OFF-AXIS PROPERTIES OF WOVEN GFRP UNDER CONSTANT TENSILE LOAD IN HYDROTHERMAL ENVIRONMENT

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Abstract

The durability of plain woven glass fiber reinforced plastics (GFRP) laminate in the off-axis direction in hydrothermal environment is investigated in this paper. The durability discussed in this paper are as follows 1) the degradation of the mechanical properties after immersion into deionized water, and 2) delayed fracture under constant tensile load in deionized water. The mechanical properties of GFRP laminate in deionized water were smaller compared to that in air. Moreover, the mechanical properties decreased with immersion into deionized water. The strain and its growth rate of GFRP laminate under constant tensile load increased with immersion into deionized water and moreover delayed fracture occurred faster in deionized water than in air under equal applied stress. In addition, it was suggested from the fracture surface observations that these decreases of the durability occurred after the diffusion of deionized water throughout the thickness direction.

1 Introduction

Glass fiber reinforced plastics (GFRP) have superior corrosive resistance compared to metal materials and have various applications. In fact, GFRP operating in corrosive environment are designed with excessive safety factors due to the lack of long-term reliability data. Unfortunately, some accidents involving GFRP operating in corrosive environments have been reported [1]. Such accidents occur due to the strength degradation of GFRP, for example, stress corrosion cracking (SCC), which is generated by the interaction between mechanical factors and environmental agents. In order to assure the long-term reliability of GFRP in corrosive environment, it is an urgent task to clarify the durability and failure mechanism of GFRP so as to guarantee its wide spreading applications.

The majority of the researches dealing with the durability of GFRP focus on the degradation in the fiber direction, basically, its material properties are dominant to the fiber reinforcement. In contrast, there are few researches dealing with the degradation in the off-axis direction. The material properties of GFRP in the off-axis direction are dominated not only by the fiber reinforcement but also by the response of the matrix resin and adhesion of the fiber/matrix interface. Thus, investigation of the creep behavior and fracture mechanism of GFRP in the off-axis direction is also required to clarify the long-term reliability of GFRP in corrosive environment.

In this paper, two patterns of durability of the woven GFRP laminate was investigated in the off-axis direction in hydrothermal environment, 1) degradation of mechanical properties with immersion into deionized water, and 2) creep behavior in deionized water, both in ±45 degrees from the fiber direction and at 40°C. Based on the results of the static tensile test and constant tensile load test, the effect of the diffusion of deionized water on both patterns of durability will be discussed in this paper.

2 Experimental

2.1 Specimen

The specimens used in this study are plain woven GFRP laminates whose glass fiber is aligned toward ±45 degrees. The material properties of the constituents are described in Table 1. The GFRP laminates were fabricated using hot-press molding and the curing condition was as follows, pre-curing at 30°C for 3 hours and post-curing at 120°C for 2 hours which was determined by differential scanning calorimetry (DSC) analysis. 20 woven glass fiber clothes were laminated by turns to align the weft strand and warp strand in each direction equally to consider the variation of the number of the strands in the warp and weft directions. The average fiber volume fraction V_f of the laminates was kept at approximately 38%. The specimen geometry for the tensile test and the constant tensile load test was determined using finite element analysis, and is shown in Figure 1 [2]. The edges of each specimen for tensile tests were polished using emery paper in order to avoid edge effects.

TEX [g/m^2]	**Ply thickness [1/mm]**	**Density [strands/25mm]**	**Fiber diameter [μm]**	**Producer**
97	0.15	Warp 19, Weft 18	6	Nittobo Co., Ltd

(a) Glass fiber

Matrix	**Hardener**	**Accelerator**	**Producer**
Ripoxy R-802	Methyl ethyl ketone peroxide	Cobalt naphthenate	Showa Denko K. K.

(b) Vinylester resin

Table 1. Material properties of the GFRP constituents.

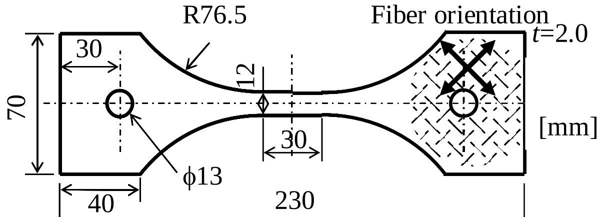


Figure 1. Specimen dimension and geometry for static and constant tensile load test.

2.2 Water absorption test

Swelling of GFRP and the degradation of GFRP constituents occurs when water diffuse into GFRP. This degradation in the GFRP constituents induces the transition of fracture mechanism, decreases the mechanical properties of GFRP and moreover degrades the long-term durability. From these points, water absorption tests of woven GFRP laminate and its matrix resin were conducted to investigate the internal water diffusion properties. The dimension of the coupon specimen used in the water absorption test is $140 \times 20 \times t2$ mm. The weight gain, $\Delta M(t)$, and swelling strain, $\varepsilon_{\mathrm{swell}}(t)$, of GFRP were evaluated by measuring the elongation of the coupon specimen toward the longitudinal direction and its weight after immersion into deionized water by the following equations,

$$\Delta M(t)=\frac{W(t)-W(0)}{W(0)}$$
$$\varepsilon_{\mathrm{swell}}(t)=\frac{L(t)-L(0)}{L(0)} \tag{1}$$

where $W(t)$ and $L(t)$ is the weight and length at time t, $W(0)$ and $L(0)$ is the weight and length before immersion, respectively.

2.3 Static tensile test

Static tensile test was conducted to evaluate the mechanical properties of woven GFRP laminate in the ±45 degrees off-axis direction and their environmental dependency, deionized water and air both at 40°C. The tensile load was introduced by inserting steel pins into the specimen holes and fixing them to the testing machine. The testing speed was 1.0mm/min. The temperature was controlled by using temperature controlled chamber and the test in deionized water was conducted by attaching a vinyl bag filled with deionized water to the specimen in order to immerse the gage length during the test. The strains in the longitudinal and transverse direction were measured during the test. The experimental condition of constant tensile load test, i.e. applied stress was determined from the results of static tensile test.

Besides, static tensile tests of GFRP laminate after immersion into deionized water were conducted to evaluate the decrease of mechanical properties with immersion time. The immersion time was 200hours, 500hours and 1000 hours.

2.4 Constant tensile load test

Constant tensile load test of woven GFRP laminate was conducted in the ±45 degrees off-axis direction in various environments, i.e. in air and in deionized water at 40°C. The test in deionized water was conducted by installing a vessel filled with deionized water and the temperature was controlled using a thermocouple and a ceramic heater. The creep strains in the longitudinal and transverse direction and the fracture time at various stress levels were measured. The applied stress was determined to be 15%~75% of its maximum stress (20MPa~100MPa) which is obtained from the result of the static tensile test.

3 Results and Discussions

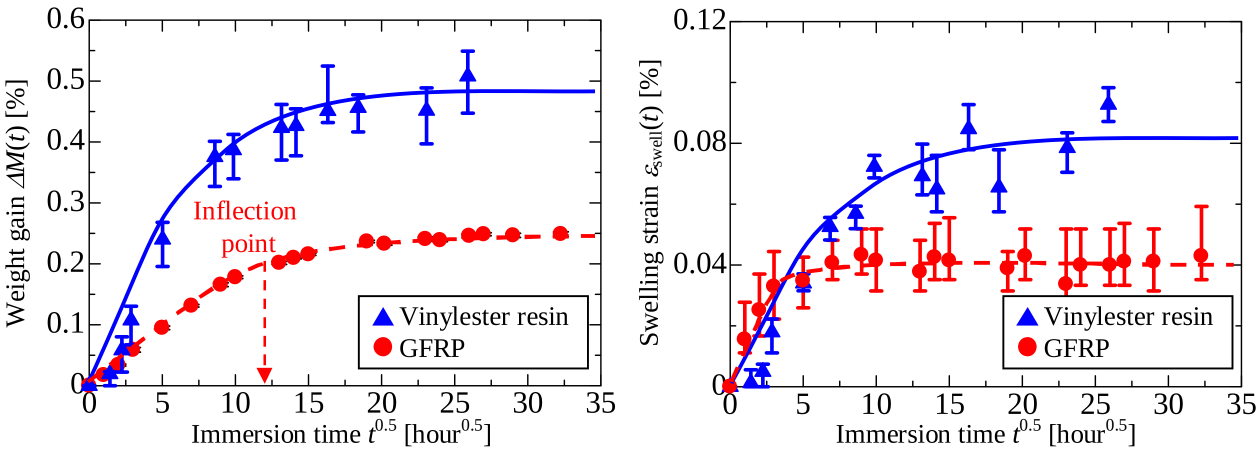
3.1 Water absorption properties

Weight gain and swelling strain of GFRP laminate after immersion into deionized water at 40°C are shown in Figure 2.

The weight gains of vinylester resin and woven GFRP both showed an inflection point at 150 hours and saturated toward certain amount. The swelling strain of vinylester resin also showed a similar behavior, in contrast, the swelling strain of woven GFRP showed an inflection point at 25 hours and showed saturation. Thus, it is suggested that the water absorption reaches saturation after 150 hours.

3.2 Mechanical properties of GFRP laminate and its degradation with immersion

The mechanical properties of GFRP laminate obtained from static tensile tests are shown in Table 2 and the stress-strain curve is shown in Figure 3 respectively. The results after immersion in deionized water are described in the legend as “Water (200 hour)”.



(a) Weight gain (b) Swelling strain

Figure 2. Water uptake properties of woven GFRP laminate and its matrix resin.

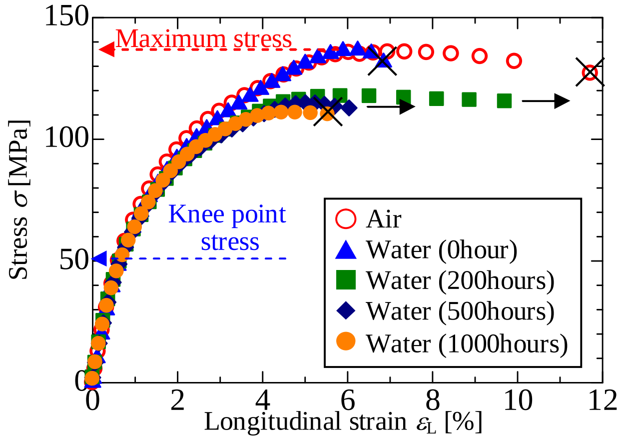


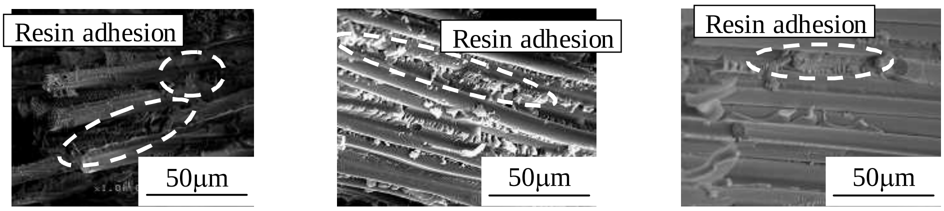
Figure 3. Stress-strain curves of GFRP laminates in air and water.

	Maximum stress σ_{max} **[MPa]**	**Failure strain** σ_b **[%]**	**Failure displacement** d_b **[mm]**	**Stiffness** E **[GPa]**	**Poisson's ratio** ν
Air	134	11.4	6.75	10.6	0.56
Water (0 hour)	130	6.94	6.29	10.1	0.54
Water (200 hours)	124	-	5.45	10.2	0.54
Water (500 hours)	120	-	5.95	9.60	0.53
Water (1000 hours)	118	8.35	5.62	10.0	0.53

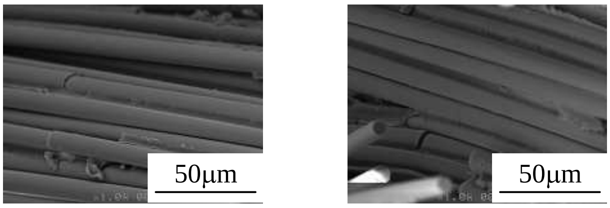
Table 2. Material properties of GFRP laminate in various environments and immersion times.

It is obvious from the results that the mechanical properties of GFRP laminate decrease with immersion and increasing immersion time. The failure strains of tests in deionized water after immersion for 200 hours and 500 hours could not be measured due to the damage accumulation in the vicinity of the strain gage resulting in the debonding of the gage. But the decrease of failure strain with water immersion can be expected from the decrease of failure displacement. The maximum stress, failure strain and failure displacement decreased drastically with immersion, in contrast, the stiffness and Poisson's ratio decreased slightly. It is reported that the stiffness of the glass fiber which dominate the stiffness and Poisson's ratio of GFRP laminate will not decrease with water immersion while the strength and rupture strain of glass fiber decrease intensely [3].

The fracture surfaces of GFRP laminate were observed using scanning electron microscope (SEM) and are shown in Figure 4.



(a) Air (b) Water (0 hour) (c) Water (200 hours)



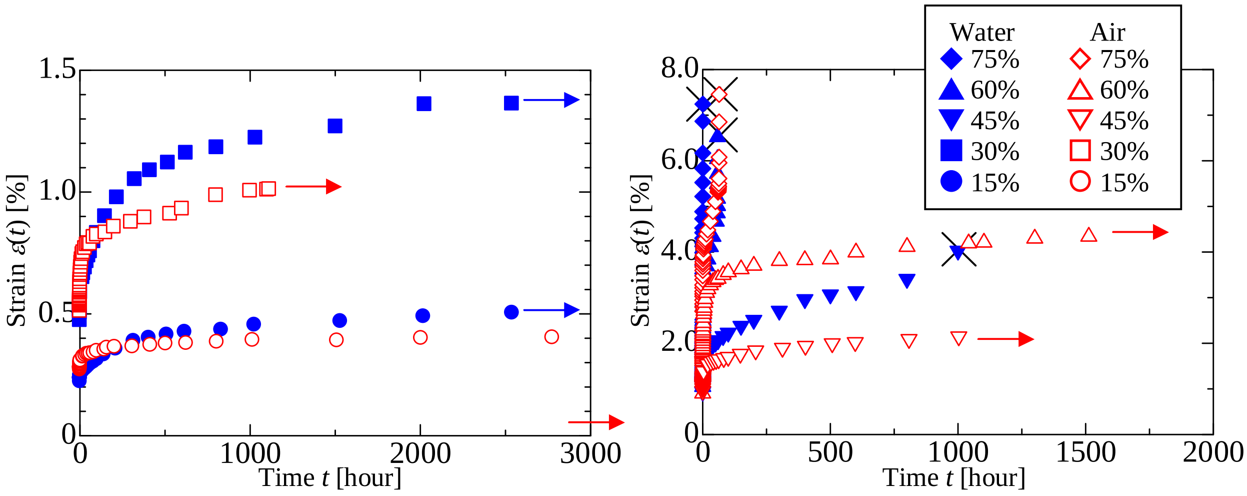
(d) Water (500 hours) (e) Water (1000 hours)

Figure 4. Fracture surfaces after static tensile test of GFRP laminates.

It is obvious from the figure that the resin adhesion on the fiber surface decreases with immersion into deionized water and with longer immersion time. Besides, the resin adhesion became similar after immersion time for 200 hours which correspond to the time required to the inflection point in water absorption test. This decrease of the resin adhesion is an evidence of the degradation in the adhesion of the fiber/matrix interface due to the hydrolysis of silane coupling agent which bonds the fiber reinforcement and matrix resin chemically [4].

3.4 Delayed fracture properties

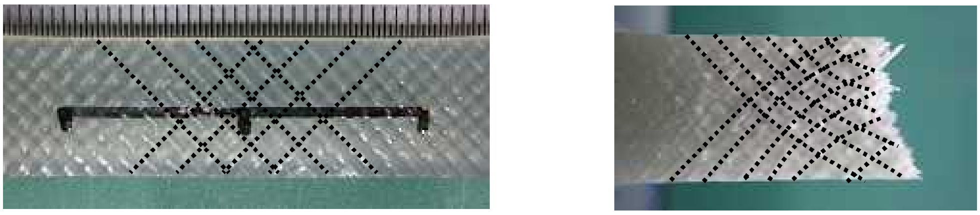
Creep strain of GFRP laminate obtained from constant tensile load test is shown in Figure 5. The legend in Figure 5 is described by the stress levels and the arrows in the figure represent that the fracture doesn't occur and strain keeps increasing.



(a) Lower applied stress (15% and 30%) (b) Higher applied stress (45%, 60% and 75%)

Figure 5. Strain curves of GFRP laminates in air and water obtained from constant tensile load test.

Strains in air at lower applied stress increase gradually, in contrast, strains in air at higher applied stress increase intensely. It is obvious that higher applied stresses exceed the knee point stress (inflection point at approximately 50MPa) in the stress-strain curve which occurs due to the internal damage accumulation resulting in nonlinear strain response. Strains in water are higher than those in air in general. This can be explained by the decrease of stiffness by water immersion within lower applied stress region, and the progress of damage accumulation by water immersion within higher applied stress region. In addition, exponential increase can be observed just before the fracture at higher applied stress region. The photograph of GFRP laminate after the test is shown in Figure 6 and the directions of the glass fibers are emphasized with dotted lines. It is obvious from the picture that the directions of the glass fibers are distorted after fracture which represents the large deformation during the test.



(a) Before test (b) After fracture at 75% in air

Figure 6. Photograph of GFRP laminate after constant tensile load test.

The fracture time obtained from constant tensile load test is shown in Figure 7. The plots which fracture didn't occur are shown in brackets and accompanied with arrows.

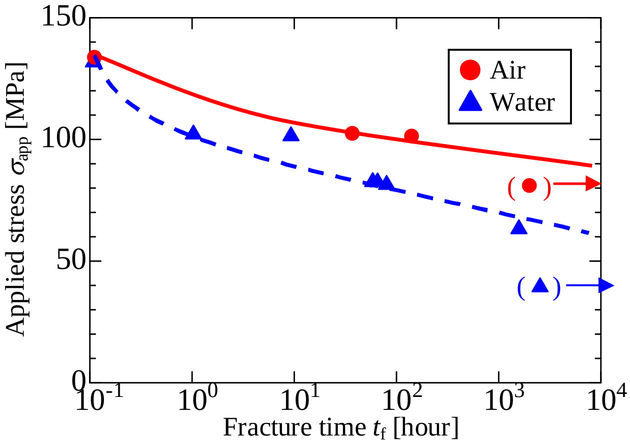
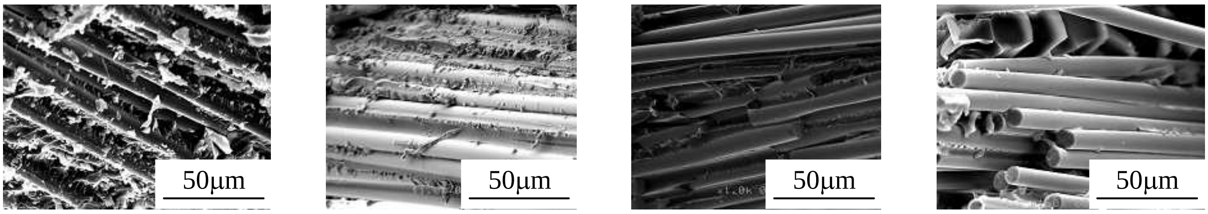


Figure 7. Relationship between applied stress and fracture time of GFRP laminates in air and water.

It is obvious from the figure that fracture time in deionized water is shorter than that in air. This is possibly due to the degradations of the GFRP constituents, glass fiber and fiber/matrix interfacial adhesion, as the vinylester resin possesses high corrosion resistance [5]. In order to clarify the fracture mechanism of GFRP laminate under constant tensile load, fracture surfaces were observed using SEM. Fracture surfaces are shown in Figure 8. The environment, applied stress level and fracture time t_f are listed in the captions.



(a) Air, 75%, t_f=142 hours (b) Water, 75%, t_f=1 hour (c) Water, 60%, t_f=80 hours (d) Water, 45%, t_f=1577 hours

Figure 8. Fracture surfaces after constant tensile load test of GFRP laminates.

It is depicted in the figure that the resin adhesion on the fiber surface is decreasing with the decrease in the applied stress. The decrease of the applied stress results in longer immersion time into deionized water and moreover weaker fiber/matrix interfacial adhesion.

4 Conclusions

The aim of this paper is to clarify the durability of plain woven GFRP laminate in the off-axis direction in hydrothermal environment. The durability discussed in this paper are as follows, 1) the degradation of the mechanical properties after immersion into deionized water, 2) the delayed fracture in deionized water. It was clarified that the mechanical properties of GFRP laminate decrease with immersion into deionized water and moreover saturate toward certain values after long-term immersion. In addition, it was also clarified that the degradation of the fiber/matrix interface affects the delayed fracture of GFRP under constant tensile load. From these results, it was concluded that the degradation of the fiber/matrix interfacial adhesion as well as the glass strength dominate the durability of the GFRP in the off-axis direction. Besides these degradation are due to water diffusion throughout the thickness direction.

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