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Failure mechanisms of GRFP after long term exposure to seawater

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Abstract

The adoption of composite polymeric materials in marine applications is fully related to factors such as reliability and cost-effectiveness. The improvement in the knowledge and deep understanding of the behaviour of these materials considering the operational environment is fundamental for avoiding exceedingly high safety factors which compromise the market price. Accordingly, the effects of immersion in seawater of glass/epoxy composite laminates were studied to better understand the failure mechanisms induced by seawater aging. The damage evolution under fatigue loading was assessed at the surfaces of the samples by the digital image correlation (DIC) technique to characterise the first principal strain fields. Additionally, the fracture surfaces of the specimens were analysed using scanning electron microscope (SEM), showing changes in the structure and resulting on a significant decrease in fatigue life of immersed specimens.

Keywords: FRP; Fracture mechanics; Hostile environments; Aging; Fatigue failure.

1. Introduction

Epoxy reinforced with glass fibre composite materials has been employed in large amounts in marine structures in the last decades. These materials are light weight, have excellent fatigue properties, and complicated designs can be built with relative simplicity, Harizi et al. (2015).

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Nomenclature

DIC	Digital image correlation
FRP	Fibre-reinforced polymer
GFRP	Glass fibre-reinforced polymer
N_f	Number of cycles to fatigue failure
SEM	Scanning electronic microscope
σ_{max}	Maximum cyclic stress
ε_I	First principal strain

Moreover, with the demand for reducing greenhouse gas emissions, projects for marine transportation vessels are becoming more weight sensitive, which obligates optimized designs and thinner structures, Davies et al., (2001). Accordingly, environmental ageing is crucial in the design process and cannot be neglected. Although fibre reinforced polymers (FRPs) have respectable corrosion characteristics compared to some metals, severe degradation can still occur, compromising structure's stability. Moreover, although FRP materials are not susceptible to marine corrosion due toheir chemical stability, they are affected by other degradation mechanisms induced by the presence and absorption of surrounding moisture, Kafodya et al. (2015). This degradation is commonly caused by multiple factors, including matrix microcracking, debonding between the fibre/matrix interface, and ply delamination, which can lower the strength and ultimately induce the failure of the structure, Schutte (1994). Numerous studies have been carried out to assess how composite materials are impacted by hostile environments, Kootsookos & Mouritz (2004) or Mourad et al. (2010) or Bian et al. (2015) or Branco et al. (2021). Ellyin & Rohrbacher (2000) showed that moisture absorption in glass/epoxy composites causes plasticisation and swelling, resulting in residual stresses that compromise the mechanical performance of exposed composite structures. Kennedy et al. (2016) conducted a study on the effect of prolonged immersion in seawater on the fatigue properties of glass fibre-reiforced polymers (GFRPs). Their findings revealed a considerable reduction in the fatigue strength of the composite after prolonged exposure to water. More specifically, after 1000 cycles, the fatigue strength decreased by 20% compared to dry conditions. Similarly, after 1 million cycles, the reduction in fatigue strength under wet conditions was 8%. In 2019, Gibhardt et al. (2019) conducted a study where they found a significant reduction of fatigue life under cyclic tension–compression. The authors validated the hypothesis that the fibre-matrix interphase is a major factor in terms of durability. Another study conducted by Pacheco et al. (2012) confirmed that the microstructure of the interphase plays an important role in mechanical strength and in promoting damage by facilitating the diffusion process.

Considering the existing literature on the mechanical effects of seawater exposure, this study aims to explore how seawater-induced physical changes affect the fatigue strength of GFRP. Consequently, notched specimens were used in fatigue tests, with immersion times ranging from 0 to 230 days. Additionally, digital image correlation (DIC) was utilized to track the damage evolution during cyclic loading, and high-quality scanning electron microscopy (SEM) was employed to assess the fracture surfaces of specimens that failed due to fatigue.

2. Experimental procedure

This study used composite laminates prepared by hand lay-up made of glass fibre (1195P) with an epoxy resin Biresin® CR122 and a hardener Biresin® CH122-3, both supplied by Sika. The laminates were composed by 12 plies arranged according to the layout [0º,45º,90º,45º,0º,90º]s and the final geometry of the plates were 330×330×2.3 mm^3. For the experiments, rectangular specimens were obtained from those plates with dimensions of 165×22.5 mm^2. A specialized twist drill bit designed for composites was used to drill a central hole measuring 5 mm in diameter. After manufacture, the samples were immersed in seawater for 230 days to evaluate the effect of exposure time on their mechanical properties.

The samples were weighed regularly to assess the water absorption rate during the immersed period. The seawater used to age the specimens was obtained directly from the port of Figueira da Foz, Portugal, which is exposed to the waters of the Atlantic Ocean. The fatigue tests were conducted at room temperature using a sinusoidal waveform, a stress ratio (R) of 0.1, and a cyclic frequency (f) of 10 Hz, on an Instron 1341 100 kN servo-hydraulic tension-compression machine. To evaluate the process of damage accumulation, the strain fields were obtained from the central regions of the samples. The digital image correlation technique (DIC) was used to monitor these regions in situ, employing the VIC-3D system from Correlated Solutions. All samples were coated with white opaque paint and air-sprayed with airbrush pro-colour black ink to produce a non-repetitive speckle pattern with high contrast. The pattern allows full-field measurement of displacement and deformation, which were captured with two high-speed cameras, Point Grey GRAS-20S4 M-C, at the maximum resolution of 1624×1224 pixels and a maximum frame rate of 19 frames per second.

3. Results

The weight gain was modelled using a Fickian diffusion model and the procedure presented in Vidinha et al., (2022). The comparison between the predicted weight gain resulting from the numerical simulations and the experimental measurements is depicted in Figure 1. Overall, the proposed function closely approximates the experimental results, regardless of the immersion time. Notably, the absolute maximum of discrepancies illustrated in Figure 1 was observed at 640 days but was below 8.8%. However, the differences are insignificant for immersion periods shorter than 500 days, and there is a strong agreement between the data points and Fick's law.

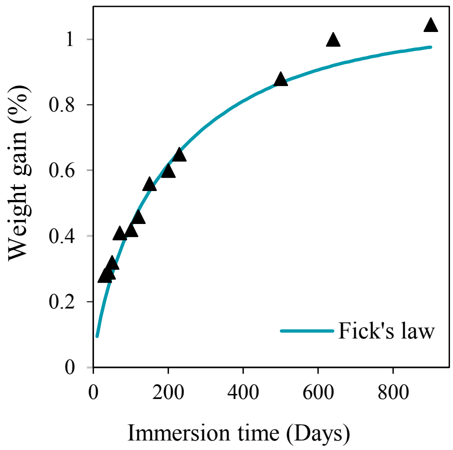

Figure 1. Water absorption curve of tested GFRP laminate and fitted Fick's law used in the numerical simulations, from Vidinha et al. (2022).

Tension fatigue tests (R = 0.1) were conducted at a constant load amplitude. The S-N diagram was the primary tool used for analysing the results of the fatigue tests. The test results were used to obtain the stress-life (S-N) curves for samples immersed 230 days in seawater and for samples not immersed. The failure criterion used in this study was the complete separation of the specimens. Figure 2 displays the S-N curves for maximum stress (σ_{max}) versus number of cycles to failure (N_f) obtained from the fatigue tests conducted at immersion times of 0 days and 230 days. The curves are presented on log-log scales. The mean curves obtained through linear regression and using the least square method for a 50% failure probability are represented by solid straight lines. The corresponding 95% confidence bands, determined in accordance with the ASTM E739 standard, are shown on the left-hand side as upper and lower limits. In general, there is some scatter in the results, but a satisfactory correlation is observed.

Regarding the cause of the fatigue failure, low-cycle fatigue failure is generally distinguished by stress dominance, and the failure of the structure is primarily caused by fiber breakage. On the other hand, high cycle fatigue failure is characterized by various forms of damage accumulation, including microcracks, delamination, and fiber-matrix debonding, Padmaraj et al. (2021). By examining the S-N curves, it is visible that the fatigue performance of the immersed specimens (230 days) is noticeably diminished in comparison to the control group (0 days) for the same level of applied stress. Additionally, it is noteworthy that the slopes of all three S-N curves remain almost constant. This observation indicates that the failure mechanisms are not significantly altered by exposure to seawater; rather, the damage progresses more rapidly with increased immersion time. When subjected to a maximum cyclic stress of

143 MPa, which was the average stress for the tested range, the fatigue life of the 230-day samples was approximately 66% of that of the control samples, which reaffirms the importance of considering the impact of seawater exposure during the initial design stages of composite marine structures.

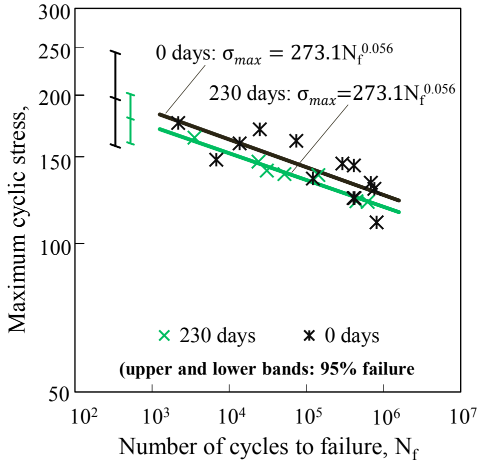

Figure 2. Comparison of the S-N curves for different immersion times (0 days, 230 days, and 910 days) under uniaxial cyclic loading (R = 0.1).

The degradation process caused by fatigue loading in the tested laminate was also accessed by using digital image correlation. Figure 3 shows the first principal strain fields (ε_I) near the notched region at various dimensionless lives (N/N_f) for the maximum applied stress of the loading cycle for a samples not immersed in seawater (Fig. 3(a)) and immersed in seawater for 230 days (Fig. 3(b)).

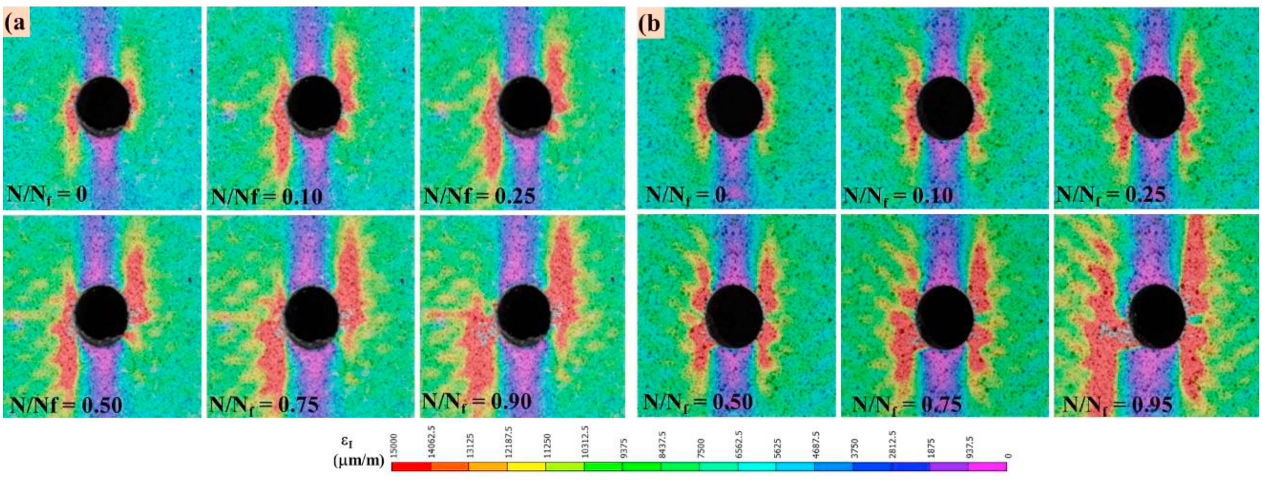

Figure 3. Evolution of the first principal strain field (ε_I) near the hole with the dimensionless life (N/Nf) for: (a) 0 days of immersion; and (b) 230 days of immersion. The images were captured at the maximum applied stress of each cycle.

As the number of loading cycles increases, higher values of the first principal strain are localized in two diametrically opposite regions around the hole. These regions identify axial splits that originate from the hole and extend towards the longitudinal extremities of the specimen. This behaviour is in line with the findings reported by Aidi et al. (2015) for laminates with central notches subjected to fatigue loading.

The fracture surface morphologies of the tested specimens caused by cyclic loading were examined by optical microscopy. Figure 4 shows examples of different failure mechanisms found for different immersion times.

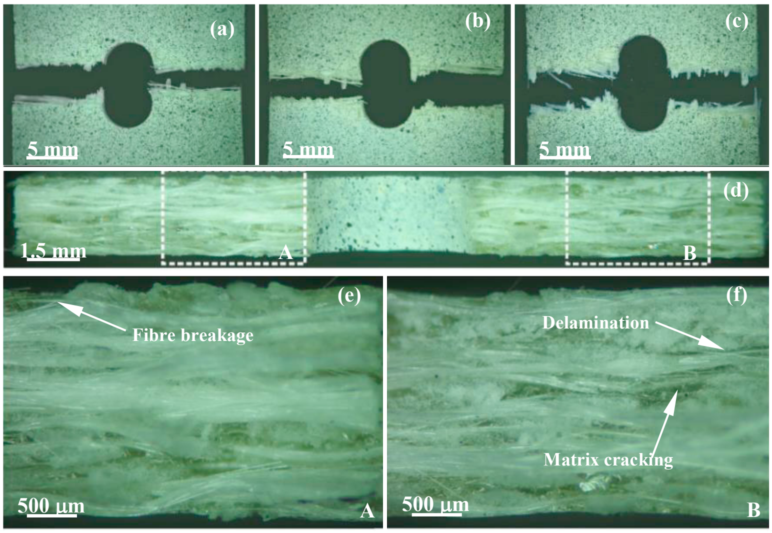

Figure 4. Fracture morphologies of the tested specimens were examined by optical microscopy. Front views: (a) 0 days of immersion; (b) 230 days of immersion; and (c) 910 days of immersion. Top views: (d) 230 days immersion; (e) magnification of region A; and (f) magnification of region B.

As shown in Figure 4, these mechanisms include matrix cracking, delamination, fibre breakage, and fibre-matrix debonding. The last one was the predominant failure mechanism found for all immersion times, which agrees with the conclusions reported in the literature, namely by Amaro et al. (2018). Regarding the effect of the immersion time on fracture morphologies, no relevant differences were observed relative to the damage mode. The unique difference, already noted above, is that the exposure time speeded up the damage propagation process. This outcome is in line with other studies focused on open-hole GFRP laminates considering hygrothermal effects, Branco et al. (2021) or Wang et al. (2022).

The characterization of the fatigue-fractured specimens was also conducted using scanning electron microscopy (SEM). Optical and scanning electron microscopy can help identify variations and effects due to the negative influence of ageing conditions on the fracture surfaces of samples, which can indicate the presence of specific damage mechanisms. SEM micrographs in Figure 5 illustrate the fractured surfaces of two samples: one unaged (Figure 5a) and the other exposed to seawater for 230 days (Figure 5b). Compared to the dry specimens (Figure 5a), the conditioned specimens (Figure 5b) exhibit greater fibre detachment from the matrix, indicating that seawater absorption affected the adhesion between the fibres and the matrix. Indeed Figure 5a displays robust adhesion between the fibres and the matrix, while Figure 5b demonstrates weakened adhesion between the fibre and the matrix.

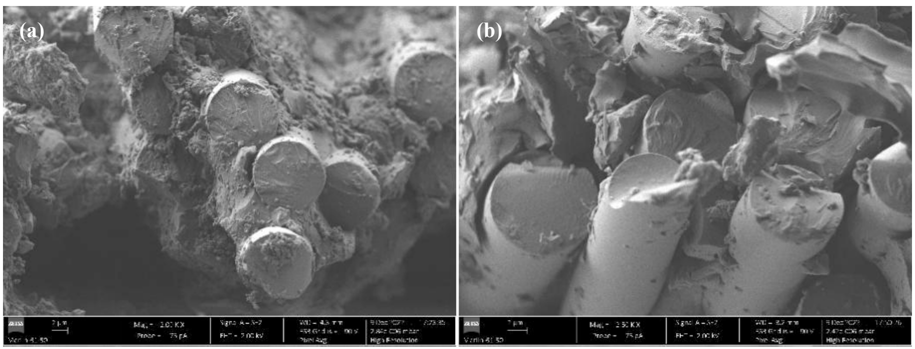

Figure 5. Representative SEM micrographs of fractured surfaces of glass/epoxy composite, a) Control sample; b) 230 days of immersion in natural seawater.

According to the open literature, water predominantly enters the composite through diffusion. Once it infiltrates the material, it causes matrix expansion, resulting in microcracks and/or micro-stresses within the composite, which can result in the debonding between the matrix and fibres, Hammami & Al-Ghuilani (2004) or Adams & Miller, (2016). When cracks propagate and tensile stress concentrations occur in the fibre-matrix interface, the matrix cannot effectively transfer force between fibres.

Additionally, it is well understood that the weakened bond between fibres and matrix leads to poor stress transfer, which greatly affects the fatigue performance of the laminate. Moreover, defects or cracks in the matrix also lower the composite's critical stress at failure, limiting its fatigue performance, Fiore et al. (2022). Accordingly, considering the outcomes of this investigation, it can be said that the fibre-matrix bonding properties play a critical role in the fatigue behaviour of glass fibres reinforced composite materials in marine environments.

4. Conclusions

This paper presents the study of the fatigue behaviour and damage mechanisms of glass fibre-reinforced polymers after long-term exposure to seawater. The first principal strain and stress fields around the geometric discontinuity measured via DIC were sensitive to the damage caused by fatigue loading. However, no relevant differences were identified relative to the effect of seawater on the damage progression patterns. Additionally, the seawater immersion had a detrimental effect on the fatigue performance of the tested glass fibre-reinforced polymer composite. Under uniaxial cyclic loading, the higher the immersion time, the lower the fatigue life expectancy at the same applied stress level. The fatigue life of the 230-day samples was about 66% of that of the control samples when exposed to the average stress of the tested range. Additionally, SEM images show that the exposure to seawater affected the adhesion between the fibers and the matrix, which was primarily responsible for the fatigue strength reduction of the tested composite material.

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