EVALUATING THE BLAST PERFORMANCE OF SANDWICH STRUCTURES WITH NOVEL CARBON AND GLASS CONSTRUCTION

Emily Rolfe[1], Cihan Kaboglu[1], Mark Kelly[1], Hari Arora[2], Paul A. Hooper[1] and John P. Dear[1]

[1] Department of Mechanical Engineering, Imperial College London, UK, SW7 2AZ,
emily.rolfe11@imperial.ac.uk
[2] The Royal British Legion Centre for Blast Injury Studies and Department of Bioengineering,
Imperial College London, UK, SW7 2AZ

Keywords: Composite sandwich structures, Blast performance, Properties, Hybrid composites

ABSTRACT

The brittle nature of composite materials results in the overdesign of composite components which counteracts their benefits. Naval vessels undergo a spectrum of loading from static to dynamic due to wave slamming, impact and blast loads. Experiments investigating the performance of composite laminates and composite sandwich panels under static and dynamic conditions are the focus of the research presented in this paper. By hybridizing composites, researchers seek to improve their ductility. Interlaminar glass-/carbon-fiber hybrids are investigated in this study as they can be manufactured in large volumes at a reasonable cost. Three interlaminar hybrids along with a glass-fiber and a carbon-fiber laminate were manufactured and tested under quasi-static tension and flexure. In flexure, one hybrid had greater strain to failure than the purely glass-fiber laminate and another dissipated more energy than the glass-fiber laminate. All hybrids demonstrated greater strain to failure than the carbon-fiber laminate and greater flexural strength than either constituent materials. In tension, the elastic moduli and the tensile strength of the hybrids lay between that of the glass- and carbon-fiber laminates. Once again all hybrids had greater strain to failure in tension than the carbon-fiber laminates, however, none exceeded the glass-fiber laminates. Composite sandwich panels with glass-fiber, carbon-fiber and hybrid laminate skins were subjected to impact testing using a gas gun and aluminium projectile. The carbon-fiber skins demonstrated brittle failure. The addition of glass-fiber layers into carbon-fiber skins improves their impact resilience and the stacking sequence of the fibers has an effect on panel deflection and rear skin strain.

1 INTRODUCTION

Composite sandwich structures are finding an increasing number of applications in the marine sector. The brittle failure of the composite skins, however, results in unnecessarily high safety margins that can counteract the benefits of the sandwich structures. Additionally, it is difficult to predict the response of composites to dynamic loads. Dynamic loads are of importance in naval vessels as they undergo wave slamming, impact and blast loading. Investigations have been carried out into the performance of different skins to determine their effect on the overall performance of composite sandwich panels. The research presented here investigates whether altering the skins to include more than one type of fiber can improve the blast resilience of composite sandwich panels.

Arora et al [1] carried out full-scale air blast experiments on a panel with glass-fiber reinforced polymer (GFRP) skins and a panel with carbon-fiber reinforced polymer (CFRP) skins both panels had an identical styrene acrylonitrile (SAN) foam core. The panels had a similar areal density. The GFRP panel had a greater deflection and suffered from a large face-sheet crack, whereas the CFRP panel did not. Following blast Arora investigated the edgewise compressive residual strength of sections of the panels [2]. The results revealed that the percentage drop in strength was greater for the CFRP panel compared to the GFRP panel. This may be key if residual strength is an important design factor.

The addition of interlayers, such as poly-urea (PU) and polypropylene (PP), has been investigated. Tekalur [3] and Wang [4] used a shock tube to load composite sandwich panels with GFRP skins and PU interlayers. Placing the interlayer behind the front skin or behind the core was found to reduce

back skin deflection. Kelly et al [5] used GFRP skins and PP interlayers in the front skin of a composite sandwich panel. This panel was subjected to full-scale air blast loading and compared to a panel without the PP interlayers. The panel with PP interlayers deflected less, suffered from less front skin/ core debonding and experienced no front skin cracking. These results demonstrate that the PP interlayers improve the integrity of the front skin which may be useful in preventing water ingress following a blast.

The underwater blast performance of composite sandwich panels with GFRP skins and poly-urea coatings was investigated by LeBlanc and Shukla [6]. The panels were subjected to pressures of 10 MPa using a conical shock tube (CST) that produces a shock load equivalent to that of a charge detonated underwater. The authors concluded that a thick coating on the back face improved panel response whereas a thin layer on the front degraded the response.

The performance of a composite sandwich panel with hybrid aramid- and glass-fiber skins was compared to a panel with glass-fiber skins when subjected to underwater blast by Arora [7]. The aramid/GFRP panel suffered from severe skin cracking. Additionally, this panel did not absorb or redistribute sufficient blast energy and transferred a larger proportion of the blast impulse loading to more core crushing. These results show that the replacement of glass-fiber by aramid-fiber lessened the skin properties rather than enhancing them indicating that this combination is not an effective hybrid.

Kelly [8] performed underwater blast experiments on four different composite sandwich panels, two with GFRP skins and two with CFRP skins. The cores were either single density or graded density foam core. This was directly influenced by the work of Wang et al [9] into the performance of stepwise graded core under shock tube loading. The strain response of the panels was recorded during blast loading using strain gauges adhered to the front and rear skin of the panels. The results from Kelly [8] supported the conclusions drawn by Wang et al [9] as the panels with graded density cores deflected less than the equivalent single core panels. Kelly [8] found that the panel with CFRP skins and a graded density core had a significantly different response compared to the other three panels. High strains were recorded at the boundary and the panel failed by cracking at the boundary on the back skin. This is due to the higher stiffness of the CFRP skins and graded core preventing the panel from deflecting to the same extent as the other panels. Following blast loading, the panels were assessed for damage using x-ray computed tomography (CT) scanning [10]. More damage was found in the single density cores as debonding between the front skin and core was able to propagate into a through thickness crack. Whereas interfaces between the foam layers in the graded cores inhibited crack propagation. The x-ray CT scans revealed that the panels with CFRP skins suffer more damage than the equivalent panels with GFRP skins due to the lower strain to failure of the carbon-fiber. There is a trade-off when selecting skin material depending on whether the desired properties are low deflection or low damage.

Tagarielli et al [11] developed a finite element (FE) model of composite sandwich beams under shock loading. When they compared the model results to a previously reported experiment they showed good agreement. The authors concluded that the ultimate failure of the sandwich beams is due to skin tearing which could be predicted by a maximum principal failure strain criterion. Therefore, the shock resilience of composite sandwich structures could be improved by maximizing the failure strain of the skins.

New fibers and matrices are the focus of ongoing research in to improving the ductility and hence failure strain of composites. Since marine applications require large volumes of composites, those that are already commercially available are a more practical option. Glass- and carbon-fiber can be used to create interlaminar hybrid composites which utilize the high strain to failure of GFRP and the high modulus of CFRP [12]. The order of the glass- and carbon-fiber layers can be optimized to resist a load from a particular direction [13].

This paper details quasi-static testing carried out on three different glass-/carbon-fiber hybrids. In naval applications, these materials will experience static structural loads along with dynamic loads including blast. Hence, it is important to understand their static properties. The paper then details high velocity impact loading, using a gas gun, of composite sandwich panels with hybrid glass-/carbon-fiber skins. The ultimate aim of this research is to carry out large-scale air blast testing experiments on sandwich panels with hybrid skins, these experiments will help determine which hybrid skins to test.

2 MATERIALS AND METHODS

Due to the large volumes of material required for marine constructions, composites that are already commercially available are the most viable option until higher performance hybrids can be manufactured in such large volumes at a reasonable cost. Interlaminar glass-/carbon-fiber hybrids are the focus of this study. Since naval vessels will experience static structural loads along with dynamic blast loads, it is important to test their static properties along with their high strain rate performance.

2.1 Quasi-static characterization

Biaxial E-glass fabric and carbon were used to manufacture three eight-layered glass-/carbon-fiber hybrid laminates along with a GFRP laminate and a CFRP laminate. The laminates were fabricated using vacuum assisted resin transfer molding (VARTM) using Gurit Prime 20 LV epoxy and slow hardener. The layup sequences of the five laminates are shown in Figure 1 and all laminates had layup sequence $[0/90/+45/-45]_2$. The laminates had an asymmetric layup with regards to fiber direction as each laminate represented a sandwich composite face-sheet. The three hybrids had an equal areal density. During fabrication, the laminates were cured at 25°C for 8.5 hours and then cured at an elevated temperature of 65°C for 6.7 hours before returning to room temperature. Following curing, the laminates were cut to ASTM standard size specimen for static tensile and flexural testing using a waterjet system. Five samples were prepared for all laminate types.

ASTM standard D3039 [14] was followed for the tensile testing of the specimen. The specimen, sized 250 x 25 x t mm^3, were tested using an Instron with strain control 0.01 min^{-1} at room temperature. Spray paint was applied to the edge of all the specimen to create a speckle pattern which could be tracked using two dimensional digital image correlation (DIC) to record the specimen displacement. Images of the specimen were taken every 2 seconds until specimen failure.

Flexural testing was performed following ASTM D790 [15] with a recommended span to depth ration of 16:1. The specimen were 127 x 12.7 x t mm^3. The tests were carried out on an Instron at a rate to cause strain of 0.01 min^{-1} in the outer fiber.

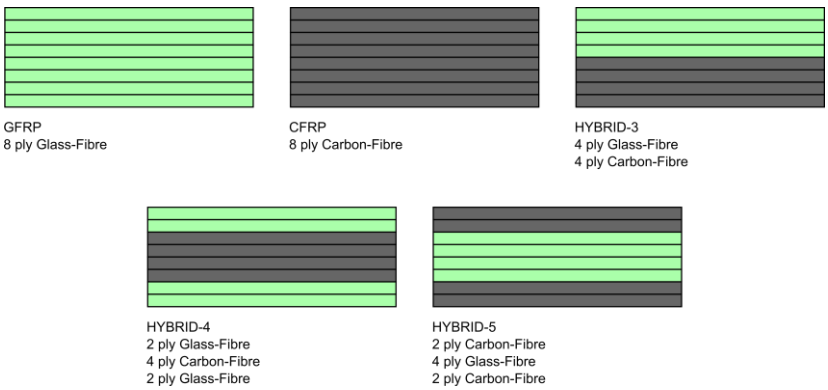

Figure 1: Layup configuration for the five laminates tested at quasi-static rates

2.2 Gas gun impact loading

Composite sandwich panels were manufactured using VARTM with similar face-sheet layups to those that were tested in the quasi-static characterization. The sandwich panel layups are detailed in Figure 2. 20 mm thick polyethylene terephthalate (PET) foam was used as the core material. The same E-glass fabric, carbon fabric and epoxy resin and hardener was used to manufacture the laminates detailed in section 2.1 and the sandwich composite panels described in this section. The panels were cut to 160 x 160 mm^2 and 12 equally spaced clearance holes were drilled such that the panel could be fully clamped within a steel frame leaving an exposed target area of 70 x 70 mm^2. The projectiles were aluminium with a hemispherical end and mass 25.5 ± 0.2 g.

A speckle pattern was applied to the rear face-sheet of the sandwich panels and 3D DIC was used to record the out-of-plane displacement of the panels during loading. Two Phantom Miro M310 cameras with 50 mm Nikon lenses were placed 25° apart. Images were recorded at a frame rate of 39 7000 fps. Two impact velocities were used to compare the performance of each panel, 89 ms^{-1} and 78 ms^{-1}. The gas gun was pressurized to the specified pressure for each velocity and the projectile was released along the gun barrel. Laser gates within the barrel were used to record the velocity of the projectile just before exiting the barrel. A top down schematic of the experimental set up is shown in Figure 3.

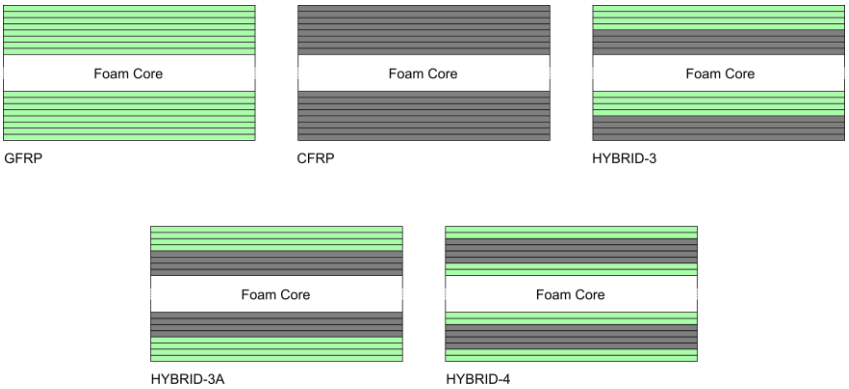

Figure 2: Layup configuration for the five sandwich panels subjected to gas gun impact

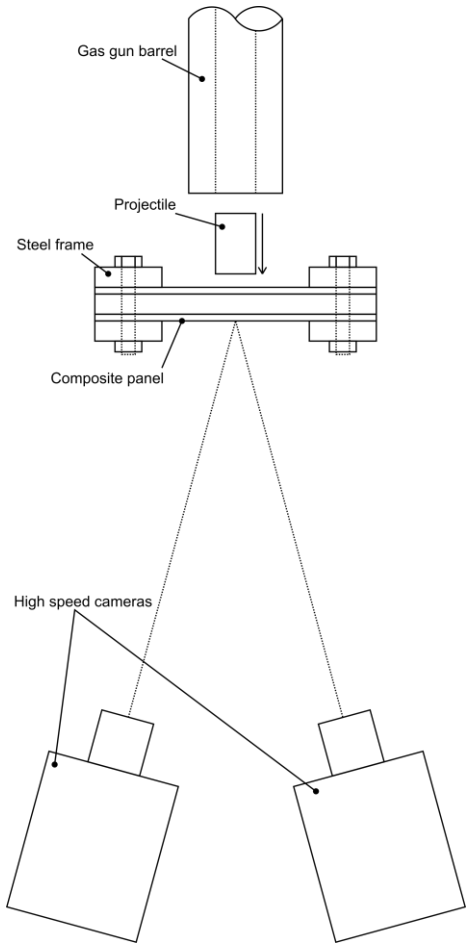

Figure 3: Top-down schematic of the setup for gas gun impact

3 RESULTS AND DISCUSSION

3.1 Quasi-static characterization

The quasi-static tensile and flexural performance of three hybrid composite laminates were investigated and compared to a fully glass- and a fully carbon-fiber laminate. The replacement of carbon-fiber layers by glass-fibers increased the strain to failure and work done during flexure compared to the fully carbon-fiber laminate. The results are shown in Figure 4. In the case of Hybrid-3 and Hybrid-4, the strain to failure surpassed that of the fully glass-fiber laminate. The work done during flexure of Hybrid-3 was also greater than that of the fully glass-fiber laminate. The flexural strength of all the hybrid configurations is greater than both the carbon-fiber and glass fiber laminates, as shown in Table 1. The difference in flexural strength between the hybrids demonstrates that stacking sequence controls flexural properties. Hybrid-3 utilizes the properties of glass-fiber and carbon-fiber by stacking them where they will undergo compression and tension respectively, hence this laminate performs well during flexural testing.

Tensile testing revealed that the initial elastic modulus of the hybrid laminates lay between the glass-fiber laminate and the carbon-fiber laminate. These modulus values are detailed in Table 1. The strain to failure of the hybrids either matched or exceeded the carbon-fiber laminate, as shown in Figure 4. No hybrid laminates, however, surpassed the strain to failure of the glass-fiber laminate during tensile testing. The carbon-fiber laminate has a considerably greater tensile strength, due to its high modulus. The tensile strength of all three types of hybrid are greater than the glass-fiber laminate. The replacement of further glass-fiber layers with carbon-fiber would increase the modulus and tensile strength, however, this may be at the detriment of strain to failure. Nevertheless, these results demonstrate the potential that interlaminar hybrids have for improving performance of composite laminates. The failure of all of the composite laminates, however, was sudden brittle failure. Gradual failure, or pseudo-ductility, due to interactions of the high elongation glass-fiber and low elongation carbon-fiber was not observed for any hybrids.

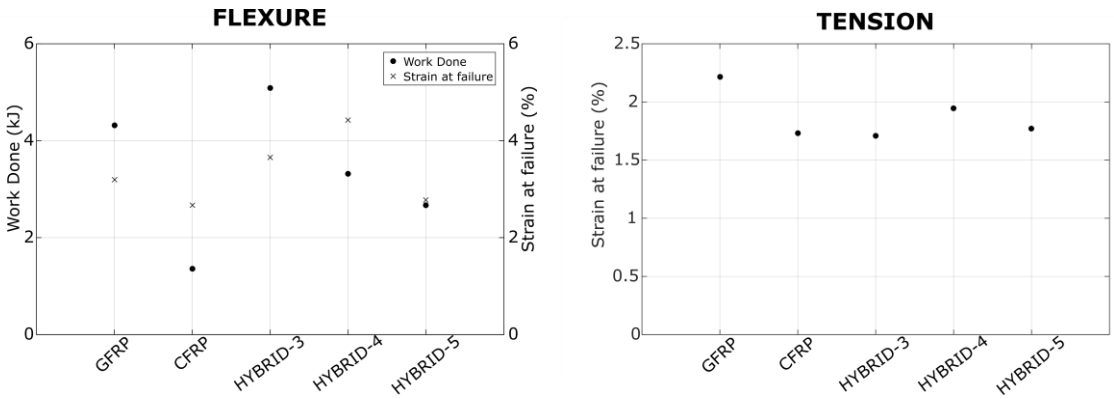

Figure 4: Strain at failure and work done during quasi-static flexural and tensile testing

Table 1: Laminate properties calculated from quasi-static testing

Layup Type	Elastic Modulus (GPa)	Tensile Strength (MPa)	Flexural Strength (MPa)
GFRP	4.9	347.3	519.4
CFRP	9.0	556.7	549.5
HYBRID-3	8.1	364.9	690.2
HYBRID-4	6.4	383.5	625.2
HYBRID-5	6.3	370.1	664.0

3.2 Gas gun impact loading

The high velocity impact performance of five types of composite sandwich panel was carried out using a gas gun. 3D DIC was used to capture the out of plane displacement of the rear skin. Figure 5 shows the deflection for every high speed image captured, from the time of projectile impact to the first maximum deflection for the composite panel with Hybrid-3 skins.

The out of plane displacement of the center point for all five panels under impact from a projectile with velocity 89 m/s is shown in Figure 6 along with the panel major strain. The traces are shown until 1.25 ms after impact, after this point the panels oscillate until coming to rest. The projectiles embedded into some of the panels so oscillation is not at the natural frequency for all panels. At this projectile velocity the rear skin of the carbon-fiber panel was damaged, therefore the DIC fails and the displacement and strain traces end. The carbon-fiber panel was unable to absorb the projectile energy and experiences the highest rear skin strain leading to fiber breakage. A photograph of the rear skin of this panel is shown in Figure 7. The glass-fiber panel experienced the largest deflection and strain, however, the panel suffered from the least damage. The panel with Hybrid-3 skins has the lowest deflection and strain, however the projectile embeds itself into the panel indicating the ballistic limit of the panel has been reached. The ballistic limit for the Hybrid-4 panels was also reached. Although the panels with Hybrid-5 skins deflects more than the other hybrids, the projectile does not embed itself in the panel. This indicates that Hybrid-5 may be able to withstand impacts with greater velocity. The results show that the panels which suffer from the greatest deflection, and largely the greatest strains, suffer from the least damage.

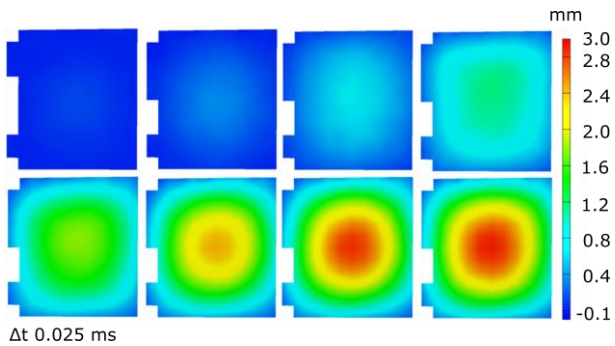

Figure 5: Out of plane displacement during gas gun impact loading for Hybrid-3 composite sandwich panel with each image 0.025 ms apart.

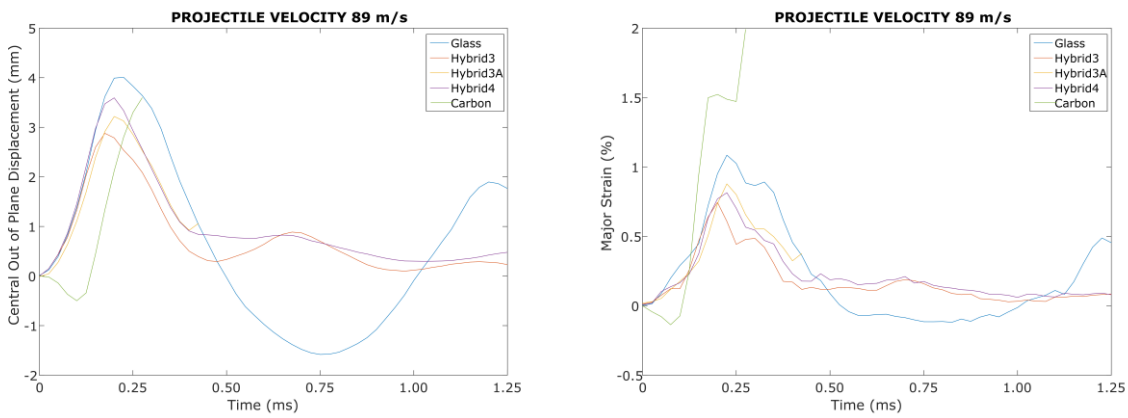

Figure 6: Out of plane displacement and major strain at the center point of the sandwich panels with projectile velocity 89 m/s

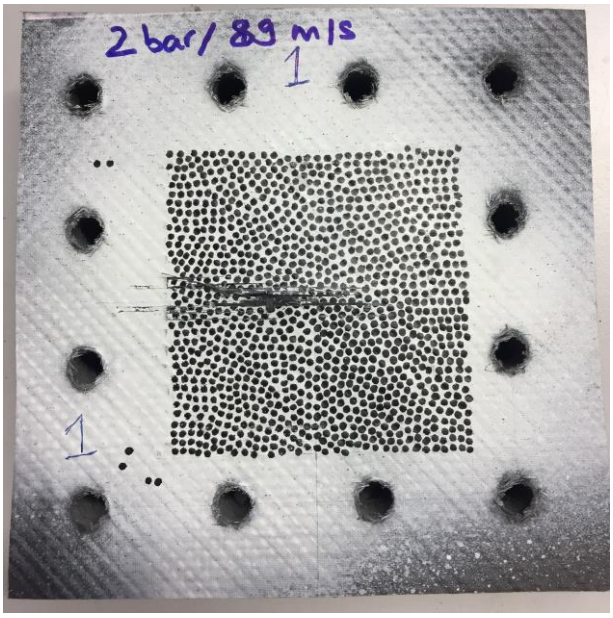

Figure 7: Photograph of sandwich panel with carbon-fiber skins showing the damage to the rear face sheet following impact from a projectile with velocity 89 m/s

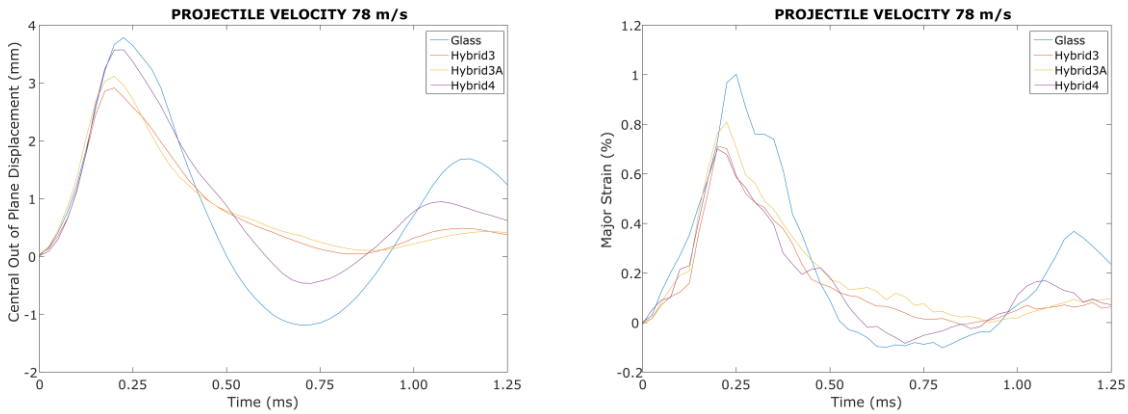

Figure 8: Out of plane displacement and major strain at the center point of the sandwich panels with projectile velocity 78 m/s

The out of plane displacement and major strain for the panels when impacted with a projectile with a velocity of 78 m/s are shown in Figure 8. Unfortunately, the DIC data for the carbon-fiber panel was lost. The carbon-fiber panel was the only panel in which the projectile embedded itself at this velocity, all other panels suffered less damage. The results demonstrate that the interlaminar hybrid composite skins, increases the impact resilience compared to carbon-fiber sandwich panels. The results from these experiments show that panels with glass-fiber skins have the most impact resilience, however, the increase in static properties may be beneficial for an overall vessel design. Further analysis of the panels, including repeated impact and post-impact residual strength testing will provide understanding of the performance of these panels following impact.

4 CONCLUSIONS

Static and dynamic characterization of composite laminates and composite sandwich panels has been carried out experimentally. The effect of laminate stacking sequence on flexural and tensile properties was investigated for three different hybrid laminates. Fully carbon-fiber laminates have higher tensile strength and elastic modulus. The addition of glass layers into carbon-fiber laminates, however, resulted in increased strain to failure and work done during flexure. Furthermore, the flexural strength of the hybrids exceeded the flexural strength of either constituent material. The results show that stacking sequence has an effect on flexural performance. Under impact loading the composite panels with carbon-fiber skins experience brittle failure and the most severe damage. The addition of glass-fiber layers into carbon-fiber skins improves their impact resilience and the stacking sequence of the fibers has an effect on panel deflection and rear skin strain. The panels with glass-fiber skins suffer from the least damage, however, the hybrid skins can offer increased static strength and may have an improved post-impact residual strength which can be key factors in vessel design.

5 FUTURE WORK

Composite sandwich panels with Hybrid-3 and Hybrid-4 skin configurations and a 30 mm thick PVC core have been manufactured for large-scale blast testing. This testing will be carried out at the DNV GL test site at RAF Spadeadam. The panels will be subjected to a charge up to 100 kg TNT equivalent. Based on previous experience and an analytical solution, a stand-off distance of 15 m will be selected for a 100kg TNT charge. The panels will be mounted side-by-side onto a test cubicle. The charge will be raised 1.5 m off the ground above a thick steel plate which provides an elastic foundation for the initial detonation. A reflected pressure gauge will be placed on the front of the cubicle, underneath the two panels and a static pressure gauge placed 15 m away from the charge. The panels will be mounted within a 5 mm thick steel frame using Sikaflex 291i marine sealing adhesive. 20 clearance holes have been drilled through the steel frame and the panels and this will be bolted to the cubicle front. The rear face-sheets of the panels will be painted white and black speckles applied to the surface. Two pairs of high speed cameras will be mounted behind the panels to record the out-of-plane displacement of the panels. The cameras will be triggered using an open transistor-transistor-logic (TTL) circuit, which is closed by the ionizing air caused by the detonation of the explosive charge. The results from blast testing will be compared to the performance of the panels under high velocity gas gun impact testing.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the strong support received from Dr Yapa Rajapakse of the Office of Naval Research for supporting Emily Rolfe, Dr Mark Kelly and Dr Hari Arora during their PhDs [grant numbers N00014-08-1-1151, N00014-12-1-0403, N62909-15-1-2004]; EPSRC for supporting Emily Rolfe for her PhD.

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