

Composite Materials in Tidal Energy Blades

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Abstract Composite materials are the natural choice for the construction of tidal energy blades; their high strength, good environmental resistance and the ease with which they may be used to form complex shapes means that they are well suited to the application. The design of MW-scale tidal energy blades has evolved over a number of years, keeping step with the requirements of turbine developers as their emphasis shifts from prototyping to production. In parallel, it has been necessary to develop a rigorous approach to materials testing and qualification. The specifics of the blade structure and the operational environment mean that it has been necessary to solve a number of complications that arise during such a qualification programme. These issues are discussed and efforts to mitigate their consequences are explained. Although this chapter is written particularly with tidal energy blades in mind, much of the content will be applicable to a wide range of other applications where composite materials are used in the marine environment.

1 Introduction & Background

Tidal energy blades (Fig. 1) represent a relatively new and challenging application for composite materials. They present a combination of commercial, environmental and loading conditions that demand a detailed engineering approach. In particular, it is necessary for a cost-effective structure to sustain very heavy fatigue loading in a submerged marine environment.

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Fig. 1 Various tidal energy blades in situ, manufactured by AEL/Airborne

Over the past decade, tidal turbines have been built to a wide variety of designs. Whilst the wind industry has converged on a 3-bladed horizontal axis turbine as the preferred solution, the tidal industry is still relatively young and there is not yet a consensus regarding the optimal configuration for a tidal turbine. In particular, developers are unsure whether it is more cost-effective to opt for a complex device that generates as much energy as possible or a simpler device that is relatively cheap to manufacture and maintain but is unable to extract as much energy from a given flow. It follows that the argument has not been won or lost with regard to a number of key design variables, and progress for many developers has been hampered by the inconsistency of government and industrial support, often meaning that operational experience is still fairly limited. Inspection of existing designs and prototypes would lead to the conclusion that designers have a number of different ideas with regard to the following aspects, amongst others:-

- **Scale:-**
Generating capacity varies from several kW to more than 1 MW. Some developers look for economies of scale in terms of production quantities, whilst others seek it in terms of machine size.
- **Foundation:-**
Machines exist whereby turbines are attached to fixed (gravity base or piled), floating and even ‘flying’ (underwater) support structure.
- **Method of deployment/retrieval:-**
Costs associated with deployment and retrieval are very significant, so methods vary greatly as designers strive to minimise the overall costs of these activities.
- **Blade mounting:-**
Blades may be mounted on a central hub or an outer ring. Furthermore, some designers favour variable pitch blades in a drive to maximise energy capture and minimise loads, whilst others prefer a simpler machine, and therefore opt for a fixed-pitch scheme. The phrase “*if it hasn’t got it, it can’t go wrong*” is particularly apt here. The cost of rectifying problems/breakdowns in service is very high, so reliability is extremely important.
- **Number of blades per rotor:—**This may vary from 2 to 10.

In many cases there are strong interdependencies between the varying design options, meaning that identification of any particular ‘best’ answer is far from straightforward (in any case the optimal solution may be site-dependent). It is likely that the field will narrow in time, as weaker solutions and developers fall by the wayside.

Whilst there are clearly many permutations in terms of the configuration of the overall turbine, it is fortunate for the blade designer that many of these options do not especially affect the blade concept design. However, the selection of a fixed or variable pitch system would have implications for the favoured blade concept. A variable pitch blade will tend to terminate in a circular root to efficiently mate with the pitch bearing; this requirement in itself has design implications that cascade along the rest of the blade. However, a fixed-pitch blade typically has no need for a circular root, so it gives the blade designer more options in terms of configuration. Unsurprisingly, the decision to mount the blades at the hub or to an outer ring is also very significant in terms of blade concept selection.

A variety of materials and configurations has also been adopted for the construction of tidal blades, depending on the specifics of the application and the experience and preferences of the designer. It is generally the case that blades are built with epoxy matrix composite materials, incorporating both carbon and glass reinforcements as appropriate. Whilst glass fibres are significantly cheaper and, therefore, represent the default choice, there is also often a case of the targeted use of carbon fibres. In particular, the superior strength, stiffness and resistance to environmental degradation of carbon fibres mean that they will find application in elements of the structure such as spar caps. In this capacity, they enable a more slender, higher performance blade than would otherwise be the case. In the quest to minimise the unit cost of power, a small increase in performance is worth a lot. In general, blades are assembled using a structural epoxy adhesive.

Both prepreg and resin infusion processes may be appropriate, depending on the detail of the requirement. Whilst the infusion process tends, in general, to result in a lower cost of material per kg and a simplified supply chain, the selection of prepreg materials would be expected to result in improved moulding consistency and a considerable reduction of development risk, particularly in cases where it is necessary to use carbon fibres. It is also the case that one or other of the processes may lend itself more naturally to the moulding of a given structural form. For example, if it is necessary to turn a mould upside-down during the production process, then a dry fabric preform intended for resin infusion will probably fall out of the tool, where a stack of sticky prepreg plies would be more likely to stay where they are needed—the reason is not always complicated!

In terms of configuration, AELs experience to date has predominantly been with MW-scale, variable pitch, hub-mounted blades. The favoured general configuration in this case (Figs. 2 and 3) is a central box-spar mounted in airfoil section skins/fairings. A rear web member provides additional reinforcement to the trailing edge. This arrangement confers a number of key advantages:-

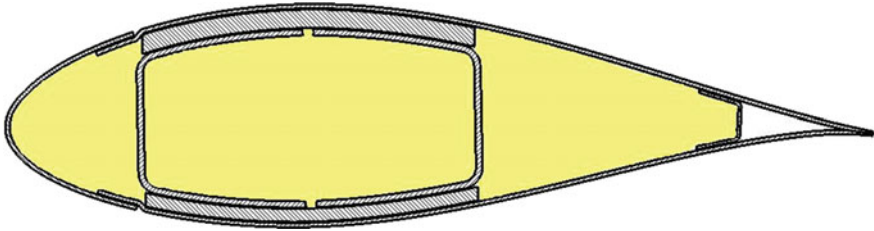


Fig. 2 MW scale, variable pitch blade section—earlier example for proof of concept machines

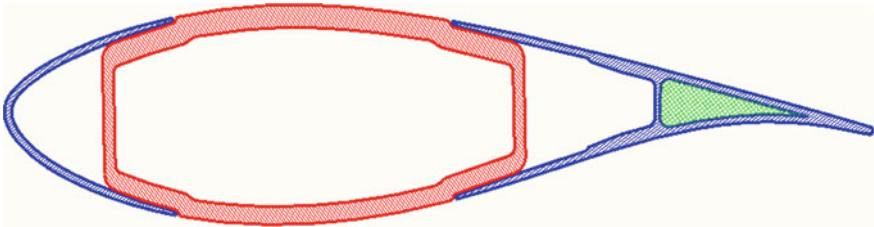


Fig. 3 MW scale, variable pitch blade section—evolved for production

- Neither the leading edge (vulnerable to impact) nor the trailing edge (relatively weak) is required to sustain serious shear loads.
- The primary structure (box-spar) is not exposed to unquantified direct leading edge impact.
- The box-spar can readily transition into a circular section at its root, where it will mate with the pitch bearing.
- In order to achieve a good hydrodynamic performance, it is important that the blade chord (distance from leading edge to trailing edge) is permitted to increase very rapidly as we move outboard of the blade root. It is straightforward to achieve this with the box-spar scheme, without requiring sudden changes of the section in the primary structure.

Whilst AEL's general scheme has tended to remain constant, there has been a considerable evolution over the years in terms of the detail, reflecting the changing requirements of developers.

In the early days, the priority would be to provide 2 or 3 blades relatively quickly for a 'proof of concept' prototype machine, whilst keeping tooling and development cost, and development risk to a minimum. Unit cost, part count and lead time to produce an individual blade were therefore of lesser importance than the overall project cost. A scheme appropriate to this earlier developmental stage is shown in Fig. 2. Whilst the relatively large number of mouldings and assembly stages means

that such a scheme would not be well suited to cost-effective volume production, each moulding is in itself relatively straightforward to tool and manufacture. Therefore tooling costs are relatively low, and the chances of project costs ballooning due to development trouble are minimised.

The requirements of a blade designed for volume production are significantly different. By the time developers contemplate volume production, they should be more robustly funded and understand that it is necessary to absorb higher tooling and development costs, and some development risk in the quest for a low blade unit cost. Therefore it is required of the blade designer to be more ambitious in terms of the mouldings produced. Figure 3 shows substantially the same configuration as Fig. 2, but consists of 3 mouldings as opposed to 8. Although this development will assist greatly in the achievement of reduced blade unit cost and lead time, the mouldings are not as simple to engineer. In particular, the development of a successful single piece box-spar concept absorbed many hours of engineering time and the creation of several sub-scale prototypes.

Qualification of Materials and Structure

The general approach to the design and qualification of tidal energy blades calls for the design process to be synchronised with a ‘pyramid’ type test programme (Fig. 4) to determine or confirm relevant material and component properties and performance.

As such, the results of a large number of small, relatively cheap coupon tests are built upon by increasingly complex element, detail and full-scale structural tests. As the complexity of the test increases, so the number of tests diminishes.

In general, the lower levels of the pyramid (1 and 2) will tend to inform the final design, and the higher levels (3 and 4) serve primarily as confirmation that the final design and underlying data and assumptions are adequate.

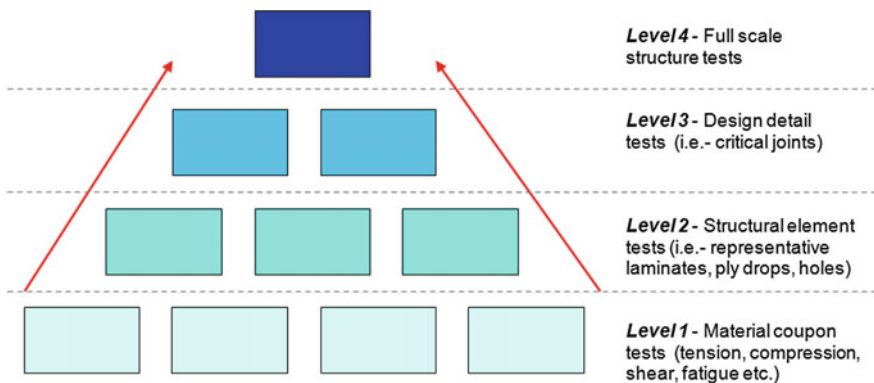


Fig. 4 Typical test pyramid

Perhaps unsurprisingly, the execution of a test programme is not without complication. Bearing in mind the size of tidal blades (8–9 m in length) and the heavy loading they endure (several MNm in terms of root bending moment), it may not be possible to locate a facility suitable for and willing to conduct a full-scale ‘level 4’ test. Wind blade test facilities are generally unsuitable, as they tend to employ winches for static loading, and resonant frequency excitation to induce fatigue loading.

In comparison to wind blades, tidal blades are relatively short and stiff, which means that it would be difficult to adequately control the applied load with winches. Furthermore, resonant frequency excitation is out of the question as a means of inducing fatigue, as the fundamental flap frequency of a tidal blade is much higher than the loading frequency at which mechanically induced heating would be expected in the structure. When it first became necessary to conduct a MW-scale blade test, AEL, therefore, found it necessary to build its own static test frame (Fig. 5). Load is distributed as appropriate along the length of the blade using a series of hydraulic rams and spreader beams, and the frame may be disassembled for storage. To date, static load tests have been successfully conducted at AEL on 2 separate blade designs.

But it is not just at the ‘full-scale test’ end of the test programme that complications are found. With regard to the effects of seawater saturation, it is generally far more practical to consider these at an early stage in the qualification process—typically as a part of the level 1 test programme. However, a seawater-ageing phase is usually very difficult to fit in the development programme for a new product (Fig. 6): One set of mechanical test coupons would normally be tested in the air with no ageing. Another set would be aged for several months at 45 °C in natural seawater, before mechanical testing in air. The design values would then be based on the least favourable data, adjusted as appropriate depending on the results of the level 2 programme. Coupons are designed to be as thin as possible (to minimise



Fig. 5 Tidal energy blade static test at AEL

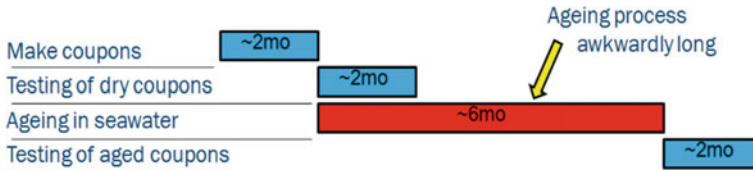


Fig. 6 Typical coupon testing timescales

time to saturate) but there are other considerations that limit achievable ‘thinness’ such as the avoidance of buckling in the case of compression tests, or the need to produce balanced and symmetrical laminates with what can be relatively thick plies.

The MARINET ‘SEADEG’ study was instigated as a collaborative effort between IFREMER, the University of Bristol and AEL to determine whether there exists any scope for further accelerating the seawater ageing of composite coupons. It follows that success in this aim could dramatically reduce the timescales required for the execution of the level 1 programme.

Another complication is the choice of a test environment for the level 1 tension fatigue coupons aged in seawater. The effect of the marine environment on the durability of composite materials has been studied in some detail since the work of Smith et al. [1]. Recent references [2–4] give an overview of current knowledge. Seawater ageing is known to result in potentially substantial reductions in the tensile strength [5] and tension fatigue performance of glass fibre composites tested in both air [6, 7] and seawater [2, 8]. Kosuri and Weitsman [9] showed that the tension fatigue performance of seawater-aged carbon composite laminates (AS4/3501-6 [0/90₃]_s) may also depend on the test environment. They found that some laminates, when aged in seawater and then fatigued also in seawater demonstrated reduced performance when compared to those aged in seawater but then fatigued in the air. The proposed mechanism for this accelerated degradation (Fig. 7) is additional to the ageing affect that is normally quantified during materials qualification programmes as follows:

- #1 -Transverse cracking of off-axis plies early in the fatigue life of a multiaxial laminate.
- #2 -Water ingresses into transverse cracks as they open up under tensile loading
- #3 -Pressurisation of the water during unloading, causing delamination between plies to grow more rapidly than would otherwise be the case.

However, the body of published experimental data relating specifically to this effect appears to be very limited. Therefore the study also aimed to identify whether such an effect would be apparent in a material/laminate typical of tidal energy blades.

The following sections describe the detail and outcome of a work programme undertaken to address some of the issues described above.

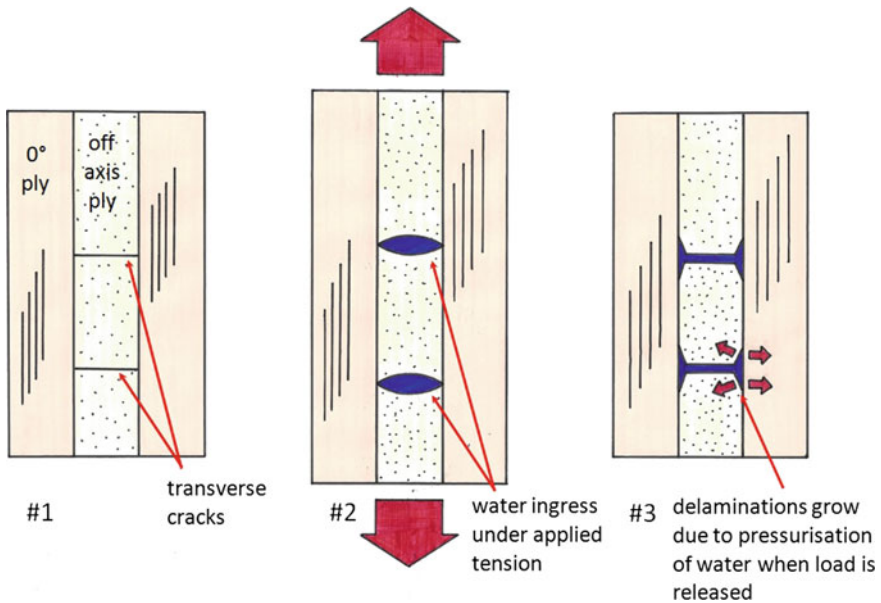


Fig. 7 Proposed mechanism by which fatigue testing in seawater may mechanically accelerate the growth of delaminations

2 Study Objectives

The objectives set for the body of work described in this chapter were, therefore, as follows:

- To determine whether the choice of conditioning medium (natural seawater or deionised water) would affect the moisture absorption characteristics, fibre direction tensile strength (σ_{11T}) and interlaminar shear strength (τ_{13}) of infused and prepreg unidirectional glass/epoxy laminates. These two parameters were selected as being good indicators, respectively, of fibre and matrix/interface performance and degradation.
- To quantify the effect of pressure and temperature on the rate at which the infused and prepreg glass/epoxy laminates absorb moisture.
- To determine whether the choice of the test environment (natural seawater or air) would have a noticeable effect on the tension fatigue strength of [0/+ 45/0/- 45]s infused glass/epoxy laminates already aged in natural seawater until close to saturation.

3 Procedures

Materials for the programme were chosen to be typical of those used in the construction of tidal blades.

Resins: As discussed in Sect. 1, the manufacture of tidal blades may require the use of prepreg and/or infusion resins. Therefore the majority of this study was conducted using representative examples of both.

Fibres/fabric: As discussed in Sect. 1, glass fibre would normally be selected for tidal blade construction in preference to carbon fibre, unless the latter was specifically required for its superior strength, stiffness or environmental resistance. Therefore glass fibres were deemed most appropriate, particularly as their greater sensitivity to environmental effects would make for clearer results. More specifically, the selected fabric comprised ‘Advantex’ fibres in a 567 g/m² unidirectional non-crimp format.

Test coupons were manufactured at AEL with an 80 °C ultimate cure temperature, then shipped to IFREMER for conditioning and mechanical testing (Table 1).

In order to establish control data, Quasi-static mechanical tests (σ_{11T} & τ_{13}) and tension fatigue tests (σ_{XXT}) were conducted on dry (un-aged) coupons according to Table 2, (M1, M4a).

Table 1 Test matrix—coupon conditioning

ID	Subject	Medium	Materials		Temperature (°C)	Pressure (bar)	No. coupons/test
			Infused	Prepreg			
Cl _a	Effect of conditioning temperature on laminate weight gain in natural seawater	Natural seawater	Yes	Yes	4	1	3
Cl _b			Yes	Yes	25		
Cl _c			Yes	Yes	40		
Cl _d			Yes	Yes	60		
Cl _e			Yes	Yes	80		
C2 _a	Effect of conditioning medium on laminate weight gain	Deionised water	Yes	Yes	40	1	3
C3 _a	Effect of conditioning pressure on laminate weight gain	Tap water	Yes	Yes	40	1	3
C3 _b			Yes	Yes		500	5
C4	Weight gain check for thicker [0/+ 45/0/-45]s fatigue coupons	Natural seawater	Yes		40	1	1

Table 2 Test matrix—mechanical testing

ID	Subject	Test type	Materials		Conditioning environment	Test environment	No. coupons/test
			Infused	Prepreg			
M1a	Mechanical properties, dry (unconditioned) control	σ_{11T}	Yes	Yes		Air	5
M1b		τ_{13}					5
M2a	Mechanical properties, after conditioning in seawater	σ_{11T}	Yes	Yes	Natural seawater, 8 months @40 °C	Air	5
M2b		τ_{13}					5
M3a	Mechanical properties, after conditioning in deionised water	σ_{11T}	Yes	Yes	Deionised water 8 months @40 °C	Air	5
M3b		τ_{13}					5
M4a	Laminate tension fatigue, effect of test environment on conditioned [0/+ 45/0/-45]s laminates	Tension fatigue R = 0.1 1 Hz	Yes			Air	6
M4b			Yes		Natural seawater, 8 months @ 40 °C	Air	6
M4C			Yes		Natural seawater, 8 months @ 40 °C	Natural seawater	10

Coupon conditioning and regular weighing were carried out in accordance with the procedures explained in Sect. 3.2. Weight gain coupons were aged according to the conditioning matrix in Table 1 to establish the effects of conditioning temperature (C1), conditioning medium (C2) and conditioning pressure (C3) on their moisture absorption characteristics.

Quasi-static mechanical test coupons (σ_{11T} and τ_{13}) were conditioned in natural seawater and deionised water at 40 °C for a period of almost 8 months. Tension fatigue coupons (σ_{XXT}) were conditioned in natural seawater at 40 °C for 9 months. Mechanical tests were then conducted on these conditioned coupons according to the test matrix in Table 2.

3.1 Design and Manufacture of Coupons

Test panels were manufactured using standard AEL methods, developed to be as representative as possible of full-scale manufacturing processes. Prepreg panels were manufactured by oven-curing the prepreg under the vacuum between a flat tool and a caul plate. Infused panels were manufactured by vacuum-infusion of the fabric stack between a flat tool and a caul plate. The panels were allowed to cure at room temperature for approximately 24 h before transfer to an oven for final cure.

Subsequently, end tab strips were bonded to the tension (σ_{11T}) and fatigue (σ_{XXT}) coupons using epoxy adhesive film and a 70 °C cure cycle. A water-cooled diamond wheel saw was used to cut coupons from the panel.

Materials specifications for both the infused and prepreg coupons are shown in Table 3. Coupon laminate details and dimensions are presented in Table 4.

Table 3 Material specifications

Matrix:-	Infused	Prepreg
Reinforcement	567gsm Advantex SE2020 Unidirectional non-crimp (587gsm including carrier fibres and stitching)	
Initial cure	24 h @ room temp	N/A
Final cure	6 h @ 80 °C	6 h @ 80 °C
Tg onset (dry)	~ 70 °C (DSC) ^a	89 °C (DMA) ^b
Tg peak tan delta	~ 89 °C (DMA) ^a	101 °C (DMA) ^b
Typical cured ply thickness	0.442 mm	0.488 mm
Typical Fibre volume fraction (structural)	49.0%	45.6%
Typical Fibre volume fraction (total)	50.7%	47.2%

^aData supplied by manufacturer for cure cycle with 24 h @ room temp, 16 h @ 50 °C, 2 h @ 80 °C

^bData supplied by manufacturer for identical cure cycle

Table 4 Coupon details

Coupon type:-	Tension σ_{11T} (M1a-M3a)	Interlaminar shear— τ_{13} (M1b-M3b)	Fatigue σ_{xxT} (M4)	Weight gain (standard) (C1-C3)	Weight gain (thick) (C4)
Layup	0 ₄	0 ₅	[0/+ 45/0/-45] _s	0 ₄	[0/+ 45/0/-45] _s
Nominal width (mm)	25	10	25	50	50
Overall length (mm)	240	16	240	50	50
Gauge length (mm)	120	12	120	N/A	N/A

3.2 Conditioning and Weighing of Coupons

Coupons (C1, C2, C4) were aged in either natural seawater or deionised water as appropriate (Table 1). Tank capacity in each case was 170 litres. The temperature was monitored and recorded, and the water was continuously renewed. The coupons were weighed periodically on a Sartorius balance: After removal from the tanks, excess surface water was wiped off with absorbent paper and the coupons were weighed before being replaced in the tanks. The relevant mechanical test coupons (Table 2, M2–M4) were aged in the same tanks, then removed at the end of the ageing period and held at 20 °C in seawater or deionised water (corresponding to the conditioning medium) until testing. To enable ageing under hydrostatic pressure (C3b), coupons were placed in tap water in pressure vessels inside temperature controlled ovens. Control coupons (C3a) were placed in a tap water bath at the same temperature, in the oven next to the pressure vessel. All measurements were made using equipment calibrated annually by a certified external calibration company.

3.3 Mechanical Testing

Tensile tests were performed on a 200 kN electro-mechanical test frame according to ISO 527. Interlaminar shear tests (short beam shear) were executed in accordance with ASTM 2344. In both cases, tests were performed under displacement control at 2 mm/minute.

Tension fatigue tests were executed on a 250kN servo-hydraulic test frame. The chosen loading frequency was 1 Hz, after preliminary measurements made with an infrared camera, (Fig. 8a), had indicated heating effects at higher frequencies in air. Tests were performed under load control at $R = 0.1$ (cyclic minimum load/cyclic

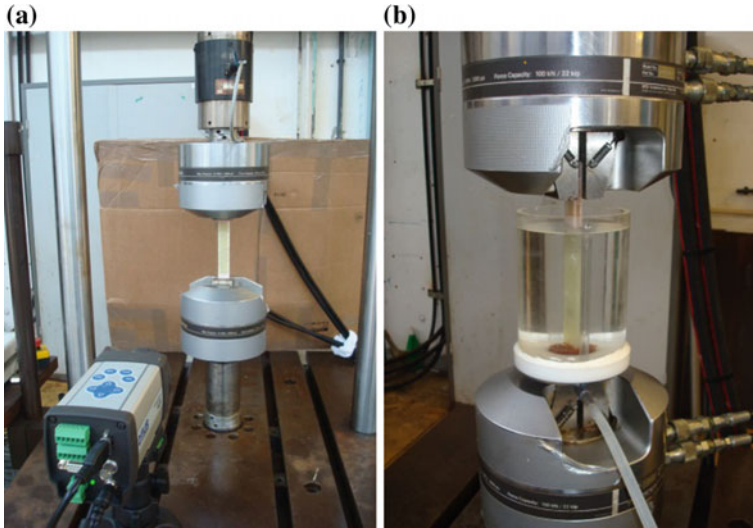


Fig. 8 Tensile fatigue test setup, **a** in air, with IR camera, **b** in natural seawater

maximum load = 0.1). A special fixture was built, (Fig. 8b) in order to perform tests in seawater. This allowed temperature controlled natural seawater (25 °C) to be circulated around the specimen during the test.

4 Results

4.1 Variation of Natural Seawater Temperature

Immersion tests of up to 2 years in duration confirmed the expectation that an increase in conditioning temperature greatly accelerates the rate of coupon weight gain (Figs. 9a, b). The infused coupons were seen to saturate at 0.9–1% weight gain. However, in the case of the prepreg coupons, only the 60 °C curve seems to have stabilised, appearing to reach saturation at 1.4% weight gain.

At all temperatures, the infused coupons were seen to reach saturation much more rapidly than the prepreg. For both materials when aged at 80 °C, colour changes and further changes in weight after apparent saturation were noted (weight gain for the infused coupons, weight loss for the prepreg). This suggests that some manner of material degradation beyond the physical effects of moisture ingress may have taken place, (possibly oxidation) and appears to confirm the normal assumption that coupons should not be aged very close to or exceeding the matrix T_g , as this would risk altering the material in a manner unrepresentative of normal service.

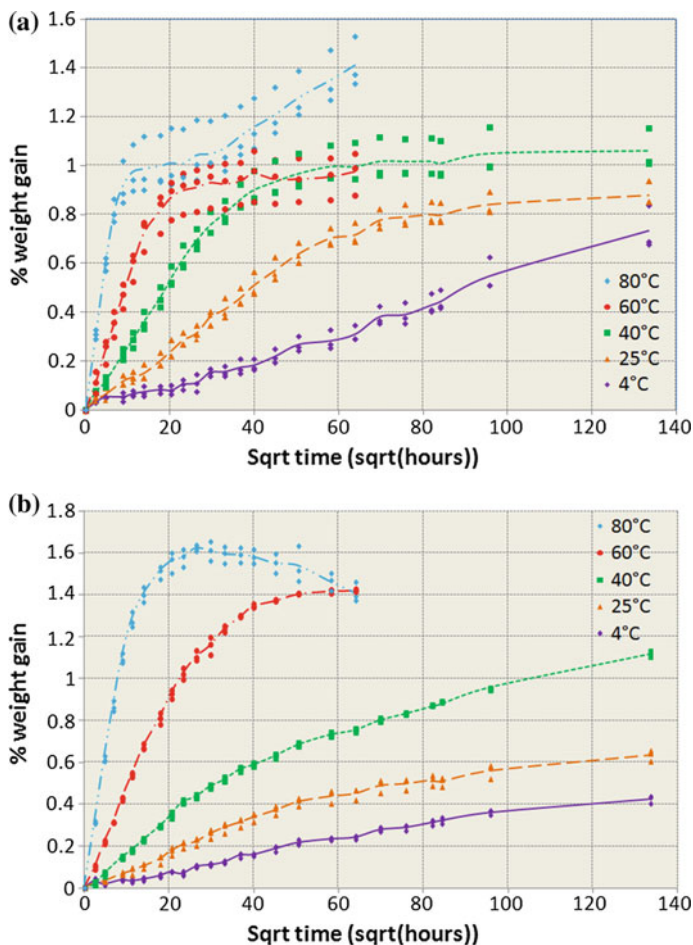


Fig. 9 a—Weight gain of infused coupons in natural seawater—effect of conditioning temperature. b—Weight gain of prepreg coupons in natural seawater—effect of conditioning temperature

It is possible for both materials to normalise the time required to achieve a certain weight gain at any temperature against the time required to achieve the same weight gain at 40 °C (Figs. 10a, b). Linear relationships can be seen to exist between the conditioning temperature and $\log[\text{normalised time}]$, particularly convincingly in the case of the infused coupons.

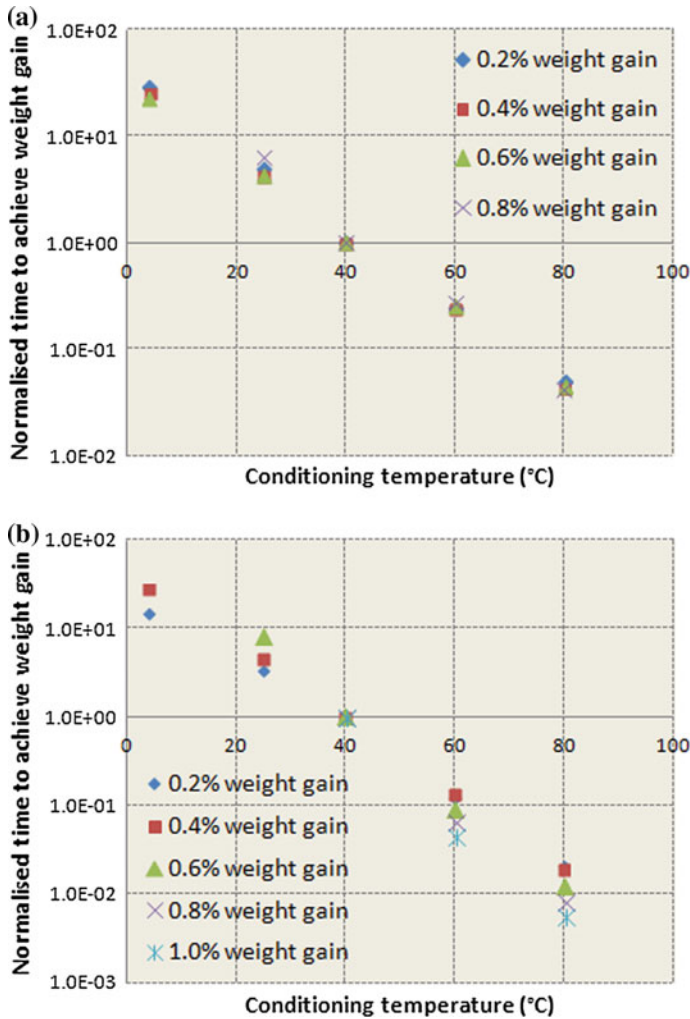


Fig. 10 **a**—Time to weight gain normalised against 40 °C data—infused coupons. **b**—Time to weight gain normalised against 40 °C data—prepreg coupons

4.2 Variation of Pressure and Conditioning Medium

The effect of increasing the ambient pressure from 1 to 500 bars is very limited for both types of the coupon (Figs. 11a, b). For the infused coupons, the effect of high pressure even appears to be to retard the initial rate of weight gain. It is suggested in other work where strong pressure effects on diffusion kinetics are noted [10], and that these effects are related to relatively high-laminate porosity. Considering the logistics of a normal accelerated ageing programme, it is not too great a

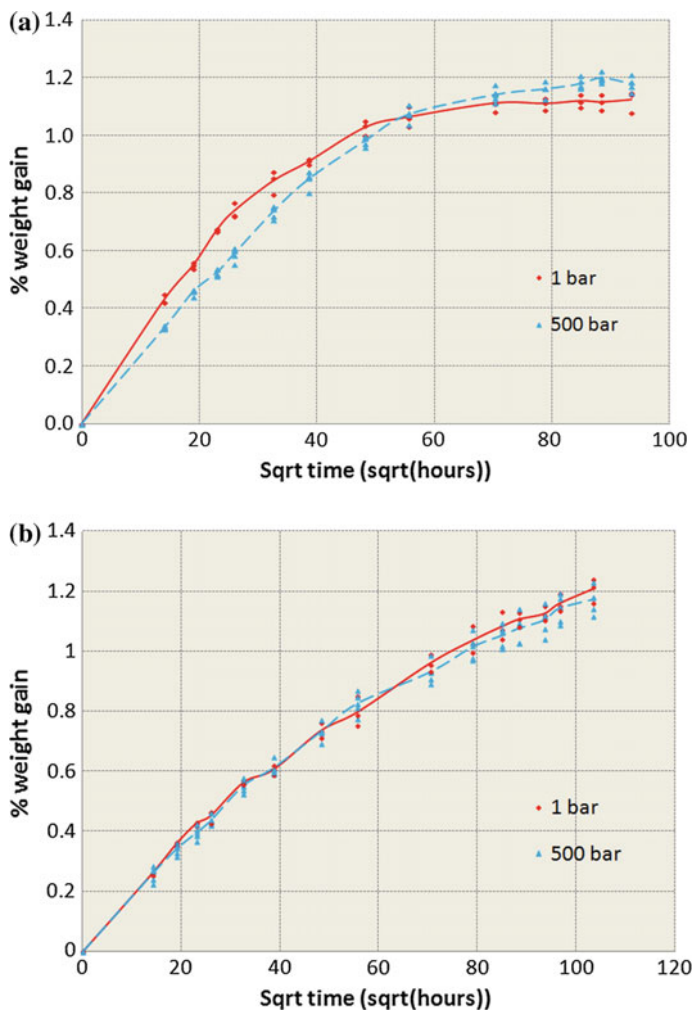


Fig. 11 **a**—Effect of pressure—infused coupons in tap water at 40 °C. **b**—Effect of pressure—prepreg coupons in tap water at 40 °C

disappointment that the use of hyperbaric equipment has very little effect. The practicalities of depressurising and re-pressurising the conditioning unit every time access was required, and the likely capital and maintenance costs of the equipment would be particularly onerous.

With regard to the effect of conditioning medium, initial rates of weight gain are similar. However, it can be seen that coupons conditioned in deionised water will ultimately achieve a greater weight gain than those conditioned in seawater (Figs. 12a, b)

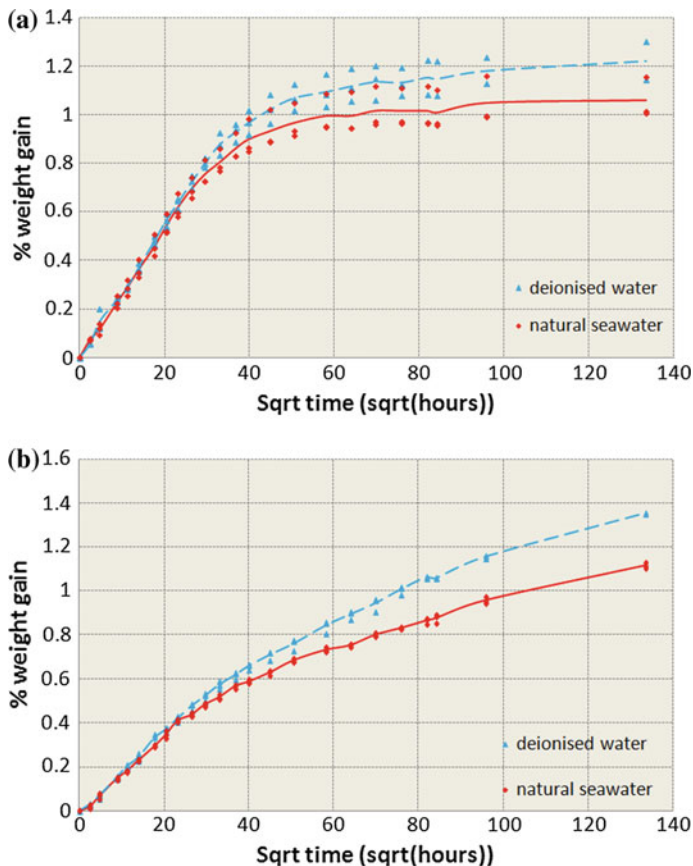


Fig. 12 a—Effect of conditioning medium on weight gain—Infused coupons at 40 °C. b—Effect of conditioning medium on weight gain—Prepreg coupons at 40 °C

4.3 Effect of Conditioning Medium on Mechanical Properties

Both conditioning media clearly have an adverse effect on the tensile and inter-laminar shear strengths of the infused and prepreg coupons (Figs. 13 and 14) with the deionised water resulting consistently in greater degradation. This means that changing the conditioning medium from seawater to deionised water would risk building too great a seawater knockdown factor into the design allowables, possibly resulting in an uncompetitive product. Note that the higher tensile strength of the infused samples is due to the higher fibre content (see Table 3).

As all coupons were manufactured using the same fabric, it is worth considering (Figs. 15 and 16) whether there could be a correlation between weight gain and strength when normalised with respect to the dry values. If it were possible to

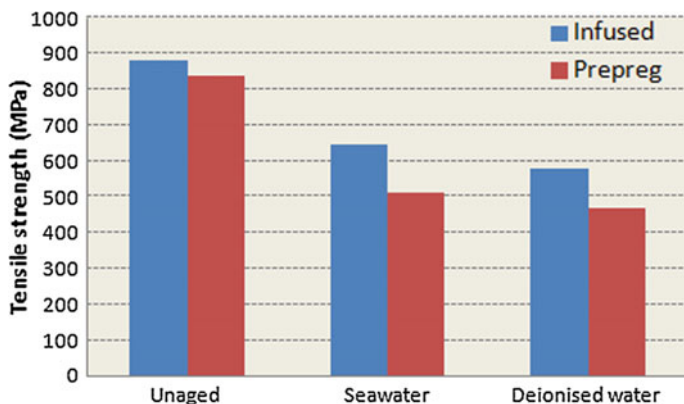


Fig. 13 Fibre direction tensile strength—effect of 8 months ageing @ 40 °C

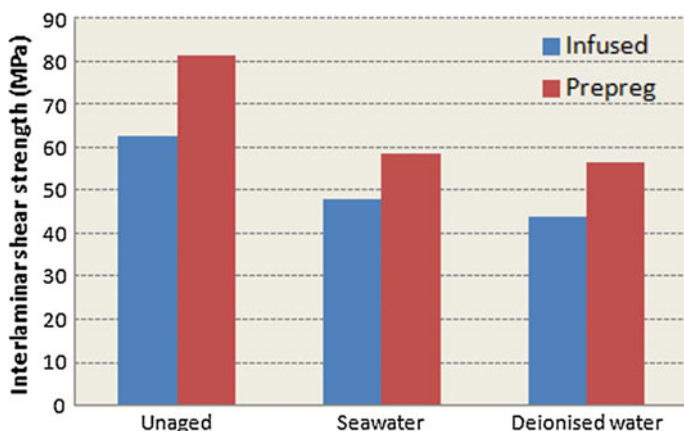


Fig. 14 Interlaminar shear strength—effect of 8 months ageing @ 40 °C

identify a relationship independent of conditioning medium and resin option, it could prove a very valuable aid to resin selection. A plot of the normalised tensile strength (σ_{11T}) against weight gain at test (estimated from the weight gain coupon data), does not show any correlation. However, if instead we plot σ_{11T} against weight gain at saturation, then it is possible to observe a reasonable linear correlation (Fig. 15) between these two parameters. Of course, the material close to the surface will be saturated long before the coupon as a whole, so the observation does make sense. However, we do not see such a convincing correlation when we plot the interlaminar shear strength (τ_{ILS}) against weight gain (Fig. 16), either at test or saturation, and it should be noted that some authors have proposed more complex correlations in the past [11].

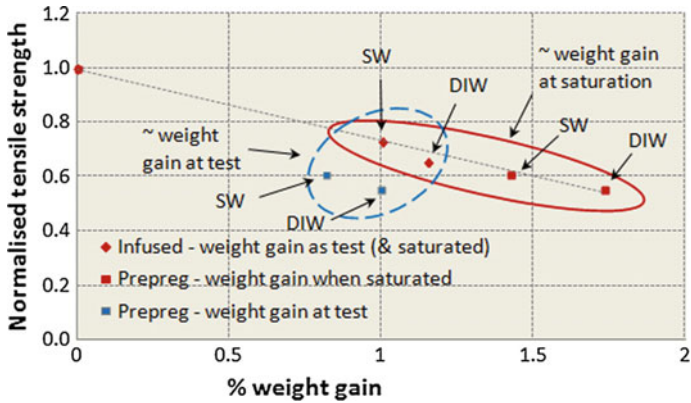


Fig. 15 Normalised tensile strength against weight gain

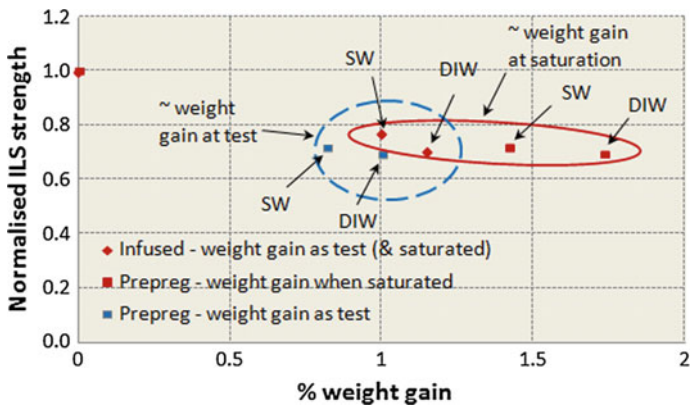


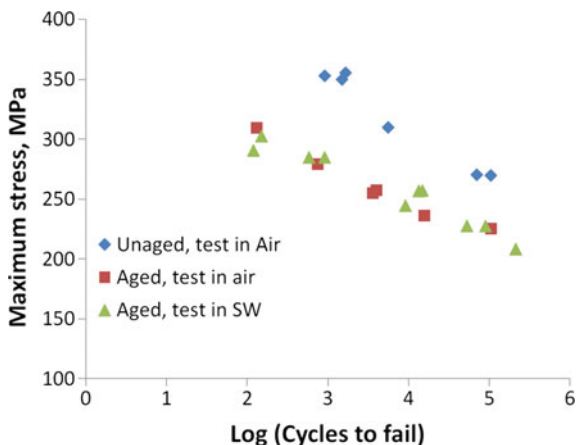
Fig. 16 Normalised ILS strength against weight gain

(Note that the weight gain at saturation for the prepreg coupons in deionised water was estimated by factoring weight gain at saturation in seawater by the ratio of *weight gain in deionised water: weight gain in seawater* at the test.).

4.4 Effect of Ageing and Test Environment on Tension Fatigue Strength of a [0/+ 45/0/-45]s Glass/Epoxy Laminate

When tested after 9 months' immersion in natural seawater at 40 °C, results show that the seawater-aged tension fatigue coupons would have been saturated or very close to saturation (1% weight gain). Figure 17 confirms that seawater ageing also

Fig. 17 Tension fatigue performance of infused glass/epoxy laminate, [0/+45/0/-45]_s, R = 0.1



has a notable adverse effect on the tension fatigue strength of a representative glass epoxy laminate. However, in contrast to the findings of Kosuri and Weitsman [9] no further degradation is noted that may be attributable to the change in test environment from air to seawater. It should be noted that this study only applies to a single laminate and that the complexity of fatigue failure mechanisms means that this result may not be universally applicable. Of course, laminates including 90° cross plies could be more susceptible to the proposed effect as a result of their greater propensity toward transverse cracking, as could carbon/epoxy laminates where delamination tends to play a greater role in fatigue degradation. In any case, the experiment appears to demonstrate for glass/epoxy composites that the ageing process is the main factor at play in terms of the environmentally induced degradation of tension fatigue performance.

5 Conclusions

Bearing in mind the concerns discussed in Sect. 1 with regard to the seawater ageing and testing of laminates for tidal blade construction, it is possible to draw some very useful conclusions from this study.

- Ageing at high pressure should be ruled out as a means of accelerating the ageing process. It does not meaningfully change the rate of ingress of moisture, nor is it a particularly practical proposition.
- Ageing in deionised water may slightly reduce the time required to achieve a given level of saturation, but it would also appear to have a greater adverse effect on mechanical performance than ageing in natural seawater. Therefore, natural seawater remains the conditioning medium of choice.

- The only practical option (of those examined) to further accelerate ageing would be an increase in conditioning temperature. However, the benefits of such a change could be significant; by increasing the standard conditioning temperature towards 60 °C, seawater-ageing timescales could be reduced by a factor of three or more. This is consistent with a 4 month saving in the duration of a qualification programme. Of course, this would depend on the specific resin system and Tg; care would need to be taken in setting a temperature limit below which any degradation effects would be representative of those anticipated in normal service.
- There can be significant differences between resins in terms of weight gain at saturation, and time to saturate.
- There appears to be a linear correlation between weight gain at saturation and fibre direction tensile strength normalised with respect to the dry value, for coupons with identical Advantex glass reinforcement, but variations in matrix and ageing medium,
- For a representative [0/+45/0/-45]_s Advantex glass laminate, there is a significant knockdown in terms of tension fatigue performance associated with ageing in seawater. However, there is no further knockdown associated with conducting the fatigue test in seawater, as opposed to air.

6 Further Work

Before any change can be implemented in terms of conditioning temperature, it will be necessary to verify that an increase in conditioning temperature (as required to accelerate the ageing process) does not confer any unexpected effect on mechanical performance. Furthermore, it would be interesting to follow up the observation of linear dependency of normalised tensile strength on weight gain at saturation. There could be significant beneficial implications for materials screening or qualification programmes, should this relationship be shown to hold more widely.

It would also be worthwhile to extend the fatigue study to consider a greater variety of laminates and materials, as it is possible that other aged laminates (particularly those including 90° cross plies and/or carbon reinforced laminates) could be more susceptible to accelerated fatigue damage when the fatigue test is conducted in seawater.

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