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Mechanical performance of sandwich materials with reduced environmental impact for marine structures

Robin Alban [1], Davies Peter [1, *], Arhant Mael [1], Le Jeune Sebastien [1], Lacotte Nicolas [1], Morineau Eliaz [2], Ioos Fanny [2], Dourlen Pascal [2], Cairo Raphael [2]

[1] Marine Structures Laboratory, IFREMER Centre Bretagne, Plouzané, France
[2] MerConcept, Concarneau, France

* Corresponding author : Peter Davies, email address : peter.davies@ifremer.fr

Abstract :

Glass fibre reinforced composite facings on PVC (poly(vinyl chloride)) foam cores are widely used sandwich materials in boat structures, but life cycle analysis suggests that alternative materials may be preferable for the environment. However, in order to design with these alternative materials their mechanical behaviour must be characterized and understood. This paper describes an experimental campaign to evaluate the performance of alternative sandwich materials with reduced environmental impact, under loading conditions relevant to boat design. Flax and bamboo composite faced PET (poly(ethylene terephthalate)) foam sandwich materials are compared to the current PVC foam sandwich on a constant weight basis. A series of quasi-static tests is described first and analysed. Then hard and soft impact tests are described, which allow a comparison to be made between existing and alternative sandwich options. The results indicate that the alternative materials show lower flexural stiffness. Damage initiation levels are also lower, but the impact energy levels they can support are promising, and facing improvements could raise these further.

Introduction

Increasing awareness of the consequences of climate change have led to research into more environmentally friendly materials. For sandwich materials this may take many forms; for face sheets one area of research is the use of plant-based fibre reinforcements to reduce energy requirements. These materials, particularly flax fibres, have been studied in detail in recent years [1-4]. Another option is the use of thermoplastic matrix polymers for the facings, to contribute to end of life recycling possibilities [5,6].

With respect to core materials, various grades of closed cell PVC (poly(vinyl chloride) foam are widely used in the marine sector. Both linear and cross-linked PVC are employed, and they can be found in military craft [7,8], pleasure boats and racing yachts. As a result there have been many studies of PVC foam cores, under a wide range of quasi-static and dynamic loads, e.g. [9,10], and various reference books provide a good overview [11]. PET (polyethylene terephthalate) foams have been available for some time [12], but they are perceived as more brittle than PVC foams and so their adoption in marine structures has been limited to date. However, the prospect of recycling, plus the availability of cores made from recycled PET [13], has stimulated renewed interest. Alternative cores which are sourced from natural materials such as cork [14,15], balsa [16] and paper or cardboard honeycombs [17,18] have also been available for some time and may provide environmental benefits. Oliveira et al [19] provide an up to date review of 'green' sandwich materials.

In the present work we focused on PET foams. Garrido et al [20] compared PET foam to a polyurethane and showed a strong sensitivity of PET properties to temperature. Ozdemir et al [21] compared the impact performance of PVC and PET foams and indicated similar behaviour.

Small boat design is largely based on experience, but an ISO document [22] provides guidelines on small boat design with sandwich materials based on end grain balsa, PVC and SAN (styrene acrylonitrile) foam cores and honeycomb. Both natural fibres and cork cores were successfully employed in recent prototype boats [23,24], and historically balsa wood has been widely used, but so far environmental considerations have not been a priority for marine applications. However, this is changing: Design of racing yachts is governed by class rules, and the governing body IMOCA (International Monohull Open Class Association), [25] introduced new rules in 2021 for the next Vendee Globe race which specifically encourage the use of alternative materials (biosourced non-structural components will be excluded from the measured boat weight up to a limit of 100 kg, and a recyclable sail must be carried). They also impose a Life Cycle Analysis (LCA) for all new boat constructions [26]. The work described here was performed within that framework.

In this paper results from a series of tests on two alternative sandwich materials, based on thermoplastic PET foam core and natural fibre reinforced facings are presented. These are compared to a reference glass fibre reinforced composite facing on a PVC foam core sandwich on an equivalent panel weight basis.

Materials and Methods

Three sandwich materials were investigated in this study. These are described in Table 1. The reference material is an 80 kg/m^3 PVC core with glass/polyester facings, used in many marine structures and particularly for boats. The two alternative materials are based on 85 kg/m^3 PET core with either bamboo/epoxy or flax/epoxy facings. The matrix resin for the alternative materials is a partially bio-based Epoxy (38% of carbon bio-sourced) from Sicomin; SR

InfuGreen™ 810, with hardener SD8822. Reinforcement fabric weights were 300 g/m² for glass and flax, 350 g/m² for bamboo.

The face sheet stacking sequence was quasi-isotropic, with one 0°/90° outer layer and one ±45° layer next to the core on both sides (i.e. symmetrical with respect to the core mid-plane) for flax and bamboo, and two layers of each for glass. The facing matrix glass transition temperatures were 54, 65 and 74°C for glass, bamboo and flax composites respectively (measured by differential scanning calorimetry). Facing axial stiffnesses were measured in tension to be around 15, 4 and 10 GPa respectively for these three materials.

All materials were manufactured by infusion as large panels, (2.3 x 1)m², which were then cut to provide samples. Table 1 provides standard properties.

Material	Facings	Core	Panel surface density kg/m²	Compression		Shear	
				E (MPa)	σ (MPa)	G (MPa)	τ (MPa)
Reference	Glass/Polyester	Airex PVC C70-75	5.2 (0.04)	104	1.45	30	1.2
Bamboo/PET	Bamboo/InfuGreen Epoxy	Airex PET T92-80	4.97 (0.27)	75	1.3	22	0.72
Flax/PET	Flax/InfuGreen Epoxy	Airex PE T92-80	5.10 (0.11)	75	1.3	22	0.72

Table 1. Materials tested and supplier core properties

The nominal core thickness was 15mm for both foams. The facing thickness was around 1mm for the glass/PVC, 2mm for the bamboo and 1.5mm for the flax. Facing tensile moduli were measured to be 15 GPa for the glass, 10 GPa for the flax and 4 GPa for the bamboo. However, the bamboo/epoxy thickness is quite variable and this resulted in high scatter for this material. The measured areal weights of the three materials are very similar, around 5 kg/m².

Figure 1 shows the three materials.

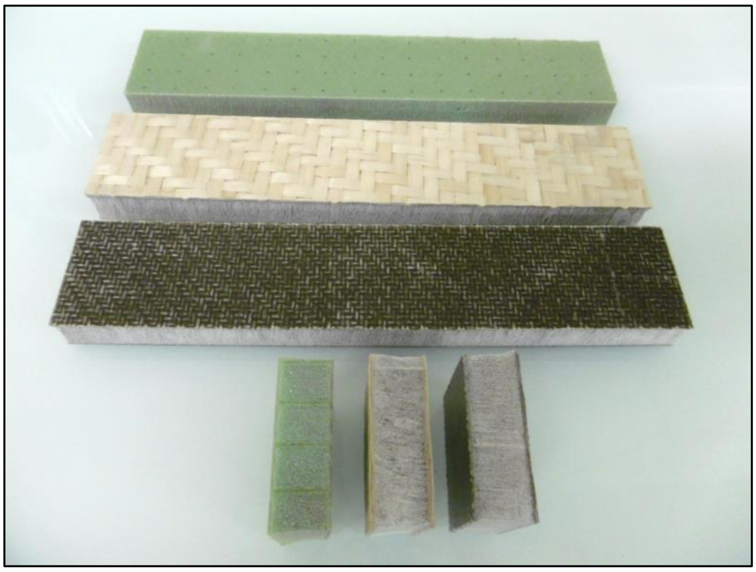

Figure 1. Materials studied

First, the quasistatic properties of each material were measured using standard test methods, in order to determine initial properties for design. These included through thickness compression tests [27] on square samples 50 x 50mm². Four-point flexure tests with support span twice the loading span [28] were performed on long 400 x 50 mm² specimens with 340mm between supports (20x thickness) to determine flexural stiffness. Short beam flexure was performed on 250 x 50mm² specimens to examine shear response, with 170mm (10x thickness) between supports. Figure 2 shows the two flexural test set-ups. All tests were performed on a 10 kN Instron 5566 test frame. The loading rate was 5 mm/minute.

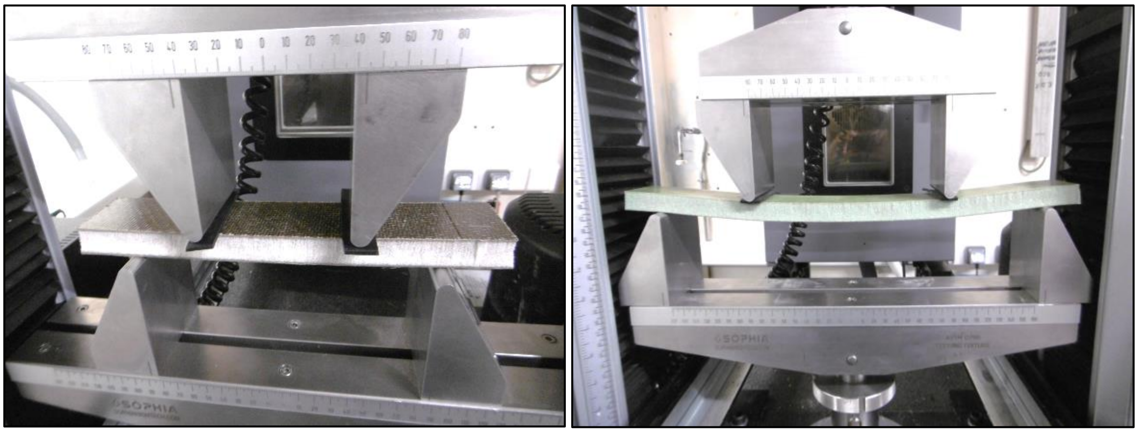

Figure 2. Flexural test set-up, short beam (L /H=10, left) and long beam (L/h=20, right)

A second series of tests investigated the resistance to local impact, using a drop weight tower and a rigid hemispherical steel impactor of diameter 25mm, Figure 3. The specimen geometry was 150 x 100 mm². Impactor weight was 4.5 kg, which was dropped from different heights. The sample boundary conditions are simply supported with a free surface window of 125x75 mm² on the lower side, and four neoprene rubber clamps restrain the specimen during impact on upper surface. This test simulates accidental impact damage to a boat deck. Impact load and sample back face displacement were measured at 100 kHz with an HBM Genesis™ HighSpeed data acquisition system.

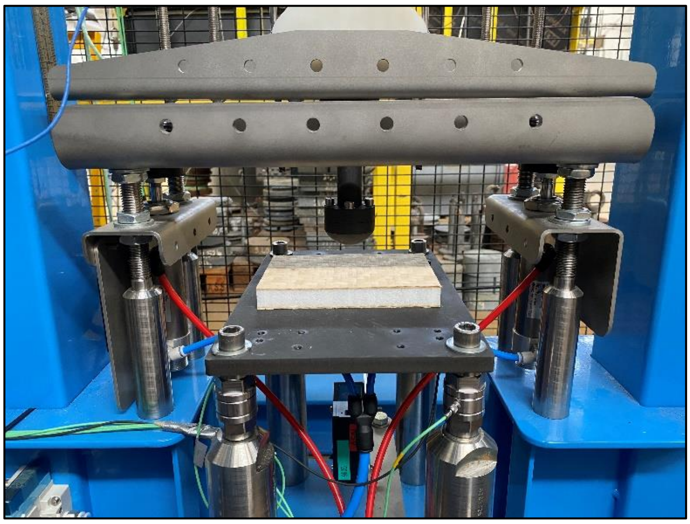

Figure 3 - Impact test set-up (neoprene rubber clamps removed to improve the visualization)

A third series of tests, which will be referred to as slamming impacts, was then performed. Here large panels (950 x 950 mm²) were bolted into a square steel frame and impacted by a medicine ball of 21 or 46 kg, a rubber ball filled with either sand or, for higher energies, with steel shot. The ball was attached to an overhead crane, drop height was measured with a hand-held laser, the ball was then released and allowed to fall onto the panel.

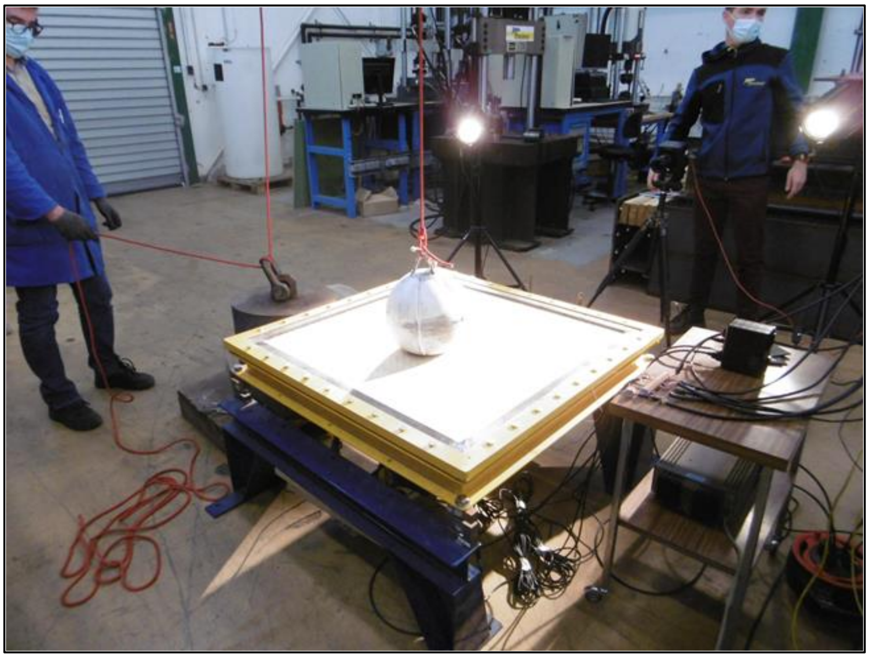

Figure 4. Slamming impact set-up

This test was developed in previous studies on racing yachts to simulate a wave impact on a boat hull [29,30], as it has been shown to produce damage in sandwich materials similar to that induced by repeated wave impacts (slamming).

Impact load (20 kN load cells at each corner of the panel support frame), central panel displacement (Keyence® LK-H157 laser transducer) and central strains (strain gauges bonded parallel to the support frame at 0° and 90°) were recorded with the same high-speed acquisition system as for the rigid impact. A high-speed camera (Photron FastCam® MINI AX200) was also used, to record the medicine ball deformation during the impact at 5 kHz, and thus estimate the impact surface area. This value, with the recorded impact force, provided an estimation of a maximum apparent contact pressure. Figure 5 shows an example of ball images just before and during impact, taken from such a film. The initial undeformed ball diameter before impact was 275mm.

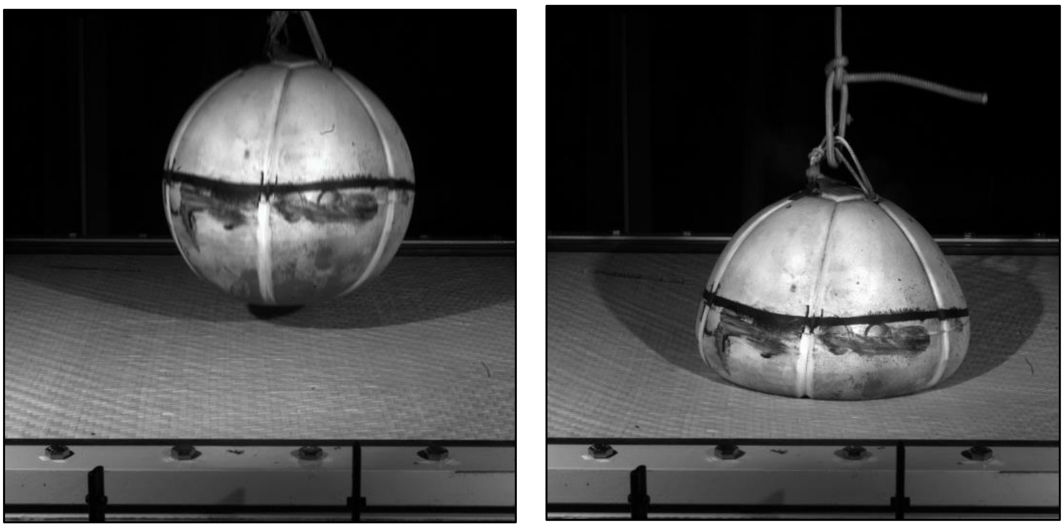

Figure 5 - Image of 21 kg medicine ball before impact (left) and at lowest point (right), bamboo/PET sandwich

Table 2 summarizes the test matrix.

Test type	Specimen Geometry mm²	Number of tests per material
Quasi-static - Facing tension - Compression out of plane - Short beam flexure - Long beam flexure	 25 x 300 50 x 50 250 x 50 400 x 50	 4 4 4 4
Rigid impact	150 x 100	12
Slamming impact	950 x 950	2 panels per material 9 impact energies for PVC, 6 impact energies for PET

Table 2. Mechanical test matrix

Results and Discussion

- <u>Quasi-static properties</u>

Table 3 summarizes the results from the quasi-static tests.

Sandwich	Flexural stiffness N/mm	Shear strength, MPa	Through-thickness Compression strength, MPa
Glass/PVC	185	>1.39 (0.03)	1.79
Bamboo/PET	70	0.89 (0.14)	1.45
Flax/PET	72	0.85 (0.07)	1.63

Table 3. Quasi-static test results

Figure 6 shows examples of load-crosshead displacement plots for flexural tests on the 3 materials. These clearly show the significantly higher flexural stiffness of the glass/PVC sandwich. This is due to a combination of lower facing stiffness and lower core properties of the alternative materials. However, simple beam theory indicates that increasing the flax composite thickness from 1.5 to around 2.5mm would be sufficient to achieve similar stiffness to the glass/PVC.

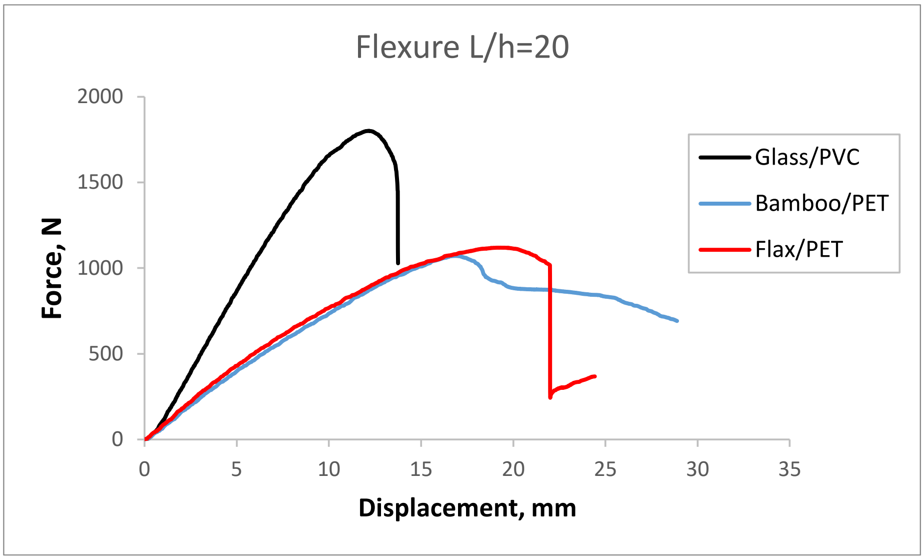

Figure 6. Examples of 4 point flexural response

Figure 7 shows examples of failure in shear (short beam flexure) for the PET foam core sandwich materials. The PVC sandwich failed by local indentation, not shear, so the value given for that material is a lower bound figure. The values for the PET foam sandwich are slightly higher than the manufacturer's mean values (0.72 MPa) in Table 1.

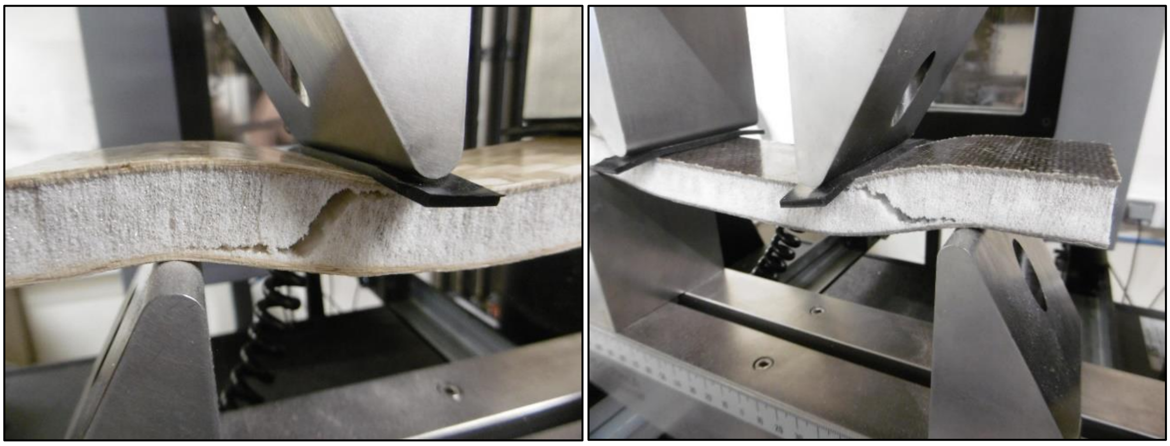

Figure 7. Shear failures, bamboo/PET (left), flax/PET (right)

Through-thickness compression behaviour is similar for the three materials, values are slightly higher for the PVC as indicated by the manufacturers (Table 1).

- <u>Rigid impact</u>

The rigid impact tests provide information on the local damage thresholds of the three materials and their resistance to perforation. Figure 8 shows the change of the maximum force as a function of impact energy determined from the mass and the velocity of the impactor just before the contact. Figure 9 shows the section of coupons of each material impacted at 21J, 43J and 82J.

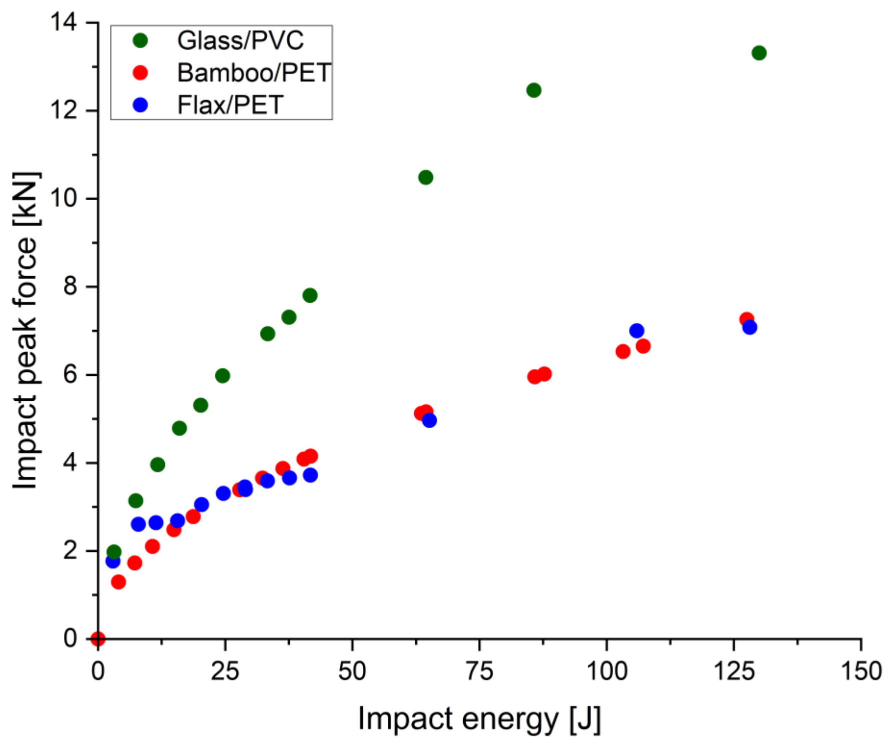

Figure 8 - Maximum force versus impact energy

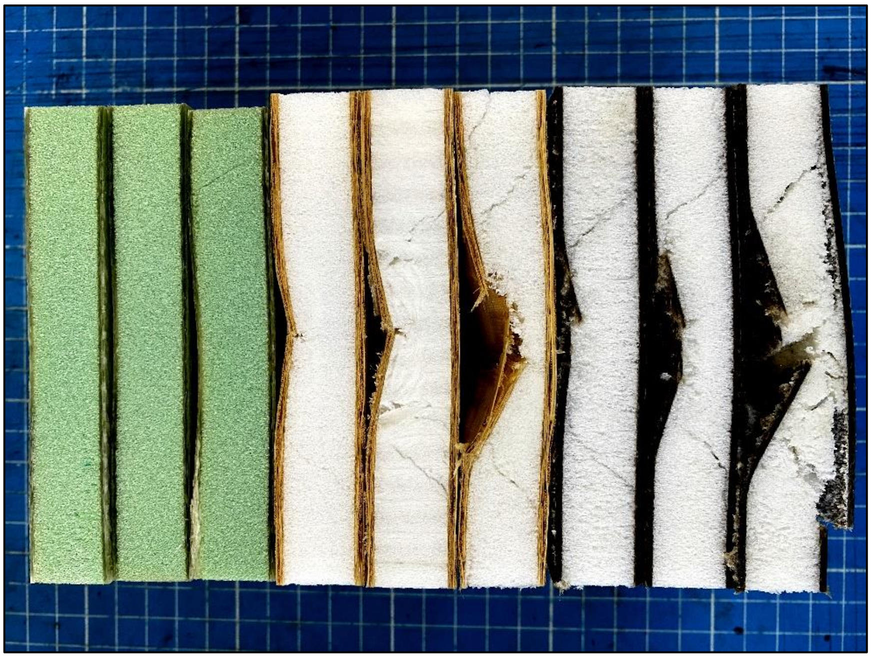

Figure 9 - Section of coupons of Glass/PVC, Bamboo/PET and Flax/PET coupons impacted at (from left to right) 21J, 43J and 82J.

- Slamming impact

When panels are subjected to a more distributed pressure loading the response is rather different. Figure 10 shows a comparison for a low energy (20 kg drop from 2-meter height) impact. This level of impact energy is much higher than those which result in perforation with a rigid impacter and results in similar peak loads (a little over 1 ton) but the spreading of the load by the medicine ball caused no visible damage in any of the panels.

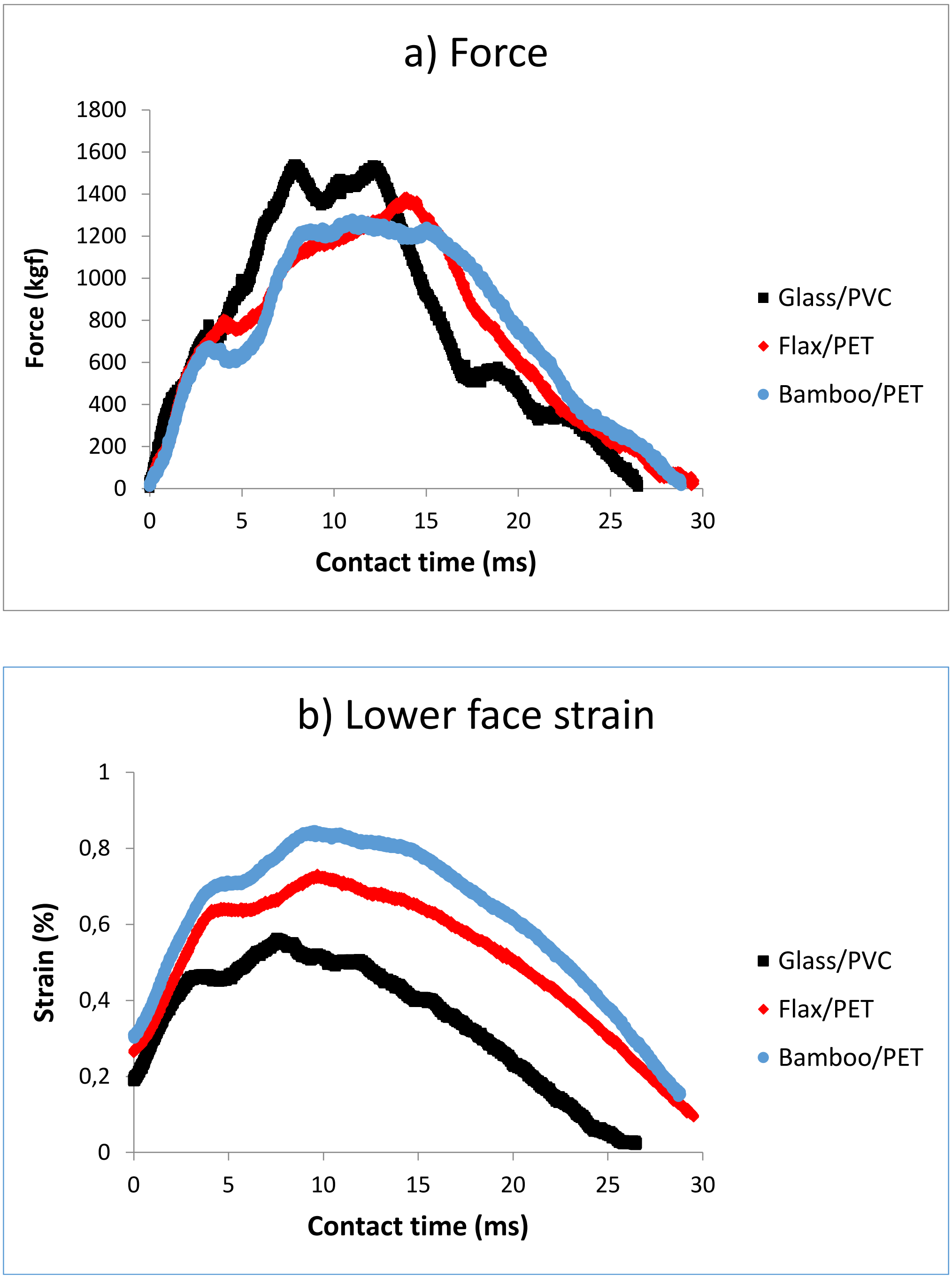

Figure 10. Examples of recorded data for (a) forces and (b) lower face strains for 20 kg drop from 2 meters.

The measured loads are similar for the three panels here but the higher stiffness of the glass/PVC results in much lower strains on the lower facing. At higher energies, damage occurs in the alternative materials. From analysis of the high-speed video images an impact area was estimated, based on the change in ball shape and this, together with the measured peak force, was used to provide an apparent contact pressure. Table 4 shows the measured values.

Panel	Max.energy, J	Estimated pressure, MPa	Nominal failure pressure, MPa
Glass/PVC	2254 no damage	1.19	1.45
Bamboo/PET	1235	0.70	1.3
Flax/PET	1235	0.52	1.3

Table 4. Apparent contact pressures, maximum values for PVC and values at failure for PET.

These estimated pressures are well below the nominal failure pressures for the PET foams suggesting that core crushing is not the critical damage mechanism.

The glass composite/PVC panel used today in many small boats is an excellent material. It resisted an impact of 46kg from 6 meters without any visible damage. The alternative natural fibre-based sandwich materials were both more sensitive to impact damage.

The damage mechanisms under slamming loads are quite different to those observed under hard impact. Figure 11 shows images of panels after testing to 1225 Joule energies. Core crushing and plastic deformation of the facings, resulting in permanent deformation of the centre of the panel, were noted for the flax/PET but there was no sign of shear cracks nor facing/core debonding. For the bamboo/PET sandwich significant lower skin cracking was observed.

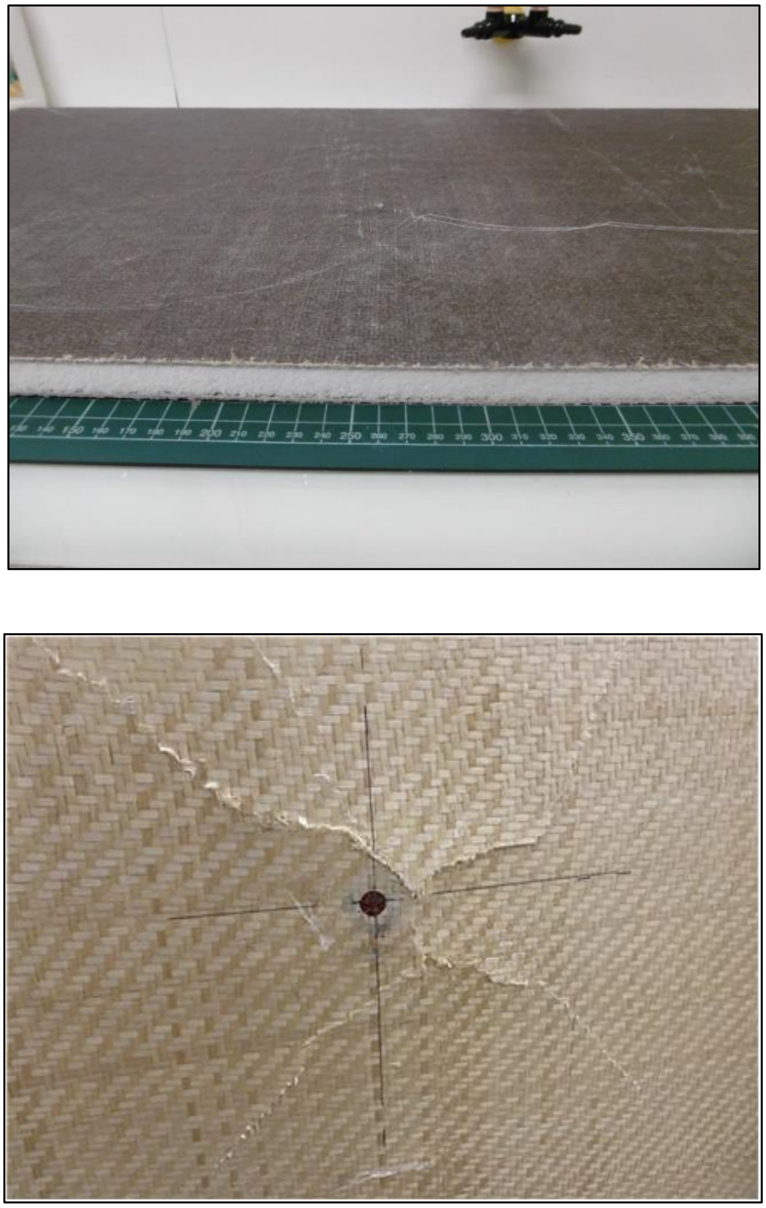

Figure 11. Images of panels after 1225J slamming impacts

Upper: Section through centre of flax/PET sandwich. Lower: Lower facing damage at centre of bamboo/PET sandwich.

Environmental impact

Evaluation of alternatives to the current petroleum-sourced sandwich materials must be considered in the framework of environmental impact. This involves many aspects. First, the choice of materials can lead to a reduced carbon footprint, for example replacing glass fibres with flax has been shown to use less energy, and lower most impacts [31]. Second, a thermoplastic core may allow recycling, improving end-of-life options. Partial or complete use of recycled feedstock will further reduce impact. These advantages must be considered in the broader context of dismantling of a boat structure, and will not necessarily be beneficial short term, but it provides the possibility for re-use. A direct Life Cycle Analysis comparison between recycled PET and PVC foam can be found in [32]. The global warming potential (GWP100), measured by kg of CO_2 equivalent produced by manufacture (cradle to gate) of 100kg of different foam cores indicated 226 kg for recycled PET, 337kg for virgin PET foam and 472 kg for PVC foam of the same density. Most of the other impact categories examined were also lower for PET foam.

Conclusion

This study provides results from a set of data obtained during tests on three sandwich materials compared on an equivalent panel weight basis. Standard quasi-static test results indicate that the two alternative sandwich materials are less stiff than the reference and show lower damage thresholds. The PVC foam-based sandwich used today shows excellent rigid and slamming impact resistance. The PET foam tested here, of equivalent density, shows lower shear strength. Under local hard impact loads damage initiates at lower energies for the PET foam materials.

When a more uniform pressure loading more representative of wave loads is applied, the alternative materials show much lower damage thresholds, with facing damage detected at impact energies around half those supported by the glass/PVC reference. However, this reflects the lower panel stiffness. Given the low weight of the natural fibre facings their thickness, and hence the sandwich stiffness, could be increased with little overall weight increase. The use of these materials for highly loaded structural parts requires further work but they are clearly already suitable for non-structural boat components. The data generated here is now being used to validate structural models, and further analysis is underway to optimize their performance.

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