Effect of water immersion on the interlaminar and flexural performance of low cost liquid resin infused carbon fabric composites

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Abstract

This study investigates some potential benefits of using non-epoxy matrices in carbon fibre composites, targeting specific marine and wind energy applications. Water uptake during and after immersion for up to 28 days in deionised water at 40°C, and the effects of such conditioning on the interlaminar shear and flexural performance of the composites with isophthalic polyester, vinyl ester and urethane acrylate matrices were compared to those of equivalent composites impregnated with three grades of epoxy resin. Results demonstrated that, although the epoxy systems perform equally or better than the alternative resins in the dry state, they are also more sensitive to property degradation due to water ingress. The relatively lower water absorption and subsequent limited reduction in performance of vinyl ester and urethane acrylate composites is sufficiently promising to justify further study.

Keywords

A. Carbon fibre; A. Thermosetting resin; B. Environmental degradation; B. Mechanical properties.

1. Introduction

Historically, polyester resins and glass fibre have been the materials of choice for composite leisure boat manufacturers. Such materials constitute an affordable combination suitable for the majority of the 'commodity' craft construction. On the other hand, performance driven designs such as speed boats are typically constructed with epoxy resins reinforced with carbon fabrics for lighter and stronger structures. Although the traditionally conservative marine sector is reluctant to eradicate such a well established dichotomy, it seems that the boundaries between the two parties are starting to fade, probably helped by the favourable carbon fibre price trend of recent years. Driven by a constant push towards lighter and more fuel efficient craft, some leisure craft manufacturers are now considering the adoption of carbon fibre in partial or total substitution of glass for local reinforcement and stiffening in critical components [1]. The use of carbon has already proven successful especially for those parts intended to be installed in the highest sections of the yachts as radar masts and covers, where excessive masses might alter the weight distribution and therefore the stability of the whole boat.

A similar trend is observed in the wind energy sector, where the production processes of composite rotor blades make extensive use of the technology and know-how established within the marine field. Carbon fibre profiles are becoming a recurrent feature in glass fibre blades, especially as these become longer and need stiffening while keeping the mass of the structure within acceptable levels.

The local use of carbon does not necessarily imply the selection of a dedicated alternative matrix as manufacturers prefer to limit the types of resin on the shop floor to a minimum. Workshops set up for the use of a single or very few resins are unlikely to undergo substantial redesigning of the pipeline layout to allow distribution of an extra resin system to the working stations; even more so if the use of the new resin dictates the implementation of additional safety systems or different curing regimes. This would be the case if epoxy resins were to be introduced in a workshop typically operating with styrene based, low temperature curing matrices. In the field of volume dominated applications such as leisure craft or wind turbine blades, the use of epoxy is also discouraged by its higher price. A typical, commodity grade epoxy can cost 2-4 times more than a vinyl ester and 3-5 times more than a polyester. Consequently, very often the carbon, glass and hybrid preforms are all impregnated with the same resin, typically polyester or vinyl ester, which thus leads to the 'unusual' combination of carbon fibre with resins commonly regarded as cheaper and less performing than epoxy.

While the use of carbon with non-epoxy matrices is becoming acceptable at an industrial level, there is a surprisingly small amount of information available on the performance of such composites, especially if compared to the wealth of studies and research dedicated to epoxy-carbon systems. Some information is available in the literature on the behaviour of carbon/vinyl ester composites [1-5], but only limited work has been dedicated to carbon/polyester [2,6], probably because the adoption of such a combination has been traditionally discouraged [7]. The objectives of this study are therefore to

investigate the mechanical behaviour of carbon fibre composites with alternative, cheaper matrices, and to compare them against an epoxy benchmark. The intention is not only to provide information to the manufacturers as to what performance to expect when carbon fibre preforms are impregnated with non-epoxy resins, but also to explore the potentially better cost/performance ratio that the implementation of less frequent fibre/matrix combinations has to offer.

2. Materials and Processing

Table 1 lists the compositions and properties of all six resin systems used in this study. The polyester (UP) was chosen as it represents the workhorse of the commodity resins, widely used for most high volume applications, especially in the marine and wind energy sectors. The vinyl ester (VE) resin can be considered a midway option between polyesters and epoxies, which is adopted for its higher resistance to water osmosis compared to standard isophthalic polyester [8]. The urethane acrylate (UA) resin represents a further, more innovative alternative to epoxy systems with good potential to be used successfully with carbon fibre. Similar modified acrylate resins have been studied previously for offshore applications [9]. The VE adopted in the present study is 30% more expensive than the UP, while the UA is priced at twicethe cost of the isophthalic polyester.

Table 1: Selected resins details and main processing characteristics

Resin type	Isophthalic polyester	Vinyl ester	Urethane acrylate	Epoxy	Epoxy	Epoxy
Resin designation	UP	VE	UA	Ea	Eb	Ec
Product name	Crystic® 701PA	Crystic® VE671-03	Crestapol® 1250	Prime™ 20LV	Araldite® LY3505	Pro-Set® 117
Supplier	Scott Bader	Scott Bader	Scott Bader	Gurit	Huntsman	Wessex Resins
Curing system	Butanox® M50	Trigonox® 239	Butanox® LPT	Prime™ 20 Hardener	Hardener XB 3403	Pro-Set® 229PF
Mix ratio *[by weight]*	2:100	2:100	2:100	26:100	35:100	35:100
Cure cycle *[time at temperature]*	24h - 21°C	24h - 21°C	24h - 21°C	7h - 65°C	4h - 60°C	24h - 21°C
Post-cure cycle *[time at temperature]*	3h - 80°C	3h - 80°C	3h - 80°C	None	6h - 80°C	3h - 80°C
Geltime *[minutes at 25°C]*	59	14 - 20	16 - 20	30 - 480	600 - 720	128
Viscosity *[P]*	1.7	3.0	3.0	2.2	3.3	1.8

The market offers a very wide range of epoxy systems, most tailored for specific applications, with properties that can vary significantly from one to another. Therefore, selecting a single grade to use as a benchmark could have led to unreliable comparisons. Consequently, three grades of epoxy resins from

different suppliers were tested. For sake of simplicity, the three epoxies will be referred to as epoxy Ea, epoxy Eb, and epoxy Ec. They are all more expensive than the alternative systems listed above: Ea and Ec are 6 and 5 times the cost of UP, respectively, while Eb is the most costly option costing approximately 16 times more than isophthalic polyester. It should be pointed out that high performance, aerospace grade epoxies were deliberately left out of this study and the three grades chosen are typically used in commodity applications such as sport equipment, speed boats and wind rotor blades.

All the resins proposed were selected among systems specifically designed for infusion processes and potentially suitable for the marine and wind energy markets. Their viscosity at room temperature allows the liquid polymer to flow freely through the fibrous preform and fully impregnate the reinforcement. Viscosity of the resins was measured immediately after blending with initiator/hardener. A 4/40° cone and plate viscometer was used at a shear rate of $4500s^{-1}$. Tests were conducted at 25°C to BS 3219:1995.

In principle, all the resins selected can be cured at room temperature, although heat may be supplied for a shorter curing cycle. The polyester and vinyl ester grades require the addition of a catalyst (Scott Bader Accelerator G) in a 2:100 weight ratio to the resin to promote cure. The time necessary to achieve full cure may vary significantly between resin grades, however, the geltime can be, in theory, adjusted within a relatively broad range by changing/modifying the curing system.

Casts of resin were prepared using released glass plates as moulds, held 3mm apart by PTFE spacers. After mixing in the initiator/hardener, the resins were degassed under light vacuum for a few minutes, until no more bubbling was observed.

Two equivalent grades of carbon fibre were used, identical in every aspect except from the chemistry of their silane sizing. The latter defines the final use of the fabric: the *general purpose* sizing (GPF) is intended for use with epoxy, phenolic, polyester and vinyl ester resins, the *vinyl ester* sizing (VEF) is specifically compatible with vinyl ester resins, although it can also be used with epoxy. The different coupling agents were examined to determine the effect of the sizing, if any, on the overall performance of the composite. The carbon fabric was woven by Sigmatex UK in a biaxial ±45° style, using 12k tows from Torayca, the areal weight being 410 g/m^2.

The plies for preform manufacturing were cut in order to obtain a filament orientation along the 0° and 90° direction of the cured panels. The appropriate number of plies was laid-up in a symmetric sequence. Fibres were arranged in order to have the filaments in the middle plane of the specimen oriented along its main direction. The obtained preforms were impregnated via Vacuum Infusion technique. The duration of the infusion process varied according to the different viscosities of the resins, without ever exceeding 15 minutes. Panels were kept under vacuum while curing. After machining, all specimens

were post-cured in oven according to the manufacturer's specifications. The theoretical fibre volume fraction of the manufactured panels was calculated on the basis of simple geometric considerations and always fell between 50% and 54%. Such a wide range of variation is expected in composite parts obtained by vacuum infusion of the resin and it will be reflected in a relatively high scatter of the test data.

3. Mechanical testing

Cast resins were characterised in tension to BS EN ISO 527-2:1996 on samples type 1A and with a loading rate of 1mm/min. Toughness was measured following BS ISO 13586:2000; coupons of cast resin, 6.5mm x 40mm x 3.2mm, were notched and a sharp crack was generated by tapping a new razor blade at the bottom of the machined notch. The raw data recorded by a 1kN load cell were post processed to calculate G_{Ic} and K_{Ic}. At least five acceptable data points were obtained for each resin.

Tests on laminates were selected among those expected to be dependent on the behaviour of the matrix resin. Interlaminar shear strength (ILSS) coupons were machined from panels made of 4 layers of carbon fabric. The procedure described in BS EN ISO 14130:1998 was followed using a loading rate of 2mm/min and testing a minimum of five specimens per category of material. The final dimensions of each coupon were 20mm x 10mm x 2mm. The 3-point bend flexure tests followed the BS EN ISO14125:1998, Class IV protocol. The specimens were machined from 4-ply panels equivalent to those used for ILSS coupons manufacturing. Load was applied to the specimens at a rate of 2mm/min. The overall size of the specimens was 100mm x 15mm x 2mm. Five to eight coupons per batch of composite were tested. The ILSS and flexure tests described above were performed not only in dry conditions, but also on coupons kept immersed in deionised water at 40°C for up to 28 days. The edges of these specimens were not sealed, therefore the whole of their external surface was exposed to water. They were weighed before, during and after conditioning in order to monitor the weight change during immersion.

Delamination resistance was measured for a selection of materials; double cantilever beam (DCB) specimens were tested according to the BS ISO 15024:2001. Only laminates obtained with the vinyl ester compatibilised fabric were used and sets of four specimens impregnated with either UP, VE or Ec resin were tested. Mild steel load blocks were bonded to the opening end of each specimen and used to attach the coupon to the testing rig. One side of each specimen was marked at 1mm intervals to visually monitor the crack propagation throughout the test. A polyester film was used as a crack starter. Its thickness was outside the requirements of the relevant standard (13μm max); however, all samples were mechanically pre-cracked in order to obtain a natural crack tip geometry before evaluating the delamination resistance. The pre-crack was created under mode I loading by clamping the main body of the specimen to avoid unwanted propagation. Both pre-cracking and testing were conducted at a rate of 1mm/min. The fracture surface of failed specimens was examined with a Scanning Electron Microscope

(SEM). The international protocol BS ISO 15024:2001 gives full detail of the test procedure and data reduction method. The initial G_{IC} value was determined using the 5%/MAX point and calculated using the corrected beam theory. The nominal dimensions of the DCB coupons were 3.5mm x 150mm x 20mm.

4. Results

Table 2 summarises the mechanical properties of the unreinforced resins. Two epoxy grades were not tested in tension; the values published by the manufacturer are listed instead. The epoxy resins are all tougher than the other systems and, out of the non-epoxy polymers, UA provided the highest toughness. The toughness of Ec could not be measured as, in the testing conditions, this material exhibits a ductile fracture, failing to meet the LEFM assumptions. The representative raw curves of the toughness tests shown in figure 1 illustrate the different behaviour of Ec when compared to the other resins.

Table 2: Cast resins mechanical properties

Resin type	UP	VE	UA	Ea	Eb	Ec
T_g [°C by DSC]	93	108	114	68 - 92 [a]	78 - 83 [a]	50
Tensile strength [MPa]	66	80	65	69-75 [a]	70-74 [a]	52
Tensile modulus [GPa]	3.6	3.4	2.7	3.2-3.5 [a]	3.2-3.3 [a]	2.9
Elongation at break [%]	2.5	4.5	5.1	3.1-4.1 [a]	3.8-4.2 [a]	4.6
G_{Ic} [J/m^2]	380	369	575	701	1922	Ductile fracture
K_{Ic} [MPa m$^{0.5}$]	1.2	1.1	1.3	1.6	2.7	4.3
E_{fract} [GPa]	3.6	3.5	3.0	3.7	3.9	3.5

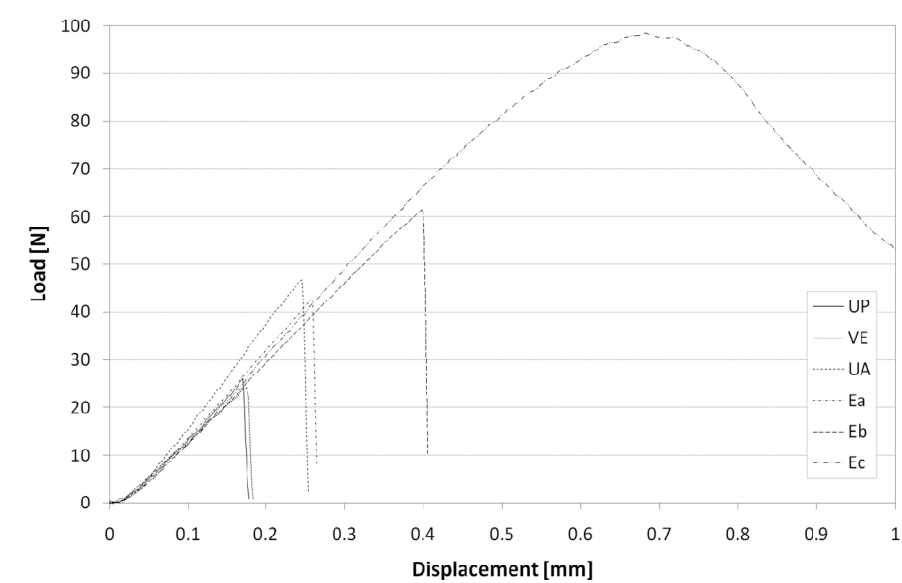[a] Values published by manufacturer

Figure 1: Representative load/displacement curves obtained by testing notched specimens of cast resin in three-point bending configuration for toughness measurement

The ILSS and flexure test results of dry and wet samples are listed in table 3. It should be noted that in the context of this study the word 'dry' refers simply to non immersed samples and not to materials artificially desiccated. Some batches exhibit a relatively high data scatter which was expected, considering the fibre volume fraction variation observed in the manufactured panels.

Table 3: Results of ILSS and flexure test before and after 28 day immersion

Resin	Fibre	ILSS [MPa]		Flexural strength [MPa]	
		Before immersion	After immersion	Before immersion	After immersion
UP	GPF	22 ± 4	22 ± 3	734 ± 59	545 ± 48
	VEF	21 ± 1	21 ± 4	702 ± 47	586 ± 49
VE	GPF	26 ± 2	25 ± 2	657 ± 35	581 ± 33
	VEF	33 ± 2	27 ± 2	704 ± 25	640 ± 27
UA	GPF	34 ± 4	28 ± 6	626 ± 42	612 ± 102
	VEF	32 ± 4	29 ± 4	668 ± 46	612 ± 78
Ea	GPF	47 ± 2	35 ± 3	628 ± 138	499 ± 100
	VEF	47 ± 5	33 ± 6	688 ± 39	657 ± 101
Eb	GPF	37 ± 7	32 ± 2	553 ± 71	576 ± 72
	VEF	44 ± 6	33 ± 3	691 ± 104	685 ± 111
Ec	GPF	46 ± 1	26 ± 1	687 ± 51	419 ± 73
	VEF	42 ± 1	24 ± 1	714 ± 32	432 ± 36

All ILSS specimens failed due to single or multiple interlaminar shear, which are the only acceptable failure modes for evaluation of apparent interlaminar shear strength according to the test protocol. The dry epoxy composites show evidence of superior interlaminar shear strength to that of the other

materials. The use of vinyl ester compatibilised fabric with a vinyl ester matrix results in an increase in ILSS of approximately 27% when compared to an equivalent laminate made with general purpose fabric. A smaller improvement (19%) due to the use of the VEF fabric was also observed in the composite impregnated with Eb, although in this case the data scatter is too high to draw any conclusion.

Testing of conditioned samples revealed a higher sensitivity to water ingress of the epoxy compared to the other systems. The interlaminar shear strength of the former was reduced considerably upon immersion, while the variation in performance of non-epoxy systems remained within the experimental error range. The resin which suffered the most from water damage was the epoxy Ec with a 43% reduction in ILSS, regardless of the type of fabric used.

With the exception of the VE/VEF combination, the use of the vinyl ester fabric grade seems to have little or no effect, if compared to the performance of the general purpose fabric, on the behaviour of both dry and wet coupons. It is interesting to note that, while a dry VE/VEF composite exhibits a higher ILSS than a VE/GPF combination, both systems provide very similar ILSS after immersion.

The adoption of different resin/fabric combinations does not trigger any substantial change in the flexural strength of dry composites. The microscopic analysis of failed coupons and of coupons under bending load suggests that the failure mechanism in flexure configuration is connected more to fibre buckling and tensile failure than to resin/fibre adhesion (figure 2). Such a fibre-dominated mechanism results in an almost equivalent performance of all selected systems.
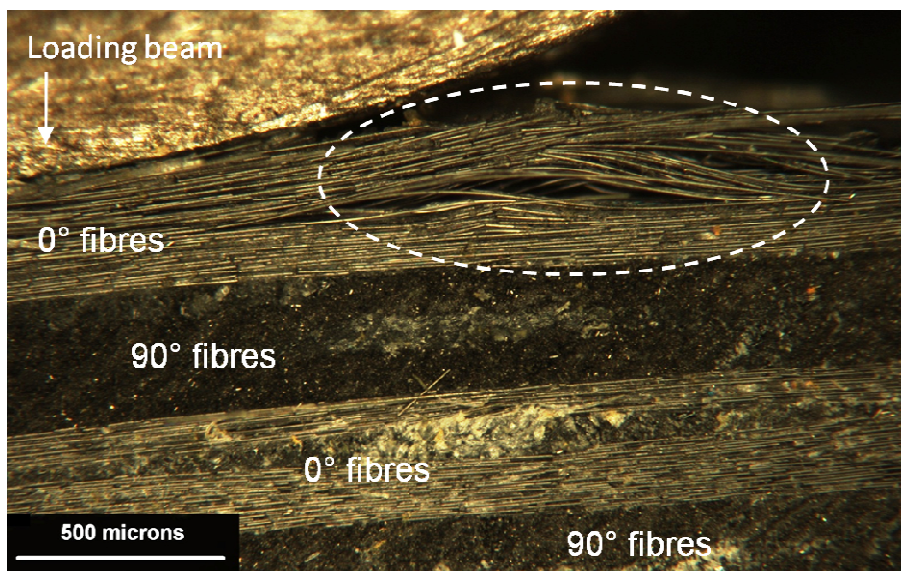

Figure 2: Detail of the loaded portion of flexural specimens at the onset of failure with buckling fibres in the dashed circle

The reduction in flexural strength upon wet conditioning varied significantly across the spectrum of materials tested. The strength of the polyester and vinyl ester composites was reduced by 17 to 26%

and by 9 to 11%, respectively. In both cases the smaller drop was recorded when the vinyl ester compatibilised fabric was used. The flexural behaviour of the urethane acrylate appeared mostly unaffected by the immersion in water: only minimal variations in strength were recorded and they all fell within experimental error. The performance of the epoxies was particularly inconsistent: the flexural strength of epoxy Eb remained essentially unchanged after immersion, as well as that of epoxy Ea when used with VES fabric. However, the strength of epoxy Ea reinforced with GPS carbon was reduced by 21% upon conditioning. The resin which suffered the highest property reduction was epoxy Ec, whose flexural strength was reduced by 39% whichever fibre was used.

The curves in figure 3 plot the variation of the specimens weight during wet conditioning as a function of the square root of time (normalised against the coupons thickness). All systems gained weight while under immersion because of a gradual physical absorption of water molecules within the polymer network. Given the limited amount of data collected, it is difficult to conclude whether the absorption curves exhibit a Fickian behaviour [10]. However, two distinct trends can be distinguished between the four families of resins: the non-epoxy systems gained most of the weight within the first three days with minimal further increments afterwards (apart from the polyester which lost some weight between the 3rd and 28th day); whereas the epoxy based composites kept absorbing water for the whole duration of the conditioning cycle. After 28 days, the epoxy laminates had absorbed more water than all the other systems, with the Ec coupons having increased their weight by over 2%. A particularly low level of water uptake was recorded for the urethane acrylate samples. The use of different grades of fabric did not make any relevant difference in the amount or rate of water uptake.
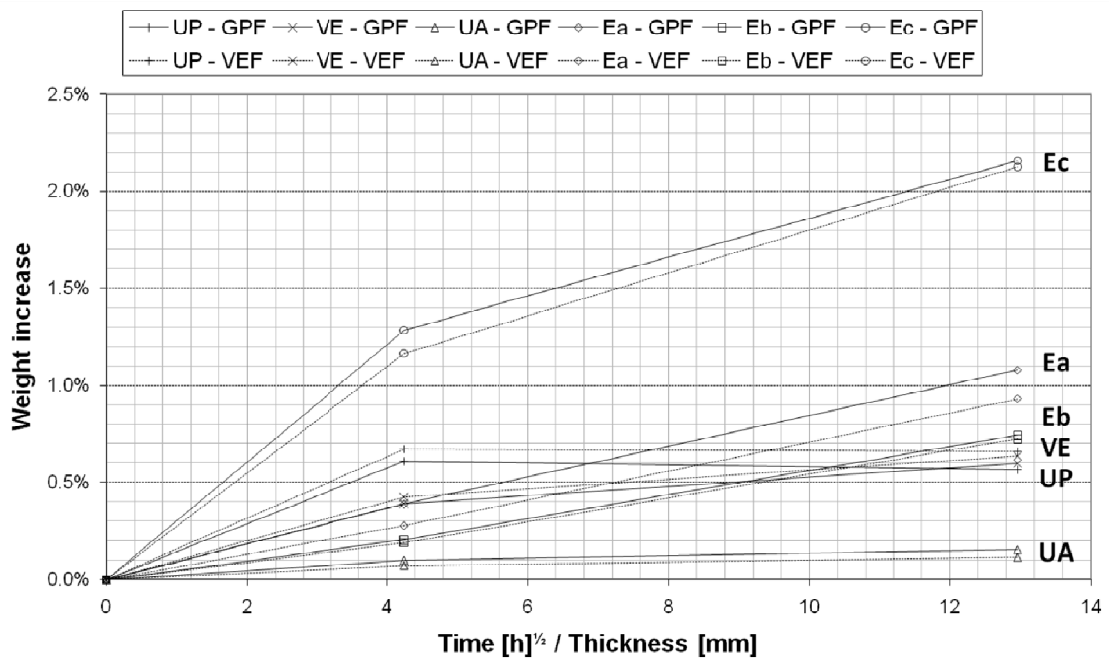

Figure 3: Weight increase of different systems after 3 and 28 day immersion in deionised water at 40°C

Values of the interlaminar fracture toughness for the three composites tested are given in table 4, in terms of energy release rate at crack initiation (G_{IC}) and crack propagation (G_{IP}); while the representative R-curves are shown in figure 4. There is a noticeable difference between the laminates responses to mode I opening at the initiation stage, although a much smaller difference was observed at propagation. Analysis of the SEM images of fracture surfaces (not reported here) did not provide any clear evidence of differences in the level of matrix/fibre interaction among the material combinations studied.

Table 4: Interlaminar fracture toughness

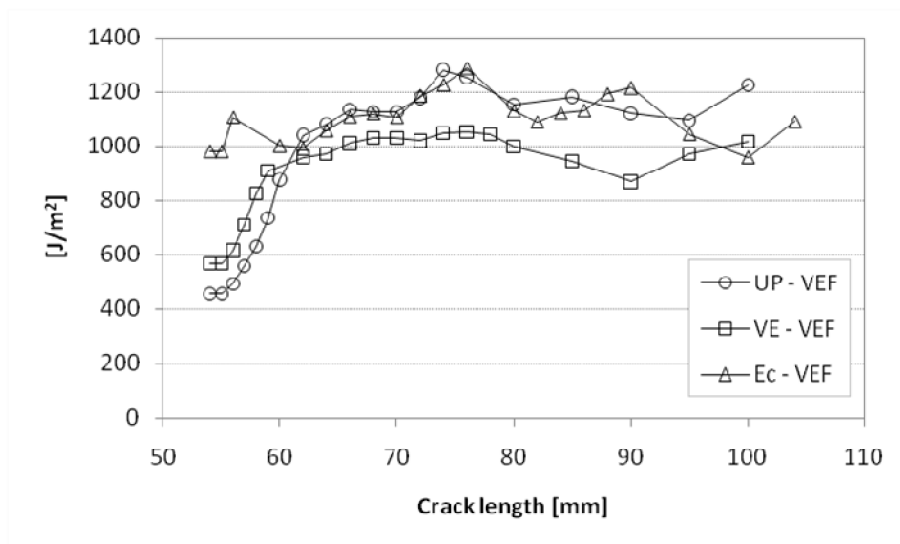| Composite	G_{IC} $[J/m^2]$	G_{IP} $[J/m^2]$
UP - VEF	384	1062
VE - VEF	575	987
Ec - VEF	855	1125

Figure 4: Representative R-curves of DCB coupons tested under mode I configuration

5. Discussion

The failure mechanism of dry laminates in flexure is fibre-dominated, consequently their response to the flexural test does not allow differentiating the matrices used. Reduction in flexural strength of most of the laminates after wet conditioning suggests that the water ingress may have triggered different failure mechanisms by plasticizing the matrix [3]. The vinyl ester performed slightly better that the polyester, confirming a similar trend reported in previous studies [11]. The urethane acrylate fully retained its strength as well as epoxy Ea, while Ec suffered the highest loss in strength highlighting that the response of epoxies to a given environment can change dramatically depending on their specific chemistry.

The ILSS test provides a simple way of ranking the systems on the basis of their interlaminar strength. The performance of the dry epoxy laminates was better than the alternative systems although the ILSS

of the urethane acrylate composite was comparable to one of the epoxies (Eb). After exposure to a wet environment, the epoxies suffered larger drops in strength than the alternative systems indicating a higher sensitivity of these matrices to water absorption. This is in agreement with other similar studies found in the literature [12]. When testing the conditioned composites, the UA and VE systems provided higher or equivalent strength than at least one of the epoxy grades (figure 5). The extent of the drop in strength is proportional to the amount of water each system absorbed during immersion. An observation of higher water uptake of epoxies compared to polyester and vinyl ester had already been reported [9].
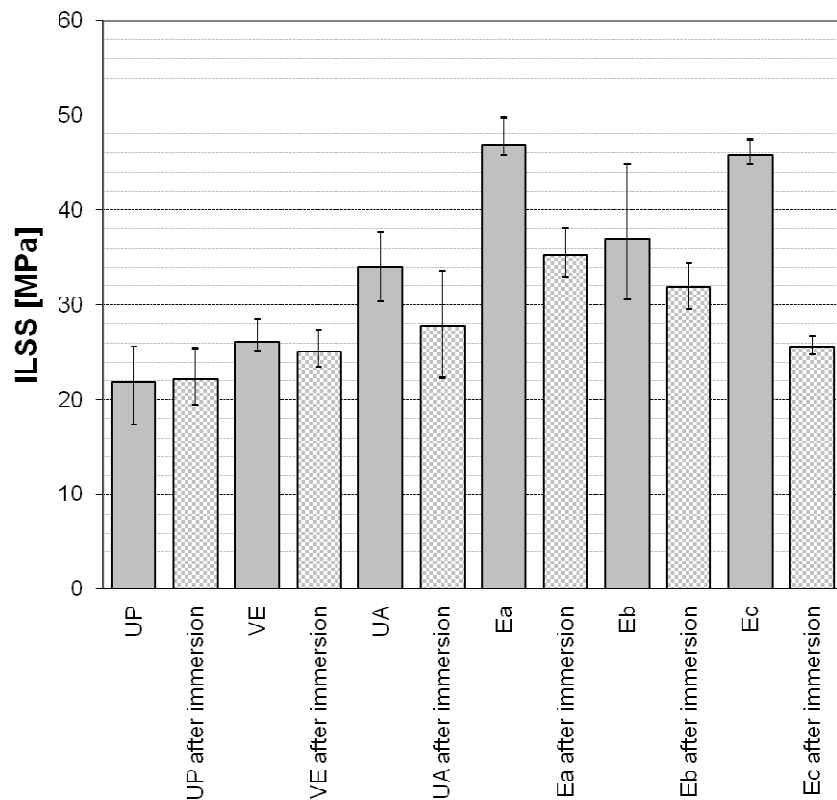

Figure 5: Comparative ILSS of systems with GPF reinforcement before and after 28 days immersion in deionised water at 40°C (solid: dry conditions, chequered: wet conditions)

The fact that using two types of coupling agent on the surface of the fibre did not promote different behaviour in the laminates after conditioning suggests that the water has a larger effect on the bulk of the matrix than on the carbon/resin interface. Or, if there is an effect on the interface, than this equally affects both types of fibres, regardless of the sizing chemistry. It is believed that the variation in the interlaminar strength is mainly attributable to a plasticizing effect of the water within the polymeric network [13], although the fact that the polyester specimens started losing weight during the conditioning cycle suggests that at least in one case other chemical mechanisms must have taken place. The unsaturated groups within the UP resins are in fact susceptible of degradation by hydrolysis, and the

low molecular weight products and by-products of this reaction tend to leach out into the water bath over time. This was expected to prompt a more pronounced drop in properties in the conditioned polyester composite which, however, was not detected. A similar behaviour of the carbon/UP and carbon/VE composites had been observed previously elsewhere [2].

Although the immersion test detailed in this study represents a useful accelerated process able to produce, after only 28 days, samples in equivalent conditions to those aged for much longer in natural environments, it should be pointed out that it cannot be considered a proper durability test. The relatively high temperature, the high specific surface of the testing coupons and the nature of the immersion fluid certainly help estimating the relative resistance of the materials to water ingress in hot climate but do not mimic closely any natural setting [14]. Consequently, it is impossible to predict the long term behaviour of these systems based solely on the results detailed here. For instance, it is unclear whether the epoxy systems have reached or not an equilibrium within 28 days, or whether it should be expected that over longer cycles other resins will start suffering chemical degradation as much as the polyester. Thorough investigations on durability of composites are, however, available in the literature; examples are given in [8], [15] and [16]. The outcomes of this study seem to support the idea that, at least in the short term, epoxy systems tend to suffer more from exposure to hot/wet environment than vinyl ester and urethane acrylate resins. The wide range of epoxies available on the market suggests that there may exist systems able to reduce susceptibility to water damage, nevertheless these are likely to be costly solutions unsuitable for the type of market being targeted in this study. In fact, the composite whose properties were reduced the least among the epoxy based laminates examined within this work was the one impregnated with epoxy Eb which is the most expensive epoxy grade tested, costing approximately 10 times more than the vinyl ester resin.

Interlaminar fracture toughness analysis of the polyester, vinyl ester and epoxy Ec systems confirmed a different behaviour of the three systems under mode I configuration testing, in good agreement with previous studies [12]. As expected, the higher fracture toughness of the neat epoxy translated in a higher resistance to crack propagation in its composite as well as the low G_{IC} of the polyester promoted a relatively poor performance of the UP laminate. A similar behaviour to the polyester was expected from the VE composite (being the G_{IC} of the two neat resins very similar), nevertheless, the VE/VES system provided a higher fracture toughness. This is believed to depend on the silane sizing on the VES fabric specifically designed to promote stronger interactions with vinyl ester matrices. This result is in agreement with the higher ILSS values measured for this particular fibre/matrix combination in comparison to those recorded when general purpose fabric is used. Such a result identifies a clear advantage of using a dedicated grade of carbon when vinyl ester is chosen, although it is unclear, at this stage, whether such an advantage will be retained after wet conditioning.

The R-curves in figure 4 show that, when the crack grows longer, the strain energy release rate of some laminates apparently increases. However, this is a consequence of the fibre bridging developed mainly in UP and VE samples (rather than an actual increase in toughness) and shown on delaminated DCB coupons in figure 6.
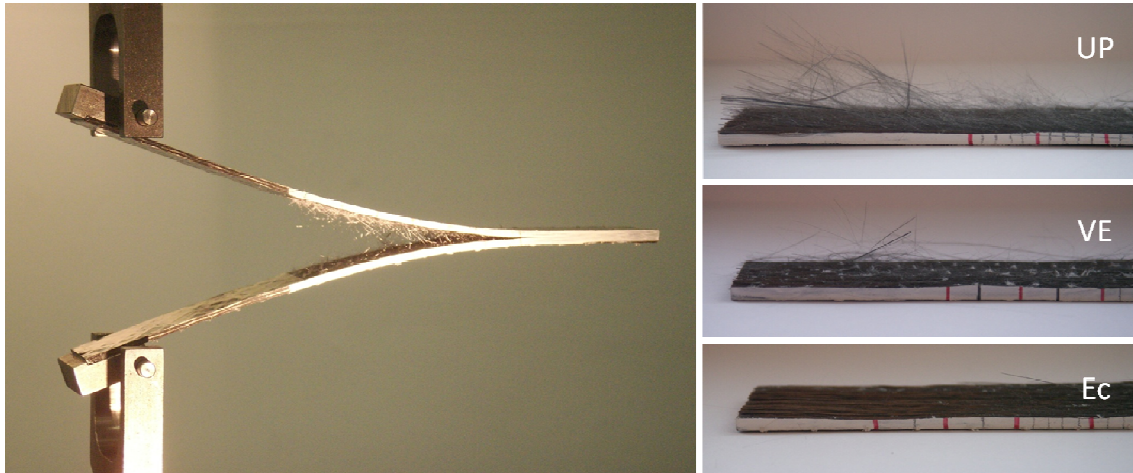

Figure 6: Polyester DCB specimen during test (left) and failed coupons (right) showing different levels of fibre bridging, fabrics being the same

6. Conclusions

The results detailed in this study show that the carbon/non-epoxy combination may be a sensible choice for the material designer depending on the working environment of the composite. In the dry state the epoxy resins and composites have outperformed the alternative matrices in terms of interlaminar adhesion and fracture toughness, although no substantial difference was observed in the flexural test. Testing after hot/wet conditioning, however, revealed a much higher sensitivity of the epoxy-based composites to water ingress, although a high degree of variability has been observed between different epoxy grades. The vinyl ester and urethane acrylate laminates have provided a mechanical performance at least comparable if not superior to some epoxies. This suggests that these resins should be considered when specifying materials in structures likely to be used in a hot/wet environment and that, in case epoxies are selected instead, an efficient protection to shield the composite from accidental water ingress should be integrated in the laminate design. Alternatively, epoxy grades less susceptible to water damage should be chosen, although this is likely to be reflected in a higher cost.

Polyester does not allow full exploitation of the potential of a high performing reinforcement like carbon, however, whenever possible, it might be replaced by vinyl ester or urethane acrylate. These resins lend themselves to be introduced easily in industrial environments set up for polyester users and offer advantages in terms of mechanical performance and water resistance for a limited price premium. In case vinyl ester is used, the selection of a fibrous reinforcement specifically designed to provide better adhesion to vinyl ester resins can offer added advantages in terms of better interlaminar shear

and flexural strengths and lower reduction in flexural properties upon wet conditioning. On the other hand, vinyl ester and urethane acrylate can potentially provide a real opportunity as an economic alternative to epoxies in several applications not only in the marine, water racing and wind energy markets, but also in off shore construction such as pylons or drilling platforms, or in those civilian constructions typically exposed to the elements.

Acknowledgements

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