MECHANICAL EVALUATION OF A FIRE RETARDANT THROUGH-THICKNESS REINFORCED SANDWICH STRUCTURE FOR MARINE APPLICATIONS

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ABSTRACT

One of the main restrictions in adopting polymer composite materials for primary and secondary structural applications in marine vessels over 50 meters in length is concerns regarding fire retardancy and also a lack of design guidelines in general. The aim of this study is to evaluate the edgewise compression strength and core-shear strength of a fire retardant sandwich structure reinforced with through thickness composite ‘bridges’ under ambient conditions. These properties are important for structural components subjected to in-plane loads such as bulkheads. Core shear strength of the through-thickness reinforced sandwich far exceeded non-reinforced sandwich. However, edgewise compression strength and stiffness of the reinforced case was found to be similar to the unreinforced case.

1. INTRODUCTION

This work is part of the FIBRESHIP Horizon 2020 funded EU project, which aims to increase the use of polymer composites in the construction of marine vessels greater than 50 meters in length by addressing a wide range of challenges associated with the design, manufacture and classification of large polymer composite ships.

Polymer composites are finding increasing application in the transportation sector due to their lightweight nature, which provides a significant advantage in terms of lower fuel consumption and greenhouse gas emissions, in line with relevant EU directives. Particularly in the marine industry, polymer composites dominate the manufacture of vessels up to 50 m in length with vacuum assisted liquid resin infusion being the most common manufacturing process. However, the wide-scale adoption of polymer composites for primary and secondary structural applications in large marine structures is restricted by a lack of design guidelines in relation to their use in structures, which must meet stringent fire regulations in addition to the standard considerations including mechanical performance, ease of manufacture and maintenance, cost and environmental impact. Structures such as bulkheads must sustain in-plane compression loads under ambient (and elevated temperature conditions in a fire situation) for prolonged durations.

This paper focuses on the edgewise compression strength of a fire retardant sandwich construction under ambient conditions. Under edge compression loading, failure can occur by Euler macrobuckling, core-shear macrobuckling, facesheet microbuckling (plastic microbuckling of the facesheets) or face sheet wrinkling (short wavelength elastic buckling of the facesheets) depending on the material combination and geometry of the test sample [1]. Core shear buckling is controlled by the shear stiffness of the core and occurs at a higher load than euler macrobuckling for a sufficiently slender column. Euler macro buckling and core shear buckling can also interact meaning the collapse load is dependent on both. Euler macro buckling involves elastic bending of the face skins and is primarily controlled by column length, geometry and the face sheet stiffness.

A review of the literature reveals that significant work has been conducted on various materials over a range of slenderness ratios. However, work regarding through thickness reinforced core materials is not widely reported. The following is an abridged review of some of the relevant data available in the open literature. Henao *et al.* [2] performed edgewise compression tests on sandwich panels constructed of glass face skins, PVC (polyvinyl chloride) and PU (polyurethane) foam core to explore the performance of sandwich structure with and without tufted through-thickness reinforcement with both test samples having the same slenderness ratio. The sandwich panels were manufactured using a vacuum assisted process. The edgewise compression strength increased by over 20% due to the inclusion of the tufting and bending strength increased by over 100%.

Mamalis *et al.* [3] investigated the compressive response of eight different composite sandwich structures with glass fibre (quasi-isotropic lay-up)/acrylic face sheets and four different core materials including PU, PMI (Polymethacrylimide) and two grades of PVC. All samples had the same slenderness ratio. The authors concluded that unstable crushing with overall column buckling is the most probable mode of collapse of a composite sandwich panel subjected to edgewise compression. PVC and PMI exhibited the highest strengths while PU core material exhibited the lowest. Lei *et al.* [4] investigated the edgewise compressive response of PVC foam-filled sandwich composite columns through experimental, theoretical and FEA methods. The samples were manufactured using vacuum assisted infusion using E-glass for the face skins with a $[0/90]_5$ layup, PVC core and a vinylester resin system. Two different slenderness ratios were investigated with corresponding compression strengths of 75 and 31 MPa. The authors reported that the critical collapse stress is significantly reduced by an increase in slenderness ratio and that first and second order buckling modes play a key role at high slenderness ratio.

The effect of fire damage on the edgewise compression properties of a sandwich containing a highly flammable PVC core and a more fire retardant core phenolic core material was evaluated by Mouritz and Gardiner [5]. The PVC and phenolic sandwiches exhibited compression strengths of 165.8 and 64.7 MPa at the same slenderness ratio prior to exposure to fire.

A wide range of fire retardant constituents (resin systems, core materials, gel coats and reinforcements) are currently available on the market as evident from the literature. One less studied material is Saerfoam®, which consists of a polymeric foam with through-thickness glass fibre tow reinforcement bridges. The objective of this study is to evaluate the edgewise compression strength and core-shear strength of a polymer composite sandwich panel manufactured using saerfoam®. The results will be compared to those of a sandwich panel manufactured using an unreinforced PET (Polyethylene terephthalate) core with the same face skins.

2. EXPERIMENTATION

Materials

The resin system used in this study is an unfilled low viscosity (300-400 mPa.s @20°C) infusible thermosetting vinylester (VE) resin system i.e. LEO Injection Resin 8500 from BÜFA with a gel time of up to 1 hour 50 mins at 20°C. The reinforcement fabric used is a Saertex LEO quasi-isotropic non-crimp E-glass fabric with a total areal weight of 821 g/m^2. The reinforcement fabric is comprised of E-glass fibre tows orientated in various directions (-45°/90°/45°/0°) stabilised by polyester stitching. The resin and reinforcement fabric are part of the LEO® fire retardant composite system. A gel coat was not used in this study.

(i) (ii)

Figure 1. Core materials used in the current study: (i) Saerfoam hybrid core material (Saerfoam PIR25 O20-35 - F3808) with through thickness E-glass reinforcement bridges; (ii) unreinforced PET thermoplastic core material (Airex PET T90.60). Both materials are 25 mm in thickness.

Saerfoam hybrid core material (Saerfoam PIR25 O20-35 - F3808) comprised of polymeric foam and through thickness E-glass reinforcement bridges was used in the current study (Fig. 1i). The E-glass reinforcement bridges were linearly orientated in the 0° and 90° directions at an angle of ±45° to the facesheets with a bridge density of 1/cm^2. The polymeric foam was PIR (Polyisocyanurate) with a density of 80 kg/m^3. The second core material is a PET (Polyethylene terephthalate) thermoplastic core material (Airex PET T90.60) with a density of 65 kg/m^3 (Fig 1ii). The PET core did not have through thickness reinforcement. The thickness of the core materials used in the current study was 25±0.5 mm. The materials and sandwich construction are summarised in Table 1.

Table 1. Summary of materials used in sandwich panel construction in the current study

Designation	**Resin**	**Core Material**	**Face Skin Reinforcement**	**Sandwich construction**
PET/E-GF/VE	Vinylester LEO Injection Resin 8500 from BÜFA	PET (25mm, 65 kg/m^3)	Q-E-821g/m²- LEO (1 layer per face skin)	[0°/45°/90°/-45°/ Core /-45°/90°/45°/0°]
PIR/E-GF/VE		PIR (25mm, 80 kg/m^3) with E-glass fibre bridging		

Manufacturing

The sandwich panels were manufactured using vacuum assisted liquid resin infusion in conjunction with a closed moulding system (Fig. 2i). The thickness of the mould cavity is adjustable. This was set to 26 mm for the current study. The lower part of the mould was aluminum alloy and the upper platen was glass supported by a steel frame (Fig 2ii). A single layer (0°/45°/90°/-45°/) of dry reinforcement fabric was placed either side of the core material in the cavity. A 15-minute leak test was performed before starting the infusion. The VE resin was then mixed (100:2.5 ratio by mass) and infused under vacuum (30 mbar absolute) at ambient temperature (approximately 20°C) without prior degassing. Monomer boiling was not observed. The panels were allowed to cure for 24 hours and post cured at 80 °C for 6 hours

(Fig.2iii and Fig. 2iv). Test coupons were extracted by water jet cutting taking care not to induce damage due to the cutting process.

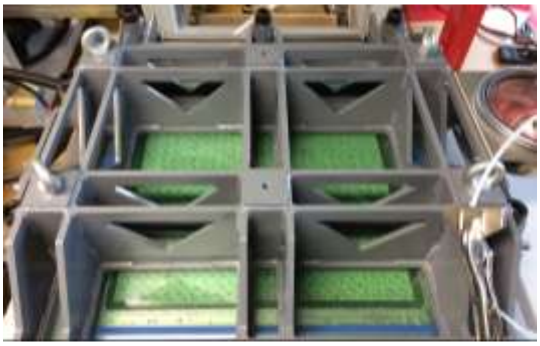
	
(i)	(ii)
	
(iii)	(iv)

Figure 2. Manufacture of sandwich panels by vacuum assisted resin infusion: (i) mould showing upper and lower platens and heating control system; (ii) fully infused PIR/E-GF/VE sandwich panel with the top surface and through core reinforcement visible through upper glass platen; (iii) PET/E-GF/VE 480 x 480 x 26 mm sandwich panel; (iv) PIR/E-GF/VE 480 x 480 x 26 mm sandwich panel;

Mechanical Testing

Test sample design, testing and data reduction was carried out with reference to ASTM C364-07 (edgewise compression) and ASTM C393-11 (core shear). Edgewise compression samples had nominal dimensions of 60 x 60 x 26 mm. Ultimate edgewise compression strength (F_{ECS}^{Ult}) was calculated using equation 1. Core shear samples had nominal dimensions of 200 x 75 x 26 mm. Ultimate core shear strength (F_{css}^{Ult}) was calculated using equation 2.

$$F_{ECS}^{Ult} = P_{max}/[w(2t_{fs})] \ldots \text{ Eqn. 1}$$

$$F_{CSS}^{Ult} = P_{max}/[(\mathrm{d}+\mathrm{c})\mathrm{b}] \ldots \text{ Eqn. 2}$$

where P_{max} is the peak load, w is the width of the edgewise compression sample, t_{fs} is the thickness of the face skin of the edgewise compression sample, d and c are the overall thickness and the thickness of the core respectively and b is the width of the core shear test sample. Edgewise compression samples were tested quasi-statically to failure at a test speed of 0.5 mm/min. The core shear samples were tested in a 4-point bend configuration quasi-statically to failure at a test speed of 6mm/min. The support span and loading span were 150 mm and 75 mm respectively. Roller diameters were 10 mm.

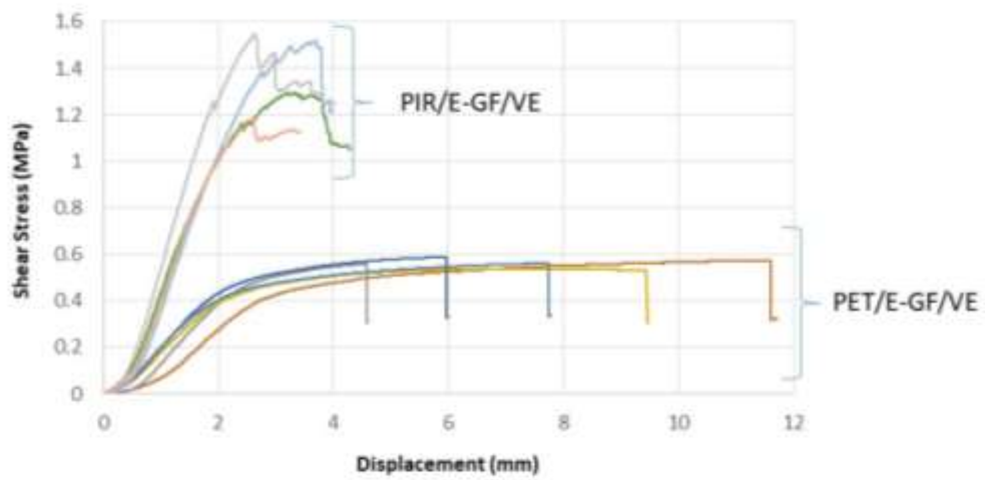
3. RESULTS AND DISCUSSION

The results of the edgewise compression and 4-point bend core shear tests performed on the PET/E-GF/VE and PIR/E-GF/VE sandwich materials are summarised in Table 2. The sandwich materials exhibited similar edgewise compression strength but significantly different core shear strength and stiffness with the through-thickness reinforced material clearly outperforming the unreinforced material in this regard.

Table 2. Summary of the results from edgewise compression tests and core shear strength tests. Standard deviation in parenthesis where available.

	Edgewise Compression strength (MPa)	Core Shear strength (MPa)
PET/E-GF/VE	223.1 (4.4)	0.569 (0.004)
PIR/E-GF/VE	214.1 (2.5)	1.284 (0.009)

It is clear that the resin filled fibre tow bridges have a significant effect on core shear strength and stiffness as can be seen in Fig.3.



(i)

(ii)

(iii)

Figure 3. (i) Core shear stress/displacement curves and failure modes for (ii) PET/E-GF/VE and for (iii) PIR/E-GF/VE

The PIR/E-GF/VE material exhibited significantly higher shear strength (+125%) and stiffness compared to the GF/PET/VE material. In both cases, the failure location was as expected outside the loading span but inside the support span (Fig.3ii and Fig.3iii). However, the resin filled fibre tow bridging elements in the PIR/E-GF/VE resist core shear deformation and bending. Relatively high stiffness and low displacement result. In contrast, PET/E-GF/VE shows a relatively low stiffness and a wide range of displacement at failure. The bridges are also thought to impede crack growth in the polymer foam providing a tortuous crack path in the PIR unlike the PET/E-GF/VE case where shear crack growth in the PET is unimpeded.

From the edgewise compression stress/displacement curves (Fig. 4), it is clear that resin filled fibre tow bridges do not increase the edgewise compression strength or stiffness for the slenderness ratio under consideration. In fact, load drops are evident in the PIR/E-GF/VE material at high stress levels possibly due to progressive failure/delamination of the composite bridges from the face skins.

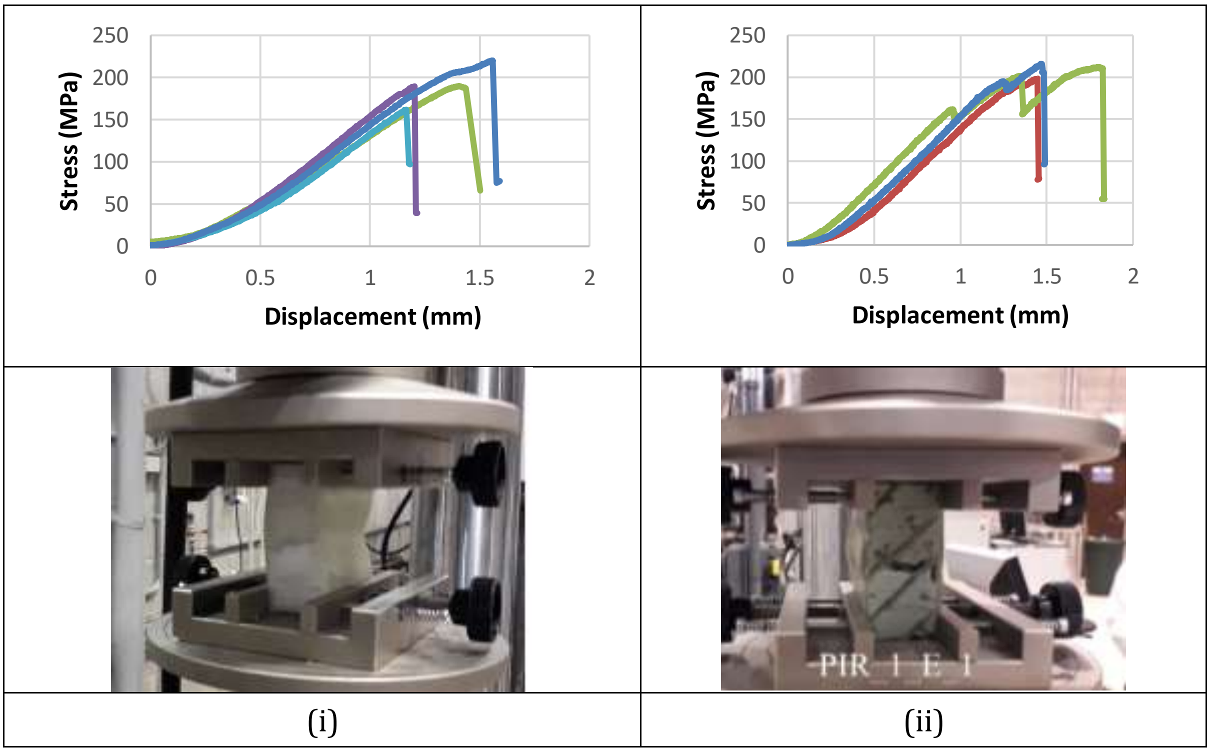


Figure 4. Edgewise compression stress/displacement curves and deformation under load: (i) GF/PET/VE (ii) GF/PIR/VE

It appear that failure under edgewise compression is dominated by buckling of the face skins as even though the core shear strength and stiffness are significantly different for these materials the edgewise compression strength and stiffness are very similar. The damage to the test samples post testing is shown in Fig. 5. Both materials exhibit damage out of plane bending of the face skins leading to cracking in the polymeric foam.

(i) (ii) (iii) (iv)

Figure 5. Representative failed test samples after edgewise compression testing: (i and ii) PET/E-GF/VE showing face skin buckling leading to core failure; (iii and iv) PIR/E-GF/VE showing cracking in PIR core material. Direction of load application is vertical.

Global buckling occurs between the supports under compression loading causing bending of the faceskins leading to damage to the face skin perpendicular to the loading direction (Fog. 6). The matrix cracking caused by the composite bridges pulling away from the face skin can clearly be seen in Fig. 6iv. Even though the damage visibly looks to be more excessive in the GF/PIR/VE material, the edgewise compression strength and stiffness is similar for both materials.

(i) (ii) (iii) (iv)

Figure 6. Representative failed test samples after edgewise compression testing: (i) PET/E-GF/VE front (ii) PET/E-GF/VE back (iii) PIR/E-GF/VE front (iv) PIR/E-GF/VE back. Direction of load application is vertical.

4. CONCLUSIONS

This paper evaluates the edgewise compression strength and core shear strength of a sandwich panel manufactured using a fire retardant vinylester resin system coupled with a fire retardant PIR core reinforced through-thickness with resin filled glass fibre tows. Sandwich structures were manufactured using vacuum assisted liquid resin infusion, which is commonly used in shipyards to manufacture large components such as bulkheads, which are subject to in-plane compression loads.

The core shear stress of the PIR/E-GF/VE sandwich was evaluated using a 4pt bend loading configuration. As expected the PIR/E-GF/VE sandwich significantly out-performed the PET/E-GF/VE sandwich manufactured using the non-reinforced PET core material. The edgewise compression strength of the PIR/E-GF/VE sandwich was similar to the non-reinforced PET/E-GF/VE sandwich indicating that the through-thickness reinforcement did not increase the edgewise compression strength compared to non-through thickness reinforced core material for the same slenderness ratio. The similar edgewise compression strength of both materials and significantly different core shear strength suggests that the dominant failure mechanism for both materials was buckling for the slenderness ratio considered as opposed to a core shear driven failure mechanism.

In future work, the mechanical properties of other candidate core materials (e.g. SAN, balsa etc) over a range of slenderness ratios will be evaluated. A comprehensive testing and qualification programme including fire resistance would of course be required before any wider endorsement and adoption of any of the material systems studied in this paper.

5. REFERENCES

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6. ACKNOWLEDGEMENT

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