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Paper

High Temperature Properties of Fiber Reinforced Composites under the Different Loading Conditions

Hu Weiguang*, Soo-Jeong Park, Yun-Hae Kim***†**

ABSTRACT: The mechanical properties of composites are significantly affected by external environment. It is essential to understand the degradation of material performance and judge the material's lifetime in advance. In the current research, changes in mechanical properties of glass fiber and unsaturated polyester composite materials (GFRP, Glass fiber reinforced plastic) were investigated under different bending stress and submerged in hot water at a temperature of 80°C. Loading time of 100 H (hours), 200 H, 400 H, 600 H, 800 H for testing under stresses equal to 0% (stress-free state), 30%, 50% and 70% of the ultimate strength was applied on the GFRP specimens. From the values of bending stress, obtained from three-point bending test, fracture energy, failure time, and life curve were analysed. Moreover, a normalized strength degradation model for this condition was also developed. It was observed that within 100 H, the decline rate of the bending strength was proportional to the pressure.

Key Words: GFRP, Three-point bending test, Fracture energy, Life curve

1. INTRODUCTION

Fiber-reinforced polymers (FRPs) are well-known composite materials that are light-weight yet strong and are produced by using high-strength fibers as a reinforcing agent with polymeric compounds [1,2]. FRPs have been widely used as structural materials related to the aquatic environment, such as fishing trawlers, ships, reservoirs, undersea pipes, mainly due to their excellent water resistance and corrosion resistance, high strength, high elastic modulus and light-weight [3,4]. However, the mechanical properties of FRPs have been found to be frequently affected by different external environmental factors, including temperature, humidity and ultraviolet radiation [5,6], leading to degradation in performance. Moreover, the by-products formed cause serious economic losses and sometimes even threatening to human life. So, it is imperative to study the changes in mechanical properties of FRPs under different external conditions.

Some studies have been carried out on the effects of the external factors, such as temperature, humidity and external pressure on the mechanical properties of FRPs. Lv Xiaojun, et al. investigated the mechanical properties of carbon fiber/epoxy resin composites at 30°C and 80°C, and observed that performance of the composites decreased at 80°C [7]. In another study, Sun Bo, and Li Yan showed that the mechanical properties of glass fiber reinforced epoxy matrix composites at different temperatures of water aging decreased significantly in the first eight weeks. The rate of decline was fast in the first four weeks, after which no decrease was observed in a year later [8]. A study by Mahmood M. Shokrieh and Mahdi Memar on stress corrosion cracking of basalt/epoxy composites under different bending loadings showed that degradation of mechanical properties was accelerated when loading was more than 50% of the ultimate strength [9].

In the present research, the GFRP, fabricated via vacuum-assisted resin transfer molding (VaRTM) method [10], was submerged in hot water at a temperature of 80°C [7] for 100 H (hours), 200 H, 400 H, 600 H, 800 H. The specimens were kept under various stresses- 0%, 30%, 50% and 70% of the material ultimate strength to study the decrease in bending stress and fracture energy with respect to external stress and time. Also, failure time and life curve were analyzed [9,11].

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*Department of Material Engineering, Chungnam National University, Daejeon, Republic of Korea
**Department of Material Engineering, Graduate School, Korea Maritime and Ocean University, Busan, Republic of Korea
***†Department of Mechanical Engineering, College of Engineering, Korea Maritime and Ocean University, Busan, Republic of Korea
(E-mail: yunheak@kmou.ac.kr)

2. EXPERIMENTAL WORK

2.1 Specimens Manufacturing

As shown in Fig. 1, the glass fibers (Plain, MSC Korea Ltd.) as a reinforcement were placed on the mold carefully. The unsaturated polyester (LSP-8020, Polynt Composites Korea Co., Ltd.) and hardener mixture were then passed through the glass fibers layered through a plastic tube from one side to the other side slowly under the action of vacuum. The proportion of resin and hardener were 100:1 and the GFRP were fabricated at room temperature.

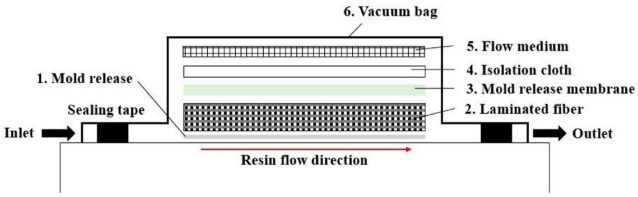


Fig. 1. VaRTM method technology

Specimens for further testing were cut according to ASTM D790-2010 standard. The span-to-depth ratio was equal to 32:1 and the detailed size parameters of the specimen are shown in Fig. 2.

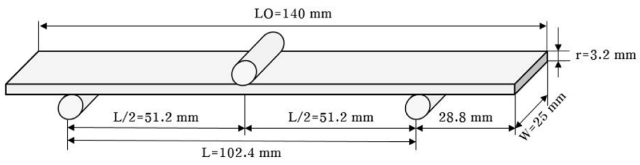


Fig. 2. Schematic of specimen

2.2 Application of Bending Stress

The bending strength of the material was estimated via three-point bending test from the corresponding displacement the specimen underwent. Following this method, the bending stress could be controlled by displacement [9]. In the above test, the pressure was kept constant, as shown in Fig. 3, and 0%, 30%, 50% and 70% of the ultimate material strength were applied on the specimen to obtain different displacements.

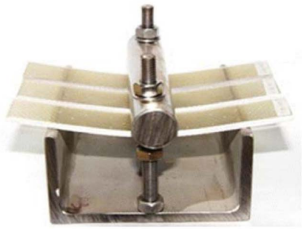


Fig. 3. Pressure fixture

2.3 Water Environment

The specimens, under applied constant pressure, were placed in a water tank at 80 ± 1°C for 100 H, 200 H, 400 H, 600 H, and 800 H.

2.4 Three-Point Bending Test

The samples were removed after the specified time, and the impact strength of external conditions i.e. pressure on the mechanical properties of the materials was analyzed via three-point bending test using a universal testing machine (UTM). The rate of crosshead motion was equal to 5.46 mm/min which was calculated according to ASTM D790-2010 standard.

3. ANALYSIS AND RESULTS

3.1 Bending Strength

Each dot in Fig. 4 shows the residual bending strength of the material under different pressure and at a different time.

The distribution of the dots in Fig. 4 shows that the residual bending strength of the material reduced with an increase in pressure and time. When the pressure was applied, the residual bending strength of the material decreased rapidly within the first 100 H, and the rate of decrease of the residual bending strength was directly proportional to the rate of pressure increase. However, between 100 H and 800 H, the rate of decrease of the residual bending strength was slow and was showed a tiny decline (all below 10%) with the change in pressure. The specimen degradation strength was fitted to an

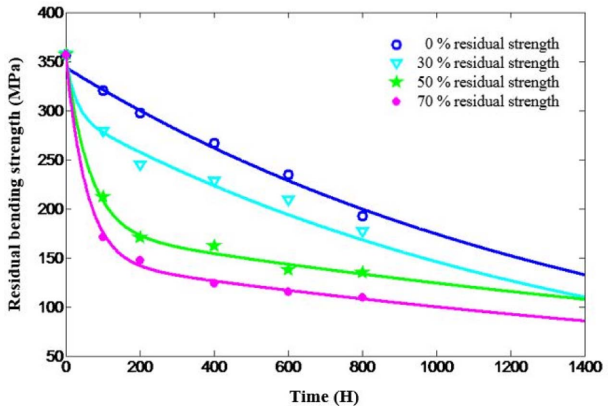


Fig. 4. Residual bending strength degradation under differed states of stress with time

Table 1. a, b, c and d constants and statistical values for residual bending strength degradation curves

Curve	a	b	c	d	R-Square
0%	12.66	-1.643	344.1	-0.0006808	0.9935
30%	59.6	-0.03735	297.1	-0.0007107	0.9783
50%	179.6	-0.01558	177.4	-0.00035757	0.9967
70%	210.3	-0.01788	147.3	-0.0003889	0.9982

exponential function $y = ae^{bx} + ce^{dx}$ [9]. Table 1 shows a, b, c, and d constants and statistical values for residual bending strength degradation curves which were solved by Matlab software. The strength degradation curves for four states of stress are shown in Fig. 4.

Furthermore, swelling of the unsaturated polyester upon immersing in water can cause swelling stress due to absorption of water by GFRP. Such swelling stress can counteract the effect of residual bending strength decrease in the material. Moreover, the secondary curing reaction of resin can occur in GFRP if it is not sufficiently cured at high temperature, which in turn can help in improving the mechanical properties of the material. However, a specimen can withstand shear stress under bending stress, when the stress reaches a certain magnitude larger than the fiber/matrix interfacial bond strength. It makes interfacial debonding and stratification easier. Lower transmission capacity moisture leads plasticization of the matrix macromolecules, which increases the distance between the molecular chains and can destroy intermolecular van der Waals force. After diffusion of water occurs within the resin, matrix, certain polar reactions occur resulting in hydrolysis of the substrate, or chain scission, which weakens the chemical bonds between molecules. Due to the factors mentioned above, the reduction of material mechanical properties was observed.

3.2 Fracture Energy

According to the theoretical crack model, fracture energy is the energy required to produce a unit area of crack (fully broken). The model assumes that no energy is consumed outside the cohesive force distribution area. It implies that specimen fracture energy is completely provided by the external force. If a specimen is statically fractured and the work applied to fracture the interface (W_F) is measured, the approximate interface fracture energy (G_F) can be computed as:

$$G_F = \frac{W_F}{A} = \frac{\int P d\delta}{A} \quad (1)$$

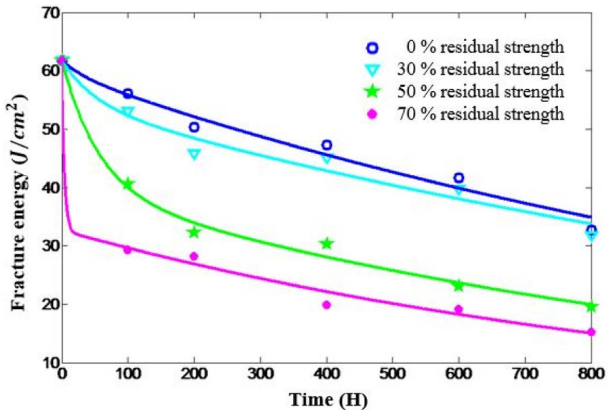


Fig. 5. Fracture energy degradation with time under different bending stress

Table 2. Constants and statistical values for fracture energy degradation curve

Curve	a	b	c	d	R-Square
0%	2.168	-0.02787	59.58	-0.000672	0.9745
30%	7.42	-0.01912	54.37	-0.0005961	0.9637
50%	22.23	-0.01781	39.55	-0.000859	0.9926
70%	29.11	-0.263	32.63	-0.0009715	0.9947

where A is the area of specimen fracture section, P is the external force, δ is the displacement [9]. The variation of fracture energy was found to be similar to bending stress, and the attenuation was also fitted with an exponential function form $y = ae^{bx} + ce^{dx}$. Each point represented the fracture energy under different bending stress at various times, and the fitting curves are shown in Fig. 5. All constants and statistical values were solved by Matlab software and shown in Table 2.

3.3 Extrapolation of Time to Failure (T_F)

Time to failure (T_F) is the time when the residual strength of samples reaches to the magnitude of applied stress. For example, at 30% stress state, T_F is the time when the magnitude of the residual strength of the sample is equal to 30% of the ultimate material strength. It is impossible to measure the T_F directly from displacement control test [9]. So, the samples were submerged in hot water at a temperature of 80°C for a specific time and then removed from the water. The residual bending strength of the sample was then measured via three-point bending test. Using cubic spline method and extrapolation of the data, time to failure under the different state of stress were calculated [9]. The results are summarized in Table 3.

Table 3. T_F values in different stress states

The stress state	0	30%	50%	70%
Residual strength (MPa)	356.725	107.018	178.363	249.708
Time to failure (h)	-	1223.3	163.5	40.8

3.4 Life Curve (S-T)

An S-T curve was derived from the T_F points for the samples under bending stress equal to 30%, 50% and 70% of the material ultimate strength states and static strength of the material (Fig. 6). The S-T curve was fitted to an exponential function $y = ae^{bx} + ce^{dx}$, using the T_F values from Table 3. Fig. 6 also shows strength degradation curves for three states of stress. Table 4 shows the values of a, b, c, and d constants and the statistical values for the S-T curves [9].

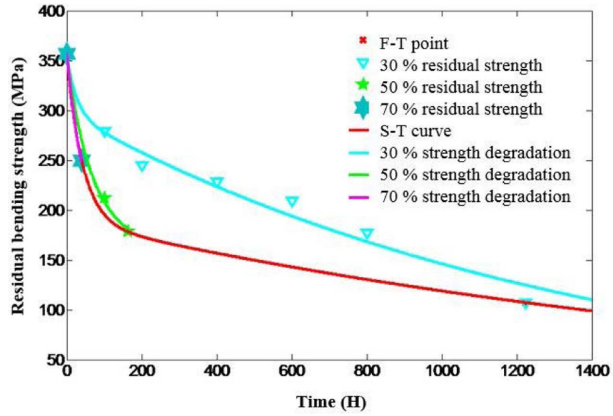


Fig. 6. Strength degradation for different stress states and S-T curve

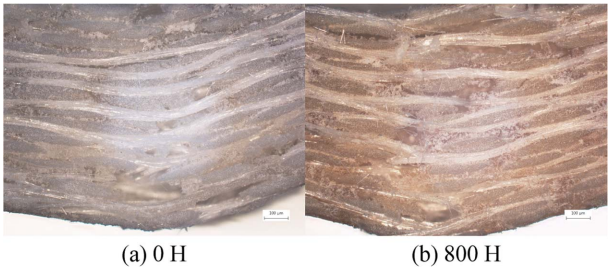
Table 4. a, b, c and d constants and statistical values for S-T curves

Curve	a	b	c	d	R-Square
S-T	168.3	-0.02339	188.4	-0.0004623	1

3.5 Optical Microscope and SEM Observation

Fig. 7 shows the cross-section of the specimen after the three-point bending test before and after submerging for 0 H and 800 H respectively at 80°C of the hot water. It can be observed that specimen tensile area was more seriously damaged than the pressure area. There were obvious cracks between the layers, and a large crack developed vertically between the layers. More fracture cracks were observed for specimen immersed in water for 800 H because the mechanical properties of the material reduced largely under bending stress in hot water. The fiber and the resin separated easily due to the water molecules, and the transferred stress became weak. With the increase in time, the fiber and resin bonding became more and weaker, and layers formed.

Fig. 8 from a top (0 H) to bottom (800 H) sequentially shows that the specimen fractured after the three-point bending test without submerging in hot water (0 H) and immersed for 100 H and 800 H at 80°C of the hot water. A subtle difference between the content of the fiber and the resin can be observed at the broken cross-section. More resin can be seen at the surface of specimen 0 H than 100 H, and 800 H. Additionally, the gaps between the fiber were also larger in 100 H and 800 H, indicating a decrease in the mechanical properties. Brittleness was seen for 0 H, and damage mechanism mainly involved matrix cracking. After treating the specimen at high temperature in water, the fracture of the specimens showed more fibers and less adhesive resin. The failure mechanism of these specimens involved mainly matrix cracking and interface debonding.



(a) 0 H (b) 800 H

Fig. 7. Cross sections of specimen observed by optical microscope

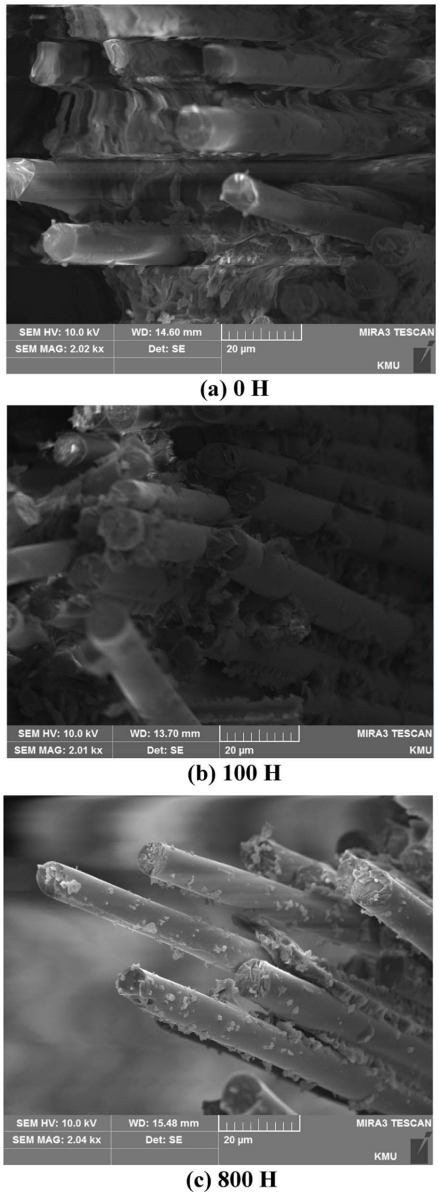


Fig. 8. Cross sections of specimen observed by SEM

4. CONCLUSIONS

To conclude, the residual bending strength of the GFRP

composite materials under bending strength in high-temperature water environment showed a deterioration with increase in pressure. The bending strength degradation followed an exponential decay. Within 100 H, the bending strength decline rate was proportional to the rate of pressure increase.

The fracture energy reduction was also similar to the residual bending strength reduction, and the degree of attenuation followed an exponential decay.

By calculating material failure time under different pressures, an S-T life curve was constructed. The damage mechanism mainly involved matrix cracking before water treatment, whereas it changed to matrix cracking and interface debonding after placing the specimens in the high-temperature water environment.

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