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# Fatigue behaviour of glass fibre reinforced composites for ocean energy conversion systems

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**Abstract:**

The development of ocean energy conversion systems places more severe requirements on materials than similar land-based structures such as wind turbines. Intervention and maintenance at sea are very costly, so for ocean energy supply to become economically viable long term durability must be guaranteed. Cyclic loading is a common feature of most energy conversion devices and composites are widely used, but few data are available concerning the fatigue behaviour in sea water of composite materials. This paper presents the results from an experimental study to fill this gap. The fatigue behavior of composite materials reinforced with different types of glass fibre is characterized in air and in sea water; the influence of testing in sea water rather than air is shown to be small. However, sea water ageing is shown to reduce the fatigue lifetime significantly and strongly depends on matrix formulation.

**Keywords:** Composite material ; Fatigue behaviour ; Sea water ageing ; Failure mechanism ; Tidal turbine

# 1. Introduction

There is considerable interest today in the extraction of energy from the oceans using wave energy and tidal energy devices [1,2]. These are subjected to severe environmental conditions, loading due to waves and currents, and interactions with seawater must be considered during material selection and design. Composite materials are used in tidal turbine blades and in a previous paper the influence of aging on quasi-static behaviour was described [3]. In the present paper cyclic loading is considered.

## 1.1. Fatigue loading experience

There have been many studies of fatigue in composites and a recent book gives a good overview [4]. A major source of data on cyclic loading of composites, both from laboratory tests and in service, is the wind energy industry. Composites are the preferred material for wind turbine blades and their fatigue performance is generally good. Glass reinforced composites have been the first choice since the 1970's, though recently carbon has found some applications as blade lengths extend over 50 meters. Echtermeyer et al. presented results from the EU Joule project [5] in 1996, and more recently the European projects FACT and OPTIMAT and work in the USA have generated large amounts of fatigue data [6-8].

There is still some discussion over how to model cumulative damage in composites, in particular how to take into account the loading history effects related to the chronology of high and low loads [9]. Nevertheless, typical loading spectra have been defined such as the eight proposed in the WISPER (Wind SPEctrum Reference) sequence [10]. These spectra can be used for the evaluation of new designs by simulation and to define appropriate test procedures. In parallel with this approach there is also interest in reliability based predictions, a recent report highlighted the strong influence of the uncertainties in S-N exponents on long term predictions [11].

## 1.2. Stress Corrosion Cracking mechanisms

Stress Corrosion Cracking (SCC) is the unexpected and sudden failure of glass reinforced composite materials subjected to a stress in a corrosive environment. Over time, SCC attacks E-glass fibres, which can lead to premature failure. SCC failure is characterized by flat fracture surfaces perpendicular to the fibres at both the macroscopic and the microscopic levels. Prevention of SCC includes proper selection of fibre and resin, and may require a protective layer between the glass fibres and the environment [12]. For applications where glass reinforced composites are exposed to aggressive environments for long periods special boron-free glass formulations have been developed, which are more resistant to SCC [13].

## 1.3. Fatigue behaviour of composite materials in sea water

Environmental exposure and mechanical stresses can combine to accelerate degradation in composite materials [14]. Strong coupling may exist, such that mechanical stresses accelerate water diffusion and water diffusion accelerates mechanical damage [15]. This phenomenon has not been extensively studied for cyclic loading, but some published studies exist. Kotsikos et al [16] showed a strong influence of water absorption on damage development in glass/polyester composites under cyclic loading. McBagonluri et al. [17] found that short exposure of unidirectional glass/vinylester composites to salt water environments resulted in property losses consistent with Mandell's postulate, namely that fatigue S-N plots have a characteristic slope of around -10% static strength per decade [18]. The relationship between hygrothermal ageing and fatigue behaviour of glass/epoxy composites has been investigated by Vauthier et al. [19] and Pauchard et al. [20] using flexural loading of unidirectional specimens. They detailed the effects of water induced physico-chemical changes on the stress corrosion mechanisms involved during the delayed failure of the glass fibres under fatigue loading. They also developed a durability model which takes into account the combined effects of time, temperature, humidity and applied stress. Kensche [21] showed some fatigue results for dry and saturated glass/epoxy specimens which indicated lower lifetimes for wet samples at high strains, though at low strain levels wet lifetimes were longer than those of dry samples. Finally, Weitsman has described fatigue behaviour of carbon reinforced composites in sea water [22], and proposed a specific mechanism which resulted in accelerated degradation of saturated specimens. This involves crack opening during unloading, due to the presence of water.

## 2. Materials and methods

Three infused glass/epoxy composites have been studied here under cyclic loading, both in air and in natural circulating sea water. In addition, fatigue tests have been performed on specimens aged in circulating natural sea water at 60°C. The same epoxy resin (MGS© RIM135) has been reinforced with three different types of quasi-unidirectional reinforcements, E-glass, Advantex® glass (ADV) and HiPer-tex™ glass (HP) fibres. The reinforcement is 6 symmetrical layers of a quasi-unidirectional fabric reference CDM 1250 with approximately 90% unidirectional fibres, 10% mat and 90° fibres (1150 g/m² warp, 50 g/m² weft and 50 g/m² chopped mat). Polyester stitching (approximately 15 g/m²) is used to hold the fibres together. Fibre sizings were optimised for the epoxy resin. Both resin and fibres are currently used in wind turbine blades. The fibre properties and the results obtained during quality control tests (glass transition temperature, fibre contents and interlaminar shear strength) were detailed in a previous study on the same materials [3]. Fibre volume fraction was around 56±2%.

Tests were performed in four point flexure on dogbone specimens described previously [3]. These are non-standard, 140mm long, 25mm wide at the ends and 10mm in the centre, and nominally 5mm thick, Figure 1. The inner loading span was 60mm and the outer span 120mm, loading point and support diameters were 10mm. The choice of a composite dog-bone specimen was dictated by preliminary results under both quasi-static and cyclic loading. When parallel sided specimens of 25 mm width were tested the failure mechanism for both was local indentation. The loading points, whatever their radius, caused local damage of the upper face of the specimen and initiated premature failure. Different dog-bone specimen configurations were therefore examined, and the one shown in Figure 1 was chosen. The loading points are within the parallel sections, allowing the load introduction to be spread over a larger area and, for the materials studied here, resulting in fatigue failures in the central section without local crushing.

The fatigue tests involved cycling specimens with a constant stress level until failure. The applied stress σ was calculated according to the beam theory expression:

$$s=\frac{3FL}{4bh^2}$$

where, F is the load level applied, b is the width and h the thickness of the specimen in the centre of the dog-bone, and L is the effective length of the specimen, i.e. the outer span. The loading frequency was 2 Hz and R, the load ratio ($R=F_{min}/F_{max}$) was equal to 0.1 unless otherwise stated. The initial quasi-static failure stress levels for the three materials are summarized in Table 1.

The flexural fatigue tests were performed on 25 kN load frames in air and in natural continuously renewed sea water. A specially-developed titanium alloy test device was used to avoid corrosion, ceramic loading points were needed to avoid excessive wear, Figure 2.

In order to understand the different phenomena involved in the fatigue in sea water, cyclic tests have also been performed on aged specimens. These specimens were aged in natural circulating sea water at 60°C with periodic weighing to check their water uptake, diffusion kinetics were presented in a previous study [3] which showed that saturation was reached after 15 weeks.

# 3. Results and discussion

First, a set of infused specimens was tested in order to compare different glass reinforcements, and to examine whether testing in sea water resulted in different fatigue lives than tests performed in air. 31 infused E-glass specimens (12 in air and 19 in natural sea water), 41 infused ADV specimens (20 in air and 21 in natural sea water) and 29 infused HP specimens (10 in air and 19 in natural sea water) were tested. The fatigue lives, $N_f$ , will be presented first, then microscopy and X-ray micro-tomography have been used to observe damage development.

A second set of 28 tests was then performed on one material (HP) to examine the influence of fibre finish on fatigue behaviour. The influence of aging on the ADV material was studied in a third set of 18 tests. Finally, 24 samples with an alternative matrix were tested, again with the ADV fibres, before and after aging. Results from a total of 171 tests are presented.

## 3.1. Fatigue life in air and in natural sea water

Various curves can be drawn to present fatigue test results, as discussed by Mandell [23]. Here, applied stress versus log(cycles to failure) plots are used, as these allow direct comparisons to be made between composites with the same matrix and similar fibre volume fractions. Figure 3 shows the influence of testing in seawater rather than in air for the three materials.

These plots clearly indicate a small effect of sea water for the E-glass and ADV composite materials, while the HP material is less sensitive to sea water testing.

Figure 4 shows a comparison between the three materials tested in seawater, both in terms of absolute stress (Figure 4a) and with the applied stress normalized by the static strength value (Figure 4b). There are various ways of representing these data [23], one of the simplest is to determine fatigue coefficients from the slopes in Figure 4, using the expression:

$$\sigma_{max.} / \sigma_o = A - b.\log N$$

With $\sigma_{max}$. the maximum stress, N the cycles to failure and A and b linear regression fitting parameters. Table 2 shows the values of b. They are all in the range from 10 to 17% strength loss per decade. With this representation these slopes, i.e. the loss in strength per decade, are significantly lower for the improved glass fibre composites in air, but quite similar for all three fibres when tests are performed in seawater.

It should be noted however, that for a given absolute applied stress the fatigue life in seawater is shorter for the infused E-glass composite than for the two other composite materials (Figure 4a).

Final failure occurs in the central part of the specimen. For all of these unaged specimens failure occurs on the side of the specimen (the upper side) in compression. Some tests on E-glass specimens were interrupted and samples were examined using X-ray micro-tomography. This allows a 3D representation of the sample to be obtained without having to section it. Figure 5 shows an example of the results.

The untested sample shows little porosity or other defects, Figure 5d. The sections of samples from interrupted fatigue tests, Figures 5b and 5c, reveal damage in the form of small interlaminar cracks. At final failure this damage accumulates and results in fibre breakage on the upper surface of the specimen in compression, Figure 5a.

### 3.2. Influence of fibre sizing

In order to examine the influence of the fibre sizing on fatigue behavior two other series of specimens were prepared with the same reinforcement (HP) and the same epoxy resin but with different size formulations. These non-optimal sizings are commercial products but designed for other manufacturing processes. Figure 6 shows the results of fatigue tests performed in seawater. It is clear that the fatigue performance is strongly influenced by the fibre sizing, the optimal sizing for infusion processing gives significantly higher fatigue lifetimes.

Static flexural tests (Table 3) also indicate a loss in strength with these non-optimal fibre sizings.

### 3.3. Fatigue of aged specimens

In order to examine the influence of seawater aging on fatigue behaviour a series of 30 ADV/epoxy samples was immersed in natural seawater as described previously [3]. Six samples were removed after 3, 6, and 10 weeks. These were kept in seawater at 20°C until testing, then 3 were tested to failure under static loading and the other 3 under cyclic loading in seawater at a maximum stress level of 60% of their dry static strength. A further twelve specimens were removed after 15 weeks, at which time the material was saturated. Figure 7 shows how the fatigue life evolved with aging time, Figure 8 shows the comparison between unaged and saturated specimens.

Damage mechanisms change after aging, in a similar way to the change noted for quasi-static loading [3]. Unaged specimens all fail in compression whereas after 15 weeks' aging at 60°C aging failure is mostly tensile. At intermediate aging times there is a gradual transition from compression to tensile failure.

By changing the matrix resin it is possible to significantly improve this result. Figure 9 shows results from the same tests performed on ADV fibre samples in an alternative matrix resin.

In this case the tests in seawater at 60% break stress show no reduction in lifetime after aging, and the S-N plot after aging is very similar to that of the unaged composite. The lifetimes of wet aged samples are a little lower at high loads and a little longer at low loads. This is similar to the results of Kensche [21]. These results in Figures 7 to 10 underline the importance of matrix selection, and indicate that simply using the same matrix as that employed in wind turbine blades will not provide optimal composite properties for an ocean energy application. By following the test procedure developed here, saturating samples with seawater then cyclic flexural tests, materials can be evaluated for this new application in a few months.

## 4. Conclusion

Ocean energy conversion devices are using composite materials in critical elements such as turbine blades. Long term reliability of these structures is essential if renewable marine energy devices are to be economically viable but few data are available to dimension composites in seawater. The results from this study show that while testing in seawater rather than in air does not result in significant differences, matrix selection is critical if very large reductions in fatigue lifetimes due to aging effects are to be limited. This underlines the importance of working closely with material suppliers, both fibre manufacturers and resin formulators, in order to develop a composite material which is optimised for the application. The test procedure proposed here, cyclic tests after saturating samples with water, allows materials to be evaluated for this application. Ocean energy devices operate in a very severe environment and materials must be thoroughly qualified to reduce risk of failure in service.

## 5. Acknowledgements

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## 6. References

[1] European Commission, Ocean Energy Conversion in Europe, 2006.
[2] Bahaj AS, Generating electricity from the oceans, Ren. And Sust. Energy Reviews, 15 (2011), 3399-3416.
[3] Boisseau A, Davies P, Thiébaud F. Sea water ageing of composites for ocean energy conversion systems : Influence of glass fibre type on static behaviour. Published on-line in Applied Composite Materials, 2011, doi 10.1007/s10443-011-9219-6.
[4] Harris B, ed. Fatigue in Composites: Woodhead Publishers 2003.
[5] Echtermeyer AT, Kensche C, Bach P, Poppen M, Lilholt H, Andersen SI, et al. Method to predict fatigue lifetimes of GRP wind turbine blades and comparison with experiments. the 1996 European Union wind energy conference and exhibition; 20–24 May,1996; Göteborg, Sweden: Stephens and Associates.
[6] Nijssen RPL, VanWingerde AM, VanDelft DRV. Wind turbine rotor blade materials : Estimating service lives. SAMPE journal, 2007;vol. 43 (no2):pp. 7-15.
[7] OPTIMAT European project, database on-line, website : http://www.wmc.eu/optimatblades_optidat.php
[8] Sutherland HJ, Mandell JF. Application of the U.S. high cycle fatigue data base to wind turbine blade lifetime predictions. Energy Week 1996, ASME; 1996.
[9] Guedes RM. Creep and fatigue lifetime prediction of polymer matrix composites based on simple cumulative damage laws. Composites Part A: Applied Science and Manufacturing. 2008;39(11):1716-25.
[10] Ronold KO, Christensen CJ. Optimization of a design code for wind-turbine rotor blades in fatigue. Engineering Structures. 2001;23(8):993-1004.

[11] Tarp-Johansen NJ, Examples of Fatigue Lifetime and Reliability Evaluation of Larger Wind Turbine Components, Riso Report R-1418 (EN) March 2003.
[12] Price JN, Hull D, Effect of matrix toughness on crack propagation during stress corrosion of glass reinforced composites, Comp. Sci & Tech., 28, (1987) 193-210.
[13] Renaud CM, Greenwood ME. Effect of Glass Fibres and Environments on Long-Term Durability of GFRP Composites. 2002.
[14] Neuman S, Marom G, Stress dependence of the coefficient of moisture diffusion in composite materials, Polymer Composite, 6, 1, 9-12
[15] Suri C, Perreux D, The effects of mechanical damage in a glass fibre/epoxy composite on the absorption rate, Composites Engineering, 5, 4, 1995, 415-424.
[16] Kotsikos G, Evans JT, Gibson AG, Hale JM, Environmentally enhanced fatigue damage in glass fibre reinforced composites characterised by acoustic emission, Composites Part A, 31, 2000, 969-977
[17] McBagonluri F, Garcia K, Hayes M, Verghese KNE, Lesko JJ, Characterization of fatigue and combined environment on durability performance of glass/vinyl ester composite for infrastructure applications, International Journal of Fatigue 22 (2000) 53–64
[18] Mandell JF. Fatigue behavior of fiber–resin composites. In: Pritchard G, editor. Developments in reinforced plastics 2. London, Applied Science Publisher, 1978.
[19] Vauthier E, Abry JC, Bailliez T, Chateauminois A , Interactions between hygrothermal ageing and fatigue damage in unidirectional glass/epoxy composites, Comp Sci & Tech, 58, 1998, 687-692.
[20] Pauchard V, Grosjean F, Campion-Boulharts H, Chateauminois A. Application of a stress-corrosion-cracking model to an analysis of the durability of glass/epoxy composites in wet environments. Comp Sci and Technology. 2002;62(4):493-8.
[21] Kensche CW, Fatigue of composites for wind turbines, Int. J of Fatigue, 28 (2006), 1363-1374.
[22] Weitsman YJ, Penumadu D, Siriuk A. On the immersed and dry fatigue of carbon fiber/vinyl ester composite material. Proc. 17th International Conference on Composite Materials (ICCM17); 2009; Edinburgh, UK.
[23] Mandell JF, Fatigue behavior of short fiber composite materials, Chapter 7 in Fatigue of Composite Materials, ed. Reifsnider KL, Elsevier, 1990, pp231-337

## Tables

Table 1. Summary of the axial tensile modulus and failure stresses for the three infused composite materials

| | E-glass/Epoxy | ADV/Epoxy | HP/Epoxy |
|---|---|---|---|
| Composite axial modulus, GPa | 49.6 (1.6) | - | 55.9 (4.0) |
| Initial failure stress $\sigma_o$ (s.d.) MPa | 1138 (69) | 1330 (47) | 1314 (83) |

Table 2. Fatigue parameter “b” for the three composite materials in air and in natural circulating sea water

| Environment | Composite material | b |
|---|---|---|
| Air | Infused E-glass<br>Infused ADV<br>Infused HP | -0.164<br>-0.103<br>-0.102 |
| Natural circulating sea water | Infused E-glass<br>Infused ADV<br>Infused HP | -0.130<br>-0.142<br>-0.132 |

Table 3. Summary of the 4-point flexure failure stresses for the three modified composite materials

| Material | HP/Epoxy Non-optimal finish 1 | HP/Epoxy Non-optimal finish 2 | ADV/Modified matrix |
|---|---|---|---|
| Failure stress, MPa | 993 (90) | 1013 (62) | 1403 (88) |

## Figures

Figure 1. Test specimens (dimensions in mm)

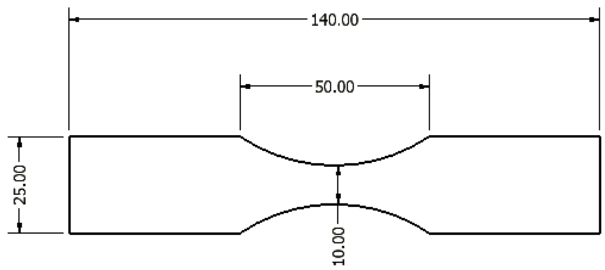


Figure 2. Fatigue test set-up in four-point bending in natural circulating sea water

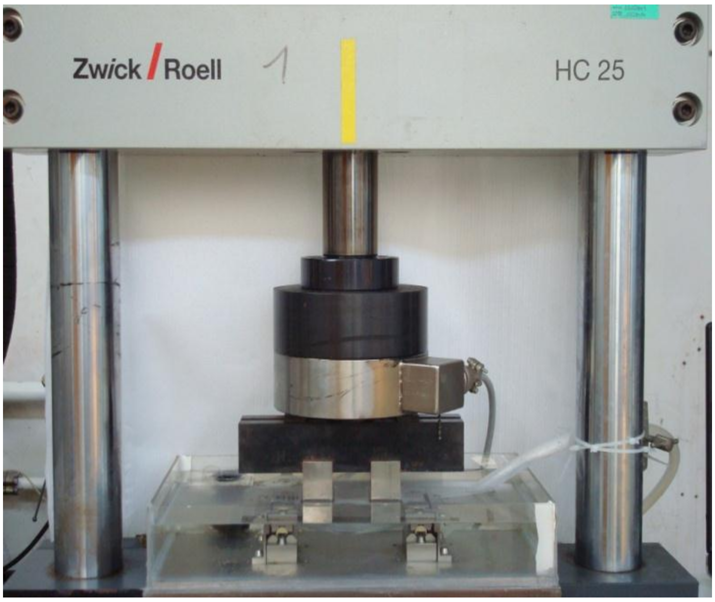
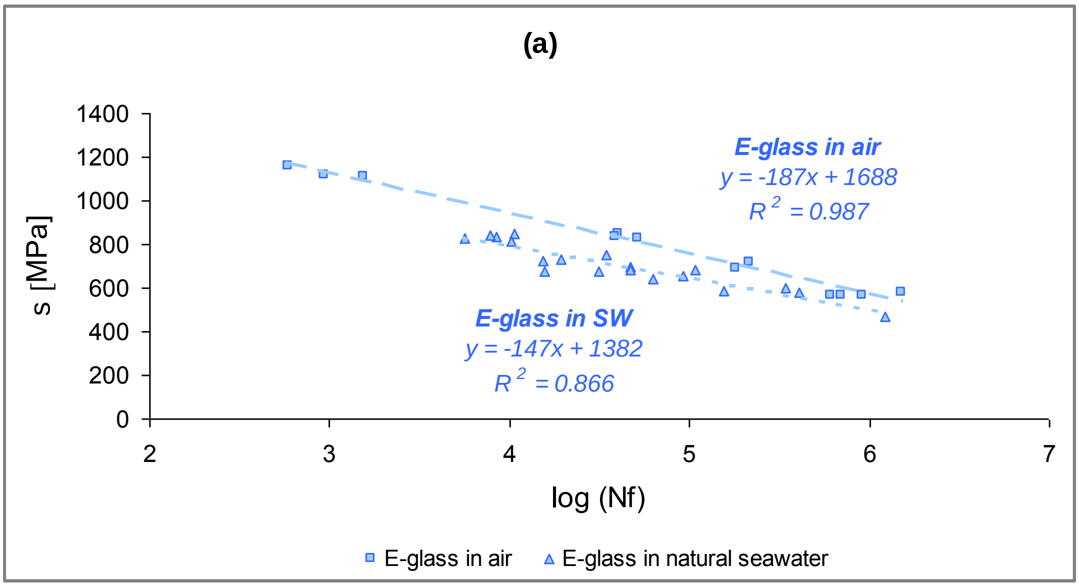
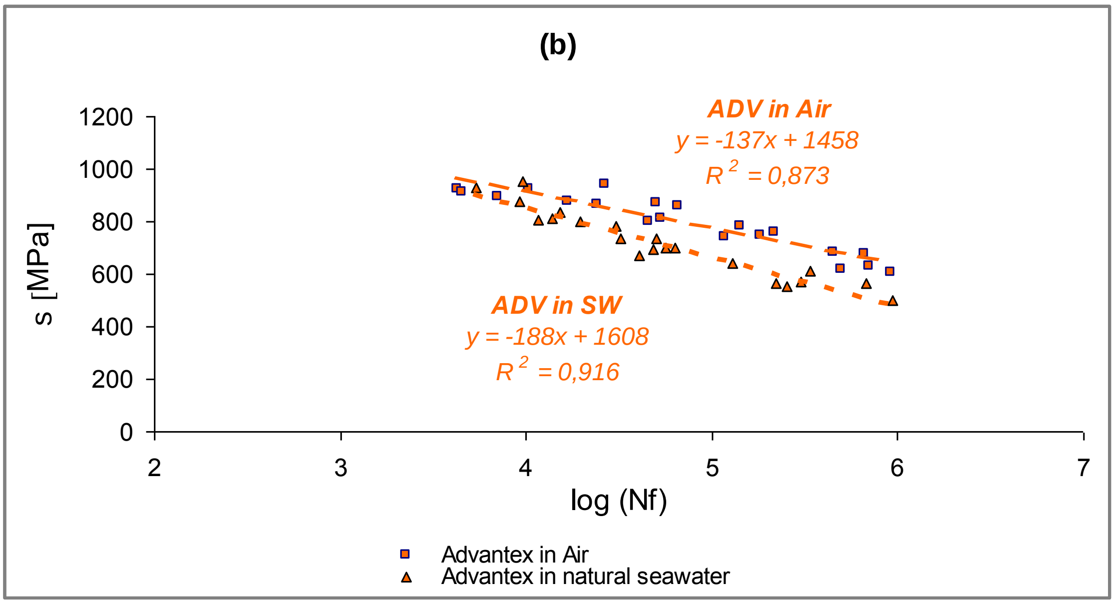



Figure 3. S-N plots for the three composite materials, Applied stress versus log Nf, in air and in natural circulating sea water , a) E-glass, b) ADV, c) HP




(b)
ADV in Air
y = -137x + 1458
R 2 = 0,873
ADV in SW
y = -188x + 1608
R 2 = 0,916
s [MPa]
1200
1000
800
600
400
200
0
2
3
4
5
6
7
log (Nf)
Advantex in Air
Advantex in natural seawater

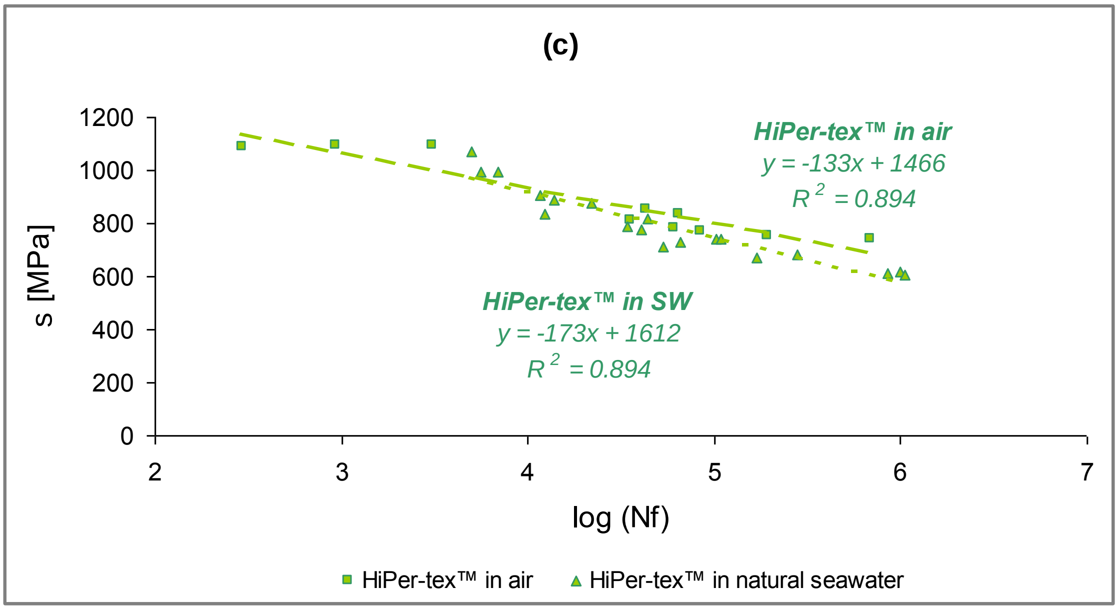
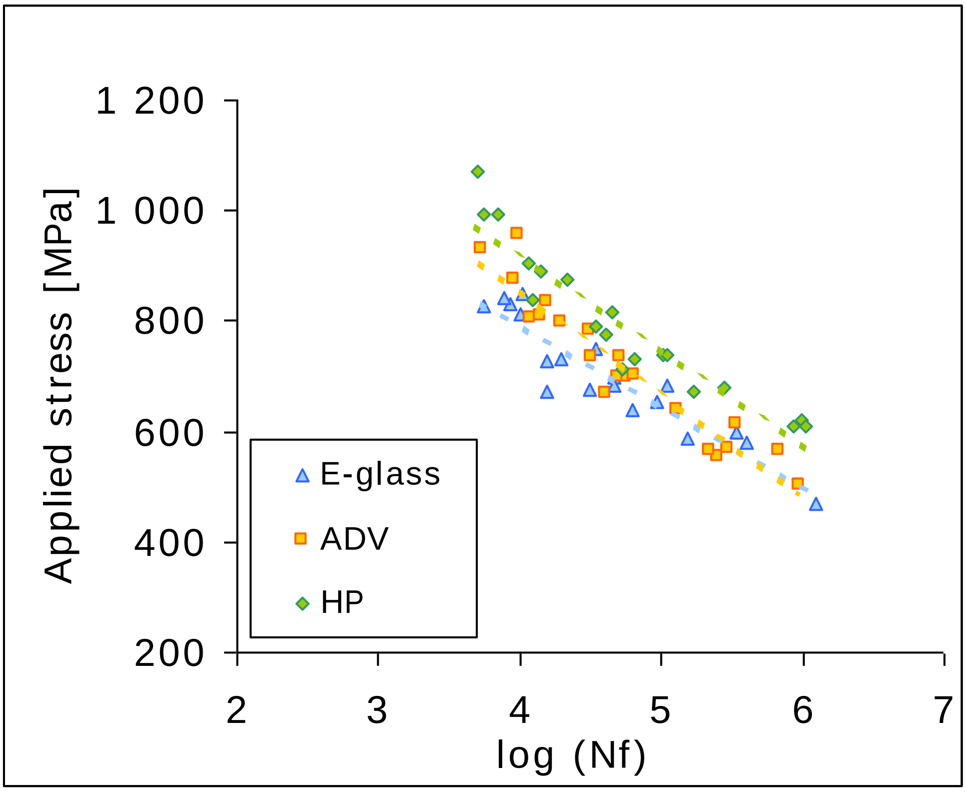
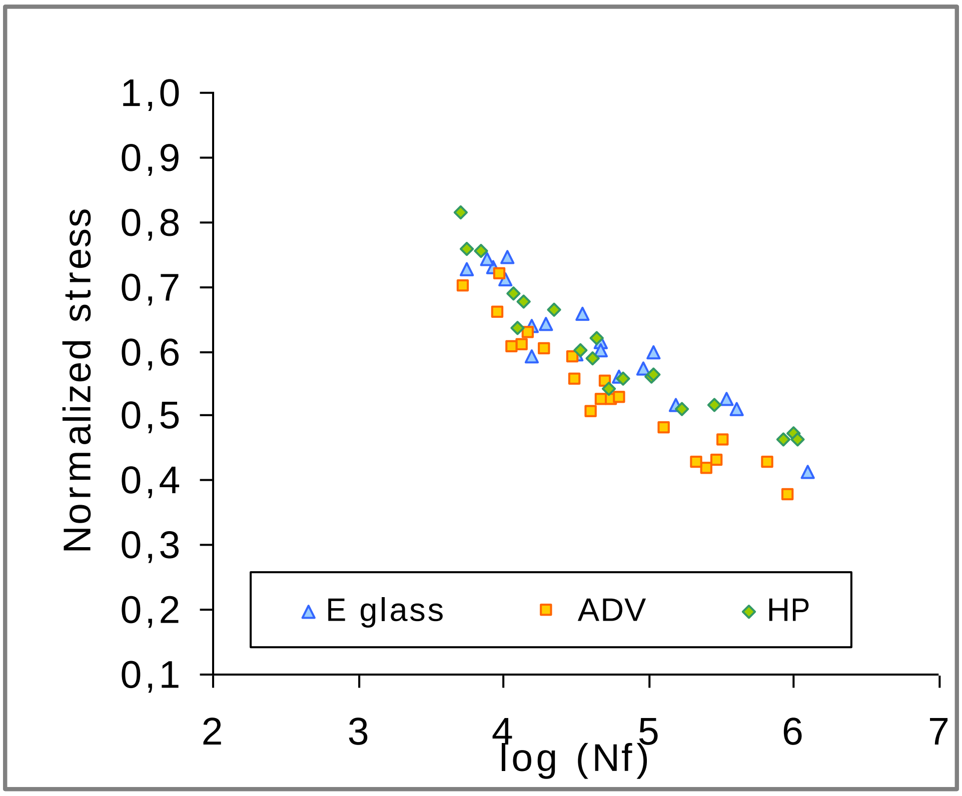

(c)
HiPer-tex™ in air
y = -133x + 1466
R 2 = 0.894
HiPer-tex™ in SW
y = -173x + 1612
R 2 = 0.894
s [MPa]
1200
1000
800
600
400
200
0
2
3
4
5
6
7
log (Nf)
HiPer-tex™ in air
HiPer-tex™ in natural seawater

Figure 4. Comparative curves for the three composite materials, in natural sea water

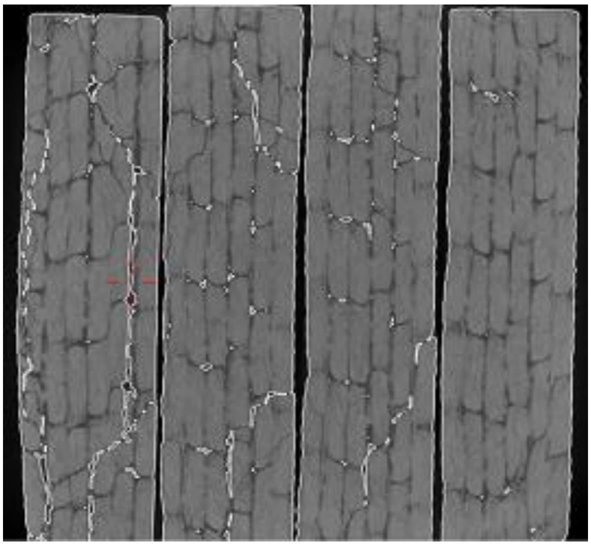



(a)




(b)

Figure 5. X-ray microtomography images of damage at the mid-sections of four fatigue specimens. Tensile loading on left
(a) Specimen completely failed, (b) test stopped at N/Nf = 0.6, (c) test stopped at N/Nf = 0.1
(d) new specimen



(a) (b) (c) (d)

Figure 6. Influence of sizing on wet fatigue behaviour, HP/epoxy

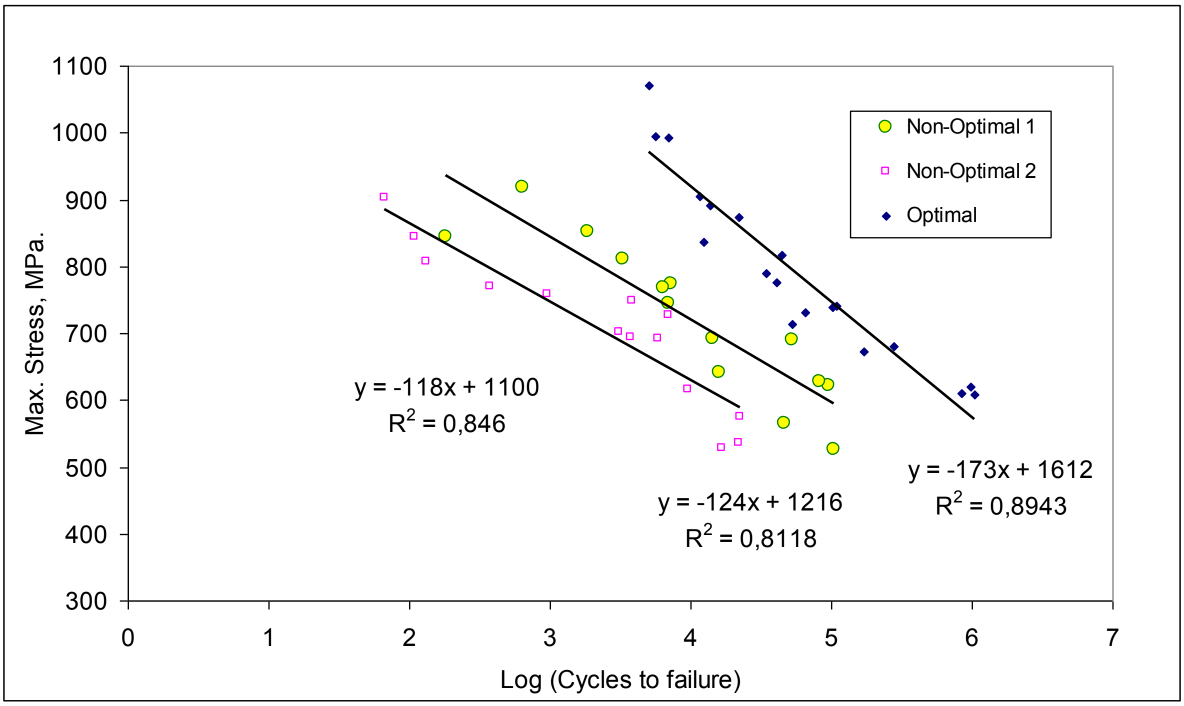


Figure 7. Evolution of fatigue lifetime with immersion period, applied load 60% dry break load, tests performed in seawater, ADV/epoxy.

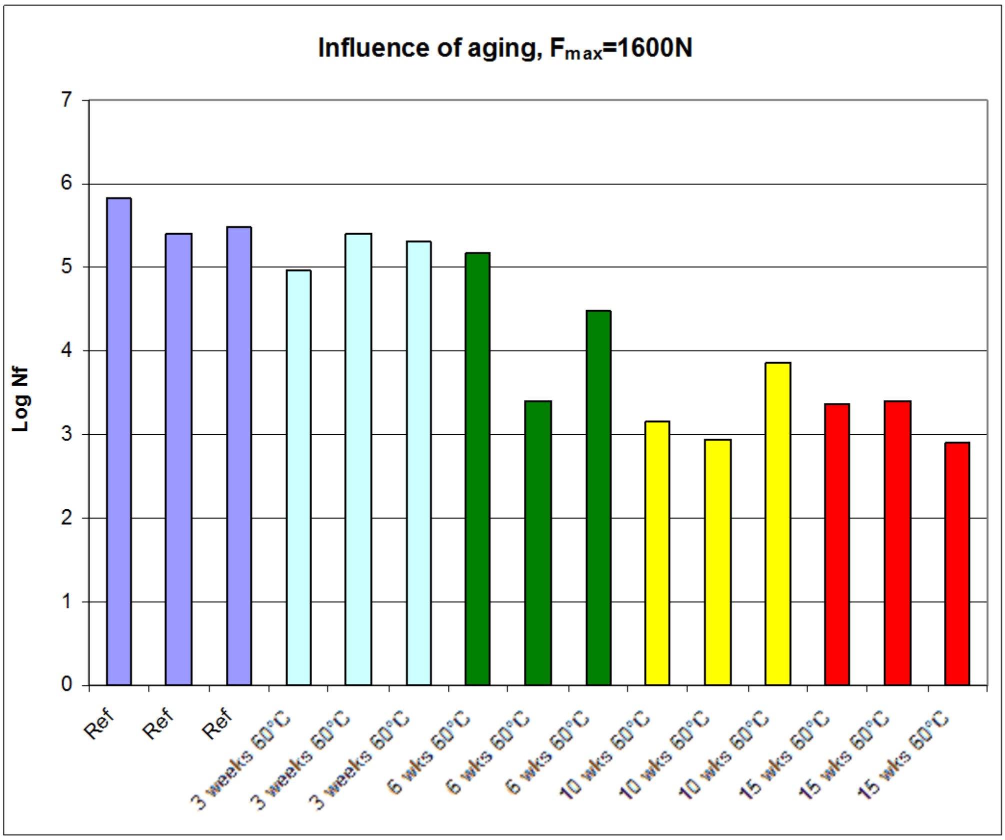



Figure 8. Influence of wet aging in seawater, S-logN plot, ADV/epoxy matrix

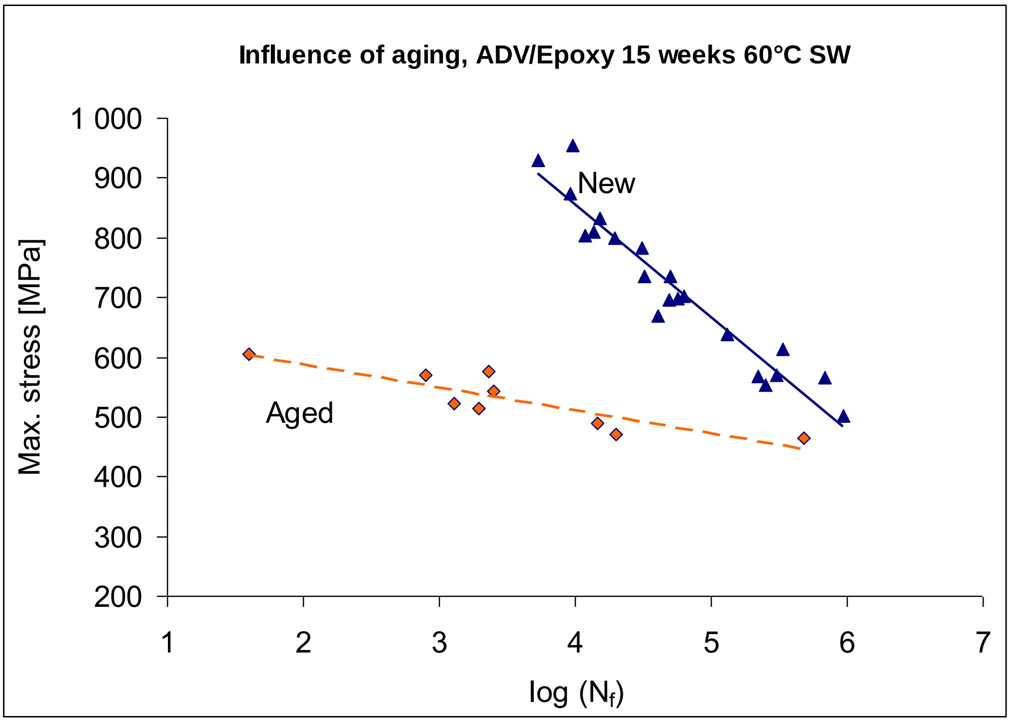


Figure 9. Evolution of fatigue lifetime with immersion period, applied load 60% dry break load, tests performed in seawater , ADV/modified matrix.

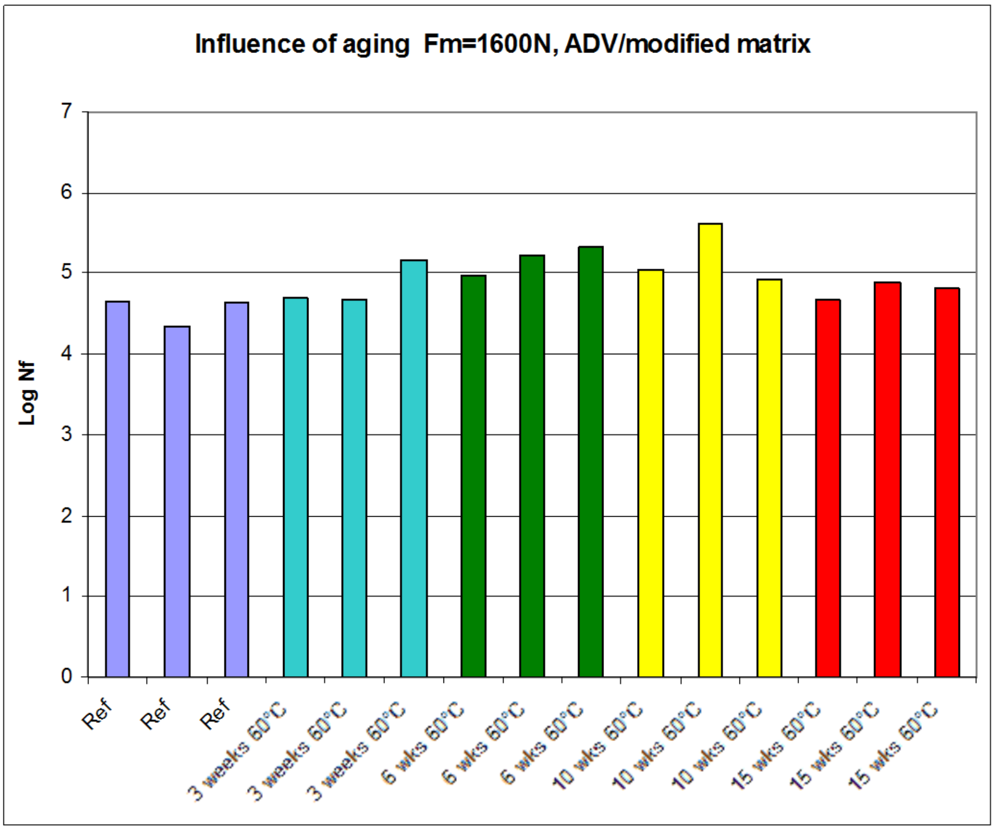



Figure 10. Influence of wet aging in seawater, S-logN plot, ADV/modified matrix