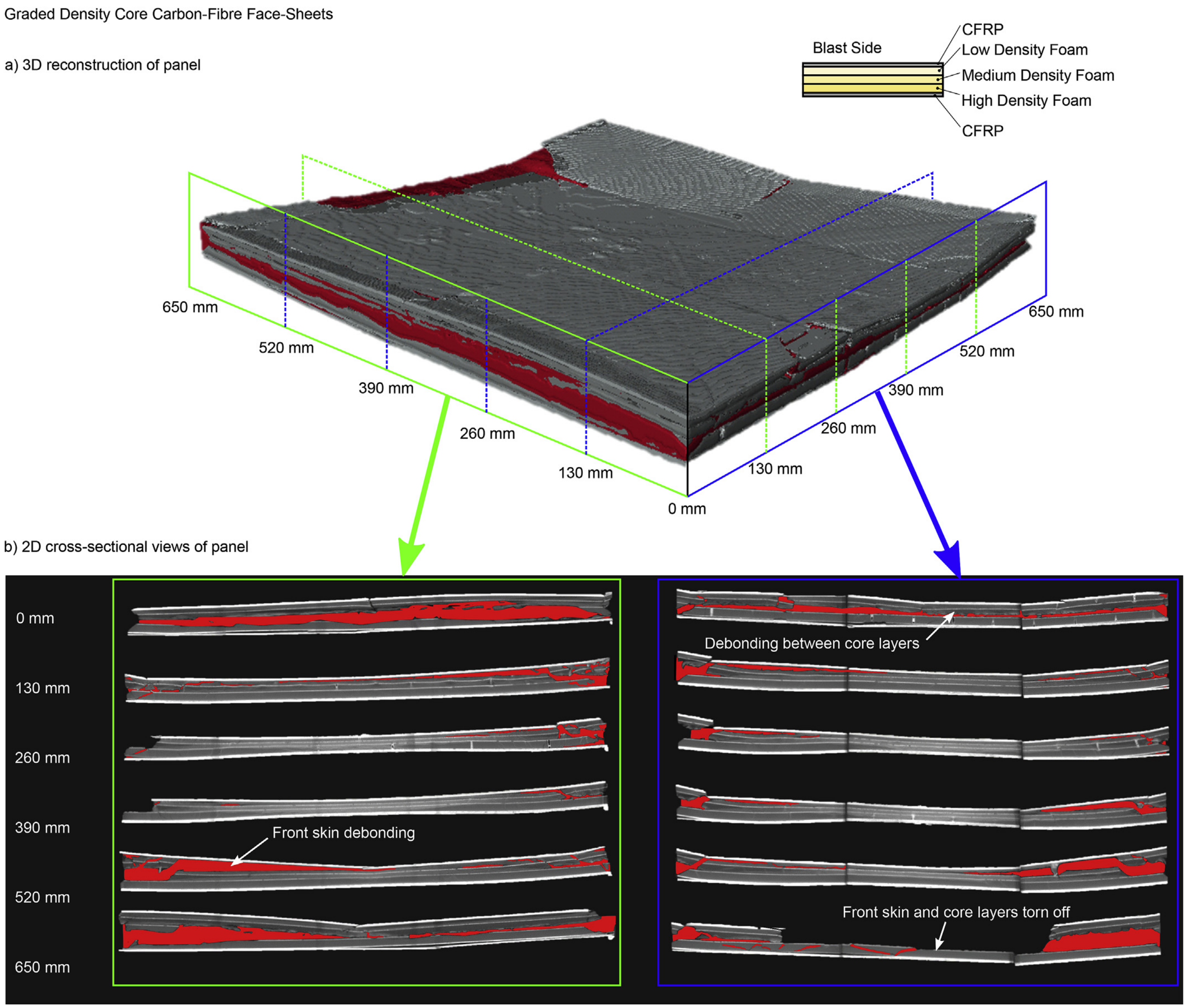

Fig. 15. a) 3D reconstruction of graded core CFRP panel from X-ray CT scans; b) 2D cross-sectional views from original scans showing extent of damage through panel.

Table 2
Summary of the damage to the panels.

	Air GFRP		Underwater GFRP		Underwater CFRP	
	40 mm M100 SAN	30 mm Graded SAN	30 mm M130 SAN	30 mm Graded SAN	30 mm M130 SAN	30 mm Graded SAN
Fraction of panel containing cracks (%)	17	4.6	–	–	–	–
Fraction of panel containing damage (%)	–	–	7.2	4.4	20.6	10.3
Fraction of panel with front skin and core debond (%)	21	12	26.9	32.5	76.0	58.1
Fraction of panel with back skin and core debond (%)	19	25	18.2	76.0	15.2	31.8

are the same along all edges. Since the boundary conditions will vary depending on the ultimate marine structure, and may even be tailored to result in preferential failure locations. Future modelling should focus on simplified boundary conditions and more detailed material response. The modelling should aim to include material damage mechanisms as this will provide further details of the blast resilience of the panels.

5. Conclusions

The performance of six large scale panels against high-explosive charges have been evaluated. Four panels were subjected to an underwater explosion and instrumented with strain gauges. The final two panels were subjected to an air blast and the response was recorded using DIC. The blast experiments have revealed the difference in performance of the selected material combinations.

The main findings can be summarised as follows:

- The strain gauges successfully recorded the initial dynamic strain experienced by the composite sandwich panels during the underwater blast experiment. From the strain data an estimate of the central out-of-plane displacement can be calculated.
- Implementing a stepwise graded core during underwater blast was found to significantly reduce the out-of-plane displacement of the panel. This is due to the interfaces between the core layers having the ability to absorb energy through debonding and due to the propensity of the lower density foam to undergo a large amount of crushing.
- Additionally, through thickness core cracking was reduced as the core interfaces inhibited crack propagation but encourage debonding.
- Although the panels with CFRP skins had a reduced out-of-plane displacement compared to the panels with GFRP skins, the CFRP panels experienced more damage due to their lower strain to failure.
- Based on the limited experiments performed in this study it appears that a graded core GFRP skinned panel offers advantages over the other panels tested. The CFRP panels suffer from more severe damage during underwater blast due to its lower strain to failure.

Supplementary video related to this article can be found at http://dx.doi.org/10.1016/j.compositesb.2017.07.022.

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