

Durability of flax and glass fibre reinforced epoxy laminates for marine applications

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ABSTRACT: The durability of an infused flax fibre reinforced plastic (FFRP) marine composite laminate has been extensively investigated via hygrothermal ageing and impact, quasi-static (QS) point loading, flexural and interlaminar shear testing. Comparisons were made with an equivalent thickness 'traditional' glass reinforced plastic (GRP) marine laminate. FFRP impact and QS indentation performance improved with ageing. That of GRP deteriorated significantly but only when aged at 60 °C did it drop to that of the much lower performing FFRP. In flexure GRP performed far better than FFRP, and both laminates deteriorated significantly with ageing. Loss of FFRP shear stiffness after ageing was substantial. Plasticisation of the resin and flax fibres is thought to be important. Sustainability-driven design decisions concerning flax composites in a marine environment should consider that they appear to be heavier, less stiff, far less robust and very susceptible to the effects of moisture. However, under severe ageing conditions, plasticisation may temper FFRP's disadvantages under impact and point (but not flexure) loadings.

1 INTRODUCTION

Composite materials are extensively used in marine applications due to such advantages as low weight, corrosion resistance, low maintenance, and the ability to create complex, seamless forms (Rubino et al., 2020). 'Traditional' marine composites use glass and/or carbon fibres, but carbon fibres are resource-intensive and energy-consuming, leading to substantial CO₂ emissions (Navaratnam et al., 2023). Synthetic fibres such as aramid also pose environmental concerns due to poor degradability. Recycling fibre-reinforced polymers (FRPs) remains a concern (De Fazio et al., 2023).

Flax is a plant fibre that offers low density, ease of handling and non-abrasiveness, making it a possible alternative to synthetic fibres (Yan et al., 2014). Practical applications, such as a racing sailboat built with flax composites have demonstrate the feasibility, at least in theory, of high-performance structures (Castegnaro et al., 2017). However, the adoption of flax fibres in the naval industry is limited due to higher costs and a lack of long-term performance data in wet, aggressive marine environments.

Plant fibres in composite structures pose challenges due to their hydrophilic nature, causing sensitivity to moisture and poor compatibility with hydrophobic polymers (Scida et al., 2013). When exposed to water, composites of these fibres absorb moisture, increasing weight, giving swelling and reducing mechanical properties, particularly when concerning flax fibre reinforced polymers (FFRPs) in marine use (Li and Xue, 2016).

While FFRPs with bio-epoxy can offer some sustainability advantages (Duflou et al., 2014), understanding their durability in marine environments and addressing hydrophilic challenges is crucial to ensure that the overall balance is not negative. In fact, Duflou et al. (2014) determined a lower environmental impact for equivalent strength GRP when compared to FFRPs.

Currently, there is a lack of experimental data on marine FFRP durability, particularly compared to GRP (since the latter is the established practice which would be substituted in the marine industry). The very rapid and sudden recent increase in the use of flax fibres and bio-based epoxy resin in the marine sector underscores the need for more experimental data. This study aims to help fill this knowledge gap.

Due to the nature of the materials used, marine composite structural design is often flexure controlled, and hence such tests are a very relevant means to quantify their durability. Similarly, interlaminar shear failure, delamination, is a common failure mode in such applications (and is especially important for point and impact loadings) and hence short beam tests were also used as a durability measure. Susceptibility to impact is a known potential fragility of marine composites (Sutherland, 2018) and the only study found (Squires,

2022) indicates a very worrying fragility of flax composites in this respect. Further, durability of these materials in this respect does not appear to have been studied to date. Quasi-static (QS) indentation testing allows both the response to point loads to be evaluated, and also provides valuable information about the impact response (Garrido et al., 2021; Sutherland and Guedes Soares, 2012).

Hence, the approach taken here is to evaluate, and compare with GRP, the durability of FFRP with a bio-based epoxy matrix before, during and after hygrothermal ageing at a range of temperatures via short- and long-beam flexural, and QS indentation and dynamic impact testing.

2 EXPERIMENTAL PROCEDURE

2.1 Materials

The FFRP and GRP laminates were manufactured using biaxial fabrics and a blended bio-epoxy resin:

Glass fibre: 840 g/m² Non-crimp 0°/90° biaxial (*Rebelco*, Portugal).

Flax fibre: *AmpliTex™ 5008*, 350 g/m² Non-crimp ± 45° biaxial (*Bcomp*, Switzerland).

Epoxy: *Greenpoxy 56* resin, *SD 7561* hardener (*Sicomini*, France).

Equivalent thickness was selected here as the laminate equivalence criteria between GRP and FFRP to give both comparable moisture diffusion and specimen dimensions in the subsequent durability assessment. A thickness of approximately 4.1 mm was deduced with forethought for the mechanical tests, which required 6 plies in each material (since this aspect had been taken into account in the selection of the fibres).

Vacuum assisted resin transfer moulding (VARTM), or ‘infusion’ was used to produce the laminates since it both reduces variability and may eliminate any problems with wetting out and compacting of the flax fibres. Before infusing, glass and flax fibres were dried for 3 and 5 hours, respectively, under vacuum below 20 mbar to ensure the hydrophilic nature of the flax fibres did not lead to variations in initial moisture content. After infusion was completed the laminated plates were left to cure at ambient temperature (for a minimum of one week), after which a post-cure cycle of 10 h at 80 °C was performed. According to the resin’s technical datasheet, this should result in a glass transition temperature (T_g) of 78 °C (SICOMIN Composites, 2018). This post cure ensured that the T_g was approximately 20 °C above the highest hygrothermal ageing temperature to be used (detailed in section 2.2), thus avoiding any state transition effects.

After production, all laminated plates were cut into 340 mm by 264 mm rectangular plates, to give equivalent surface areas for moisture absorption and allowing conservatively for all the planned test specimens to be cut out at the various following stages of hygrothermal ageing. FFRP plates were cut out at an angle of ± 45° to give the same 0°/90° fibre orientation as in the GRP plates.

Ignition loss tests as per the *ASTM D2584-02* standard were conducted on 6 dry GRP specimens giving an estimated fibre volume fraction (FVF) of 0.52. An alternative, method (*ASTM D3171-22*) had to be applied for the heat-degradable flax fibres, measuring the weight and exact dimensions of nominally 70 mm by 70 mm specimens and considering the densities and areal weights given in the datasheets:

Epoxy resin density: 1.198 g/cm³, Flax density: 1.35 g/cm³, Glass density: 2.54 g/cm³.

In this way, both matrix and fibre volume fractions may be independently calculated. This *ASTM D3171* method was also applied to the GRP laminate (12 specimens for both laminates) giving the following results:

FFRP FVF 0.37

GRP FVF 0.50

Thus giving confidence in the results due to the practically equal values obtained for both the GRP FVF using the different methods.

To give an additional comparison of the unaged materials, ISO 527-1,4 (2012) tensile tests along the longitudinal direction were also conducted:

GRP (7 specimens):

Strength 437 ± 30 MPa, Modulus 25.2 ± 1.1 GPa

FFRP (5 specimens):

Strength 112 ± 4 MPa, Modulus 8.5 ± 0.3 GPa.

2.2 Hygrothermal ageing

Three temperatures were selected for the hygrothermal ageing in order to investigate distinct ageing environments up to easily conceivable summer or tropical deck temperatures, but below the cured resin glass transition temperature:

20 ± 2 °C, 40 ± 2 °C, and 60 ± 2 °C.

The 340 mm by 264 mm plates were immersed inside plastic boxes containing water. The use of sea water was considered, but was discounted at this stage in order to decouple any durability effects of water absorption from the inevitable and difficult to control fluctuations in the complex composition of seawater under hygrothermal ageing conditions. Further, this aspect is not at all straightforward, for example concentrations of natural salts and other chemicals (from the composite laminate itself, paints, fuel etc) will vary wildly between, and within, cases (for example at the outer hull and in the bilges).

The currently reported phase of the work fitted into the timescale of an MSc thesis and hence withdrawal of specimens for durability testing was carried out after 1 and 3 months' ageing. However, enough additional laminated material was produced and immersed to allow removal and durability testing after 6, 12 and, depending on results, 24 months).

Specimens were tested 'wet'; defined here as immediate immersion in water at room temperature on removal of the aged plates from the hygrothermal ageing bath, being only removed from this water for CNC router cutting into individual specimens (taking a maximum of 1 hour) and for removal for testing (after wiping dry with a cloth) – which occurred at the latest on the morning after specimen cutting if this cutting occurred in the afternoon.

To try to avoid wicking along the plate edges (which should not, in theory anyway, occur in service) and hence to promote equivalent (for both materials) unidirectional diffusion through the panel faces and thence the thickness of the laminate, the cut edges of the immersed plates were coated with a two-part epoxy adhesive (*Icosit K-101 N*).

To measure the rate of this moisture diffusion into the laminates, a set of 12 (70 mm by 70 mm epoxy adhesive edge-sealed) control specimens for both materials was also placed in the heated ageing water baths (4 of each at each of the three temperatures for each material). These specimens were accurately weighed before immersion and then daily for the initial period, and then progressively less often as their water mass uptake stabilised for a period up to 3720 h. These measurements are ongoing and will continue up to the end of the planned future work. The relative mass uptake, M_t (%), was defined and calculated via Equation 1 (Scida et al., 2013),

$$M_t = \frac{w_t - w_0}{w_0} \times 100 \quad (1)$$

where w_t is the weight of the "wet" specimen at time t (g); w_0 is the weight of the unaged specimen (g).

2.3 Durability Testing

2.3.1 Flexural properties

Flexural stiffness and strength were determined via tests based on the *ASTM D7264-07* standard. Seven specimens were tested in each case with a *Instron 5982-100kN* universal testing machine (UTM) using a three-point bending setup with a span of 132 mm, loading nose and support roller radii of 5 and 3 mm, respectively, and a loading rate of 20 mm/min.

The stress and strain at the outer surface at mid-span, σ (MPa) and ϵ (mm/mm), respectively, were determined as per the equations found in the *ASTM D7264-07* standard. The flexural chord modulus of elasticity, E_f^{chord} (MPa), was estimated between strains of 0.003 and 0.005.

2.3.2 Short-Beam strength

The short beam tests were based on the *ASTM D2344-00* standard. Seven specimens were tested in each case with the same UTM using a three-point bending setup with a span of 16.5 mm, loading nose and support roller radii of 5 and 2 mm, respectively, and a loading rate of 2 mm/min.

2.3.3 Quasi-static indentation

Quasi-static (QS) indentation tests were based on standards *ASTM D7136/D7136M-15* and *ASTM D6264-12*, and were performed on a calibrated computer controlled servo-hydraulic mechanical test machine.

70 mm by 70 mm test specimens were impacted on a 50 mm internal diameter circular support – simply supported to avoid any disparities in the achievable level of clamping between static and dynamic tests that would occur in a clamped configuration. In all cases, five specimens were tested for both QS indentation and low-velocity impact. A cylindrical indenter with a 10 mm diameter hemispherical tip was used, both to try to ensure that the damage area did not propagate to the specimen edges, and to remain true to typical marine impact scenarios where impacts with flat objects are rare. A constant rate of 0.5 mm/s was used and absorbed energy, AE (J), was determined by integrating the force-displacement data.

Perforation is both an important response and yet is surprisingly difficult to define, the most obvious definitions – the creation of a ‘hole’, or the complete passing of the hemispherical part of the indenter, through the laminate are actually practically impossible to define, identify and measure. Hence, an easily and consistently identifiable point in the force-displacement data corresponding to a repeatable degree of ‘perforation’ was used as a definition here, as was done in previous work (Sutherland et al., 2017). For these materials, a clear peak in the force-displacement plot is followed by a significant drop in force until this levels out into a ‘plateau’ when the indenter’s hemispherical tip has passed through the specimen (see (a)). The start of this plateau, however is not well defined and its exact form a source of variability. Hence, in order to accurately and repeatedly define this onset of ‘perforation’, a given and relevant indenter displacement is taken. This displacement is constant for a given material, but to define the same degree of perforation one needs to take on different values for different materials (and ageing periods). This approach makes sense practically since ‘perforation’ will occur for a given material at a given indenter displacement. Values of 13 and 15 mm for glass and flax fibre laminates (the higher latter value due to the lower stiffness of flax laminates) were found to give equivalent points in the force–displacement plots for both laminates and this consistent approach minimized variations in absorbed energy measured at perforation.

2.3.4 Low-velocity impact

The low-velocity impact tests were based on the standard *ASTM D7136/D7136M-15* and were performed on a Rosand IFW5 Instrumented Drop Weight machine (see Sutherland and Guedes Soares (2012) for more details). To ensure valid comparisons between QS indentation and these low-velocity impact tests, identical test setups were employed by using the same specimen dimensions and physical support and indenter (in this case ‘impactor’).

The QS AE results obtained here were used to estimate the impact incident kinetic energies (IKE’s) required for the same degrees of damage as seen in the QS tests. This was achieved using the method proposed in Sutherland and Guedes Soares (2012) which showed that the first damage (usually start of delamination and/or contact damage) occurs at the same force/displacement/ AE , but that the AE to perforation energy for impact and QS tests are related via a simple proportional ratio, or ‘dynamic scaling factor’, and as outlined in Castilho et al (2015), Sutherland et al (2017) & Garrido et al (2021). This factor for GRP was estimated in this previous work at between 1.5 and 2, and hence a value of 1.6 was taken here initially and then refined using the first impact results obtained.

Since GRP impacted specimens exhibited very similar behaviour (in terms of displacement) up to ‘perforation’ (as defined above) as was seen for the equivalent QS tests, the same displacement value of 13 mm was defined as the onset of impact perforation. However, for FFRP the displacements required to achieve this level of perforation for impact were seen to be higher than the equivalent QS values, and hence a value of 20 mm (versus 15 mm for QS) was defined for the impact of the flax laminates.

3 RESULTS AND DISCUSSION

3.1 Mass uptake

The mass increase was significantly higher for FFRP than for GRP as shown in Figure 1. This is mainly due to the far more hydrophilic nature of the flax fibres. Very significant mass uptake occurred for FFRP during the first hours of immersion (2.5% in the first 96 h at 20 °C, versus 0.1% for the GFRP), which was accompanied by a noticeable thickness increases (~7%, versus <1% for the GRP). During the 3720 hours of mass measurements only the FFRP aged at 60 °C had apparently reached saturation at a mass uptake of about 12%; the mass of the laminates aged in the other environments were absorbing water. It should also be noted that at the end of the immersion period considered here the water uptake for FFRP laminates even at 20 °C was approximately 75% of that at 60 °C whilst for GRP this figure was only around 20%. Hence, water absorption is severe for FFRP even at relatively low temperatures, whereas for GRP water uptake exhibited a much more pronounced temperature dependence.

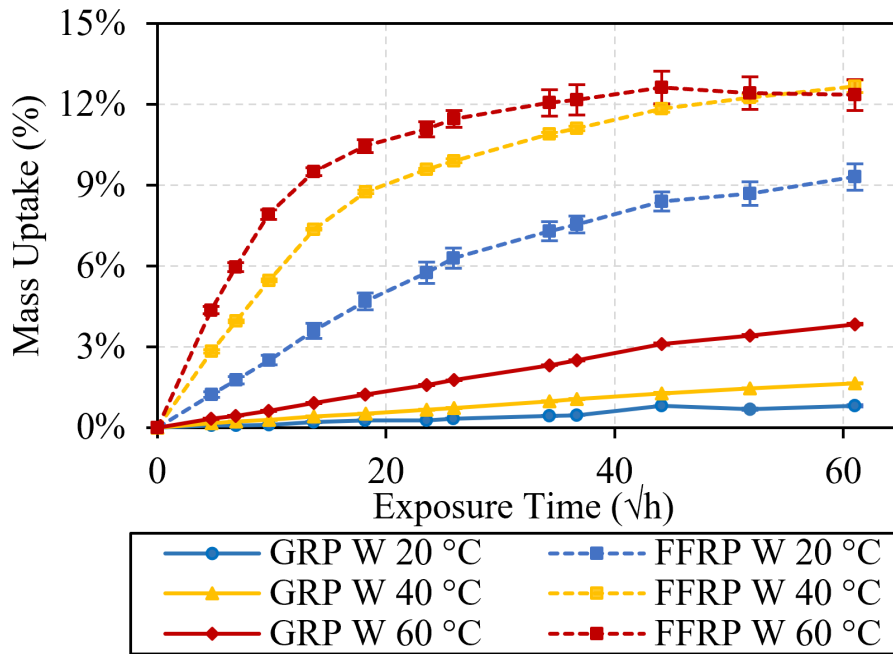


Figure 1– Mass uptake for FFRP and GRP laminates

GRP mass uptake was approximately linear with respect to the square root of time, following the Fickian diffusion model. However, since after the 3720 hours immersion saturation had not yet been achieved these results have not yet been fitted to this model. For the FFRP an initial higher mass uptake was followed by a gradual reduction in the rate of mass increase. The first stage could well be dominated by water absorption into the fibres, which progressively (but relatively quickly) saturate leading to the second stage, where absorption in the matrix becomes more dominant, but further work would be required to confirm this or otherwise.

3.2 Flexural behaviour

GRP exhibited consistent failure modes in flexure for unaged and aged specimens across all ageing conditions. Failure firstly occurred in compression of the top ply, as shown in Figure 2(a), followed by tensile failure of the lower ply. For FFRP the unaged specimens failed in tension at the lower ply at large deflections (around 34 mm) as shown in Figure 2(b) and aged FFRP suffered even larger deflections and rupture was not achieved.

The flexural stress-strain curves shown in Figure 3(a) show these different behaviours. The GRP response was approximately linear up to the first ply failure, which was immediately preceded by a slight stiffness reduction and followed by a clear drop in force. The aged GRP suffered reductions in stiffness and maximum stress with increasing ageing temperature, as illustrated in Figure 3(b) by representative stress-strain curves for specimens aged for 3 months. The aged FFRP exhibited severe reductions in flexural chord modulus of elasticity. These likely occurred mostly in the initial days of hygrothermal ageing, with similar retention between 1 and 3 months for all ageing temperatures.

The average flexural chord modulus of elasticity and maximum flexural stress were 20.0 ± 0.7 GPa and 382.2 ± 33.5 MPa for the unaged GRP and 6.1 ± 0.2 GPa and 103.8 ± 2.8 MPa for the unaged FFRP, respectively. The property retention values after ageing are presented in Table 1.

3.3 Short-beam strength

Valid failure modes for interlaminar shear strength (ILSS) were only obtained for the GRP (Figure 2(c)), with the unaged FFRP exhibiting tensile failure and the aged FFRP experiencing large deflections followed by crushing at the supports (invalid failures), as shown in Figure 2(d). For this reason, it was only possible to obtain ILSS estimates for the GRP.

The typical force-displacement curves for the GRP and FFRP are displayed in Figure 3(b) where representative curves for the 3-month ageing results are displayed for clarity (curves for other ageing periods exhibited similar behaviour). Even though the FFRP did not suffer valid failure modes, a clear and significant decrease in the apparent stiffness of the material was seen with hygrothermal ageing. This trend was also observed by Cuinat-Guerraz et al. (2016), where FFRP laminates with a moisture content higher than 3% did not present clear failure in short-beam tests due to excessive deflections.

The ILSS value obtained for the unaged GRP was 33.7 ± 0.7 MPa and the corresponding ILSS retention is shown in Table 1. A severe loss in ILSS retention was seen, especially for the GRP aged at 60 °C. This was likely caused by the significant deterioration of the matrix's mechanical properties due to severe plasticisation. Similar results have been reported in Ray (2006), where the hygrothermal ageing of glass/epoxy laminates led to a reduction of 40% in the ILSS for laminates aged for 150 h at 70 °C at a relative humidity of 95%.

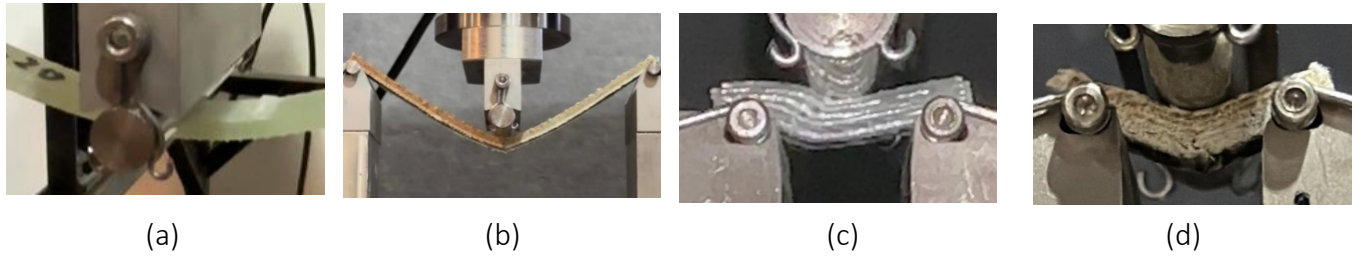


Figure 2 – Typical failure modes for the flexural tests on (a) GRP and (b) FFRP, and short-beam tests on (c) GRP and (d) FFRP

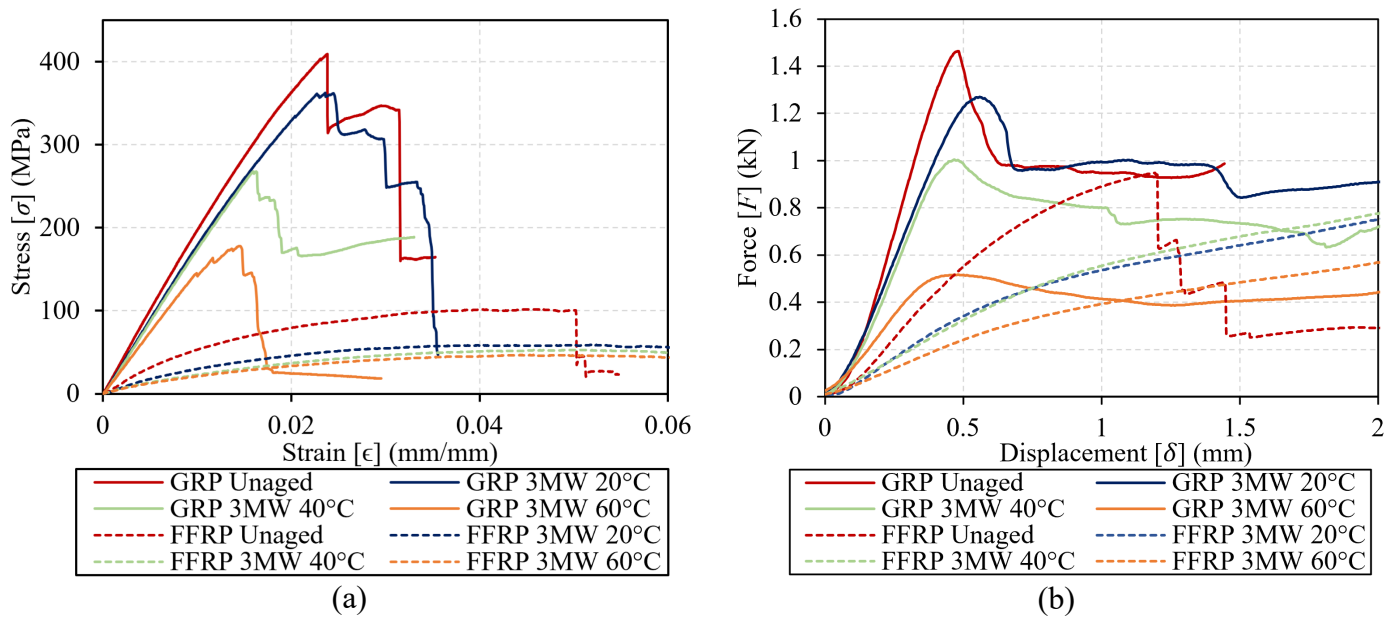


Figure 3 – GRP and FFRP aged 3 months: (a) flexural stress-strain curves and (b) short-beam force-displacement curves

3.4 Quasi-static indentation tests

The QS indentation tests force-displacement curves are shown in Figure 4 and the respective failure modes in Figure 5. As expected, the first GRP damage was delamination (Point A in Figure 4), reflected by the sudden force-displacement stiffness reduction accompanied and a visible whitening in the area around the indenter contact point. After this point, stiffness increased again for the unaged GRP, but not for the aged laminates, as shown in Figure 4. For the FFRP laminates delamination was seen in the specimens but its effects were not apparent in the force-displacement plots.

At higher displacements both materials experienced initial fibre failure, evidenced by a small force drops against a still ascending trend (Point B). Generally, this point was close to the maximum force for the GRP. Fibre damage was more evident on the back face of specimens, as shown in Figure 5.

Both delamination and fibre failure were more significant in unaged specimens or in those aged at lower temperatures. The final damage stage, perforation, was, as previously mentioned, defined here at indenter displacements of 13 mm for the GRP and 15 mm for the FFRP, and corresponded to an asymptotic approach to a constant low force as the cylindrical indenter passed through a hole of its own making in the specimen (Point D).

The property retentions of each material are given in Table 1. Generally, property retentions were higher for the FFRP, despite these properties being generally lower than those of the GRP (even with ageing induced degradation), with the exception of the longest period at the highest temperature. One of the most significant parameters was the AE at the defined perforation as this describes the impact absorbing capacity. Perfor-

ation AE for the unaged GRP was 47.2 ± 1.1 J, and after ageing for 3 months at 60°C this decreased to 19.9 ± 0.4 J. The corresponding values for FFRP were 23.9 ± 0.7 J and 24.5 ± 0.4 J, with this increase due to the effects of the higher forces seen with ageing just exceeding those of the reduced stiffness exhibited. Both effects are most likely due to fibre and/or matrix plasticisation reducing the degree of damage. This could be due to arresting resin cracking (delamination) and/or reducing brittle fibre breakage, but although these results provide valuable clues, it is impossible to explain this behaviour in terms of damage modes with the available data.

For force and AE at initial fibre failure, the unaged GRP achieved values of 6.8 ± 0.2 kN and 15.4 ± 1.3 J, whereas for FFRP these values were 1.9 ± 0.1 kN and 2.5 ± 0.2 J. These values both actually increased with ageing for FFRP; for three months at 60°C retentions reached 126% (2.4 ± 0.1 kN) and 254% (6.4 ± 0.7 J) for force and AE at fibre failure, respectively. Conversely, the GRP experienced severe deterioration with ageing in both the force and AE at fibre failure, with corresponding retentions of 34% (2.3 ± 0.2 kN) and 28% (4.2 ± 0.8 J), respectively.

The maximum force (Point C) and corresponding AE for the unaged GRP were 7.3 ± 0.4 kN and 20.0 ± 2.6 J, respectively. For the unaged FFRP, an average maximum force of 2.1 ± 0.1 kN was obtained; due to the significant variability in the displacement at which the maximum load occurred in the fibre failure plateau for FFRP, AE estimates were not taken from the obtained results. With ageing, similar trends as those described above for force at initial fibre failure were found for these parameters.

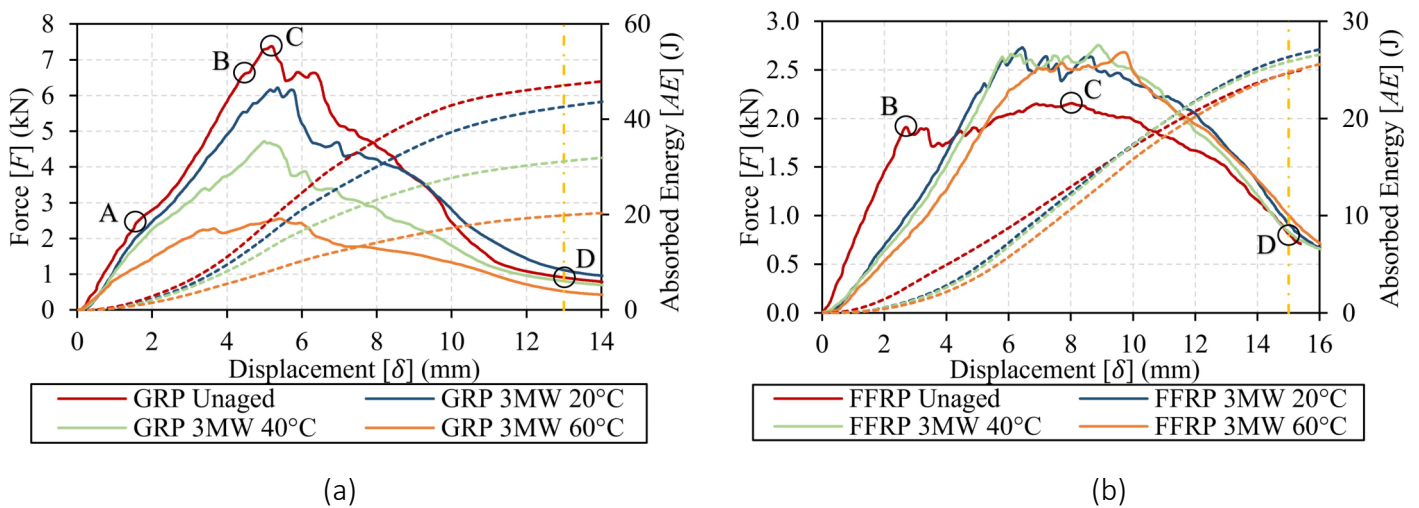


Figure 4 – Force-displacement curves (solid lines) and AE-displacement curves (dashed lines) from QS indentation tests on (a) GRP and (b) FFRP aged 3 months and tested "wet"; perforation is marked with a yellow dot-dash line

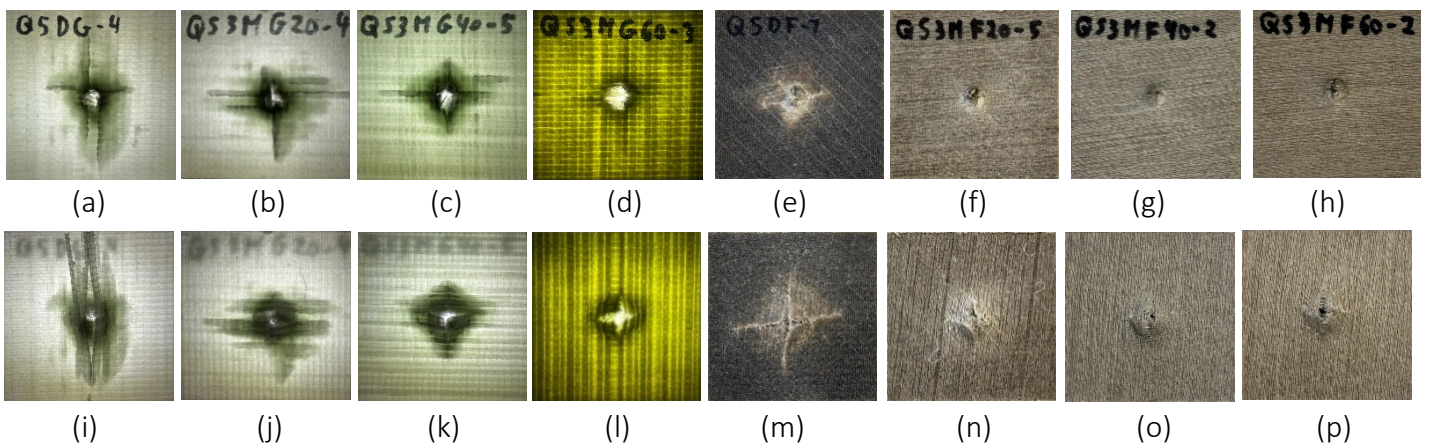


Figure 5 – Failure modes from QS indentation test: top face GRP, (a)-(d), top face FFRP, (e)-(h), back face GRP, (i)-(l), and top face FFRP, (m)-(p), for unaged specimens and aged at 20°C , 40°C , and 60°C , respectively

3.5 Low-velocity impact tests

In general, and as expected, the low-velocity impact force-displacement curves were similar in form to those of the QS indentation tests and are presented in Figure 6. Impact failure modes are illustrated in Figure 7 and property retentions with ageing are summarised in Table 1.

Impact AE at perforation (as defined previously) was 68.9 ± 5.7 J for the GRP, decreasing to 30.7 ± 3.4 J after ageing for 3 months at 60°C . The corresponding unaged and aged FFRP values were 23.8 ± 2.0 J and 24.8 ± 1.3 J, respectively. The plasticising effect of the flax fibres and matrix can explain the increment seen for FFRP. The ‘dynamic scaling factor’ ratio between impact and QS AE at perforation values were very different for the two materials: approximately 1.5 for the GRP (agreeing with previous work) yet only 1.0 for the FFRP.

The unaged GRP maximum impact force and corresponding AE at this force were 11.3 ± 0.6 kN and 36.2 ± 5.6 J, respectively. For unaged FFRP the maximum force was 2.3 ± 0.1 kN, again very similar to that for the equivalent QS indentation tests (consistent values of the AE at maximum force for FFRP were unavailable, as described previously).

Hence, a rate effect for maximum force was seen for GRP but not for FFRP, for both maximum force and for perforation. The hypothesis that some sort of flax fibre ‘plasticization’ occurs with aging (and these fibres are far less brittle in their natural very hydrated state) and the fact that no rate effect was seen for FFRP in the onset of fibre controlled penetration (around maximum force) and perforation is consistent with the hypothesis made in Sutherland, L.S., Guedes Soares, C., 2012 that this rate effect in GRP is connected to the speed of propagation of the (brittle) glass fibre failure modes when compared to the loading rate - i.e. at impact loading rates the brittle fibre (progressive bundle) failure simply does not have enough time to propagate as far as it can at QS loading rates.

As expected, force oscillations induced by the test machine and/or vibrations around the material contact stiffness seen in the low-velocity impact test results made identification (or even confirmation) of features of the force-displacement plots corresponding to initial matrix delamination and initial fibre failure (identifiable from the corresponding QS curves) impossible.

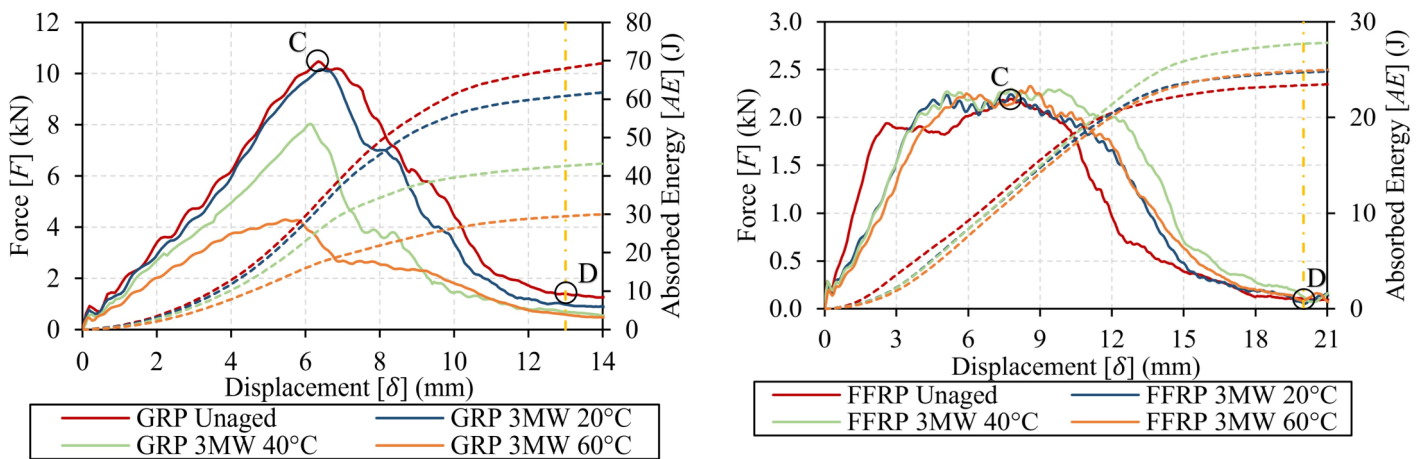


Figure 6 – Force-displacement curves (solid lines) and AE -displacement curves (dashed lines) from low-velocity impact tests on (a) GRP and (b) FFRP aged 3 months and tested “wet”; perforation is marked with a yellow dot-dash line

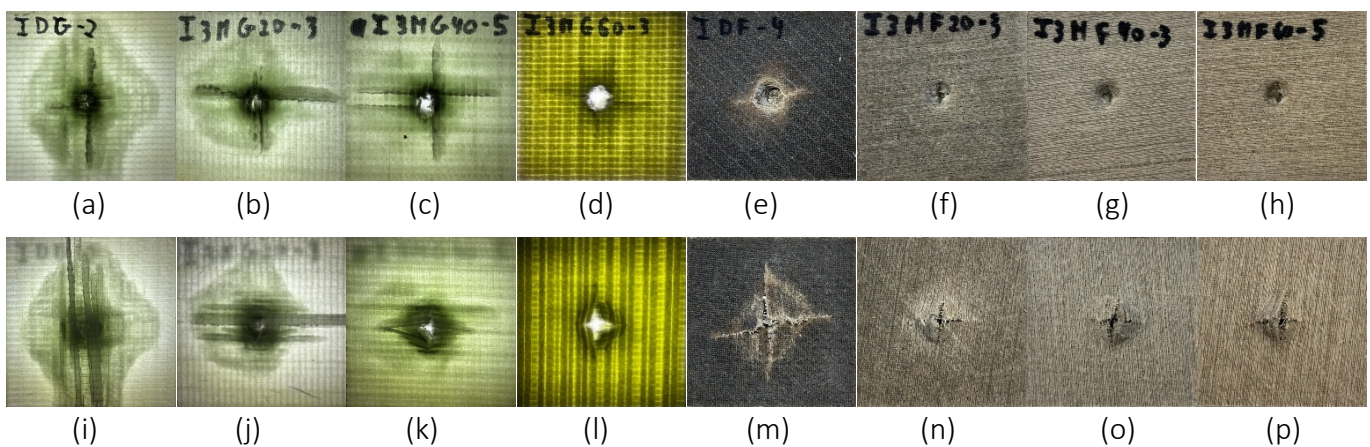


Figure 7 – Failure modes from low-velocity impact test: top face GRP, (a)-(d), top face FFRP, (e)-(h), back face GRP, (i)-(l), and top face FFRP, (m)-(p), for unaged specimens and aged at 20°C , 40°C , and 60°C , respectively

Table 1 - Property retention (%) after ageing for GRP and FFRP specimens

NB Higher property retention does not mean better properties

Material	Variable	Aged at 20 °C		Aged at 40 °C		Aged at 60 °C	
		1M	3M	1M	3M	1M	3M
GRP	Flexural Maximum Stress	85%	99%	72%	66%	51%	42%
	Flexural Chord Modulus of Elasticity	100%	96%	93%	88%	86%	73%
	ILSS	97%	91%	81%	68%	48%	32%
	QS indentation AE at Perforation	90%	88%	77%	60%	47%	42%
	QS indentation Maximum Force	89%	85%	79%	59%	43%	35%
	QS indentation AE at Maximum Force	100%	89%	75%	57%	43%	39%
	QS indentation Initial Fibre Damage Force	92%	86%	83%	50%	40%	34%
	QS indentation AE at Initial Fibre Damage	91%	86%	88%	45%	32%	28%
	QS indentation AE at Initial Matrix Damage	83%	73%	75%	65%	37%	26%
	QS indentation Initial Matrix Damage Force	91%	84%	85%	73%	55%	38%
	Low-velocity impact AE at Perforation	94%	89%	83%	63%	46%	45%
	Low-velocity impact Maximum Force	94%	90%	86%	67%	43%	39%
	Low-velocity impact AE at Maximum Force	93%	88%	88%	66%	39%	39%
FFRP	Flexural Maximum Stress	59%	56%	50%	52%	45%	44%
	Flexural Chord Modulus of Elasticity	52%	50%	37%	38%	38%	36%
	QS indentation AE at Perforation	104%	107%	107%	107%	102%	102%
	QS indentation Maximum Force	122%	123%	130%	127%	134%	125%
	QS indentation Initial Fibre Damage Force	131%	123%	134%	133%	137%	126%
	QS indentation AE at Initial Fibre Damage	205%	208%	263%	240%	260%	254%
	Low-velocity impact AE at Perforation	117%	107%	115%	111%	112%	104%
	Low-velocity impact Maximum Force	102%	102%	104%	106%	105%	100%

4 CONCLUSIONS

The durability of an infused flax fibre reinforced plastic (FFRP) marine composite laminate has been extensively investigated via hygrothermal ageing and impact, quasi-static (QS) point loading, flexural and interlaminar shear testing. This durability was compared to that of an equivalent thickness 'traditional' glass reinforced plastic (GRP) marine laminate (although both used a commercially available bio-based epoxy resin).

FFRP resin content was 25% higher than that of GRP, and FFRP initial mechanical properties were much lower. Hence, for equivalent structural designs FFP laminates would need to be significantly thicker and heavier.

Hydrothermal ageing produced complex trends dependent on which property / response was considered, but overall the performance of FFRP under impact and QS indentation actually improved with ageing, whilst that of GRP deteriorated significantly. However, it is imperative to note that the impact and indentation performance of the unaged FFRP was substantially worse than that of the unaged GRP, and that only under the most severe 60 °C ageing conditions did the GRP performance drop to the much lower level of that of the FFRP.

In terms of flexure, FFRP exhibited far lower properties compared to GRP, and the performance of both deteriorated significantly with ageing. Loss of FFRP shear stiffness with any ageing was so great that ILSS failure was not achievable in the tests due to excessive deflections.

The exact mechanisms of each of these multifarious trends are not identifiable from the current data, but plasticisation of the resin, and also of the artificially dried flax fibres, due to ageing are thought to be instrumental in many cases.

The results show that sustainability-driven design decisions concerning flax composites in a marine environment must take into account the fact that they do not perform at all well under flexure, impact and point loadings. This may well potentially more than negate any apparent sustainability advantages of flax, for ex-

ample where product resistance and durability is considered. However, ageing under severe conditions may temper FFRP's disadvantages under impact and point loadings, if not under flexure.

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