

INFLUENCE OF HYDROTHERMAL ENVIRONMENT ON MECHANICAL BEHAVIOR OF FIBER REINFORCED POLYMERS: CHARACTERIZATION AND MODELING

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1 Introduction

Due to their desirable specific strength and specific stiffness properties, carbon fiber reinforced polymer matrix composites (CFRP) has been used in different industrial sectors. However, polymer resin can absorb water from the surrounding environment followed by diffusion of water into all of composite. The presence of water would result in the plasticization and hydrolysis of polymer matrix, and weakening the fiber-matrix interface [1-2]. Additionally, the difference of the amount of water-sorption between fiber and matrix would lead to different volumetric expansions, which causes localized stress and strain field in the composite [3]. It has been reported that hydrothermal environment influences the mechanical behavior of CFRPs greatly, especially the properties dominated by the matrix or the interface [2, 4].

The intent of this research was to better understand the aging of CFRPs immersed in water and the degradation of mechanical properties, and to predict their long term behavior. Water-sorption is experimentally determined by gravimetric methods. Fickian diffusion model and finite element analysis were employed to describe the water-sorption. In addition, the comparison of compressive strength between dry specimens and water-immersed specimens is performed in this article. A finite element model is also employed to simulate the mechanical behavior after immersion.

2 Materials and methods

The material used in this study was T700/9916 carbon fiber-reinforced epoxy laminate. The fiber volume fraction was around 65%. The dimensions of specimens are given in Table 1.

Type A specimens were prepared for open-hole compression tests and there is a hole of 6mm diameter in its center. The stacking sequence specimens is [+45/0/-45/90]_{4S}.

Prior to exposing to hydrothermal environment, type A specimens were preconditioned by drying at 80°C for 164 hours. The immersion tests were conducted at 70°C with temperature-controlled water bath for 344 hours. After immersion, open-hole compression tests were carried out on the wet specimens immediately. Compression tests were also conducted on the specimens that had not been hydrothermally exposed.

Type B specimens were used for the witness of relative weight gain, and immersion test was conducted at the same condition. During the testing, type B specimens were periodically weighed with an electronic balance (precision 0.01mg). The amount of absorbed water in specimens was calculated as equation (1).

$$M_i = \frac{W_i - W_b}{W_b} \times 100\% \quad (1)$$

Where: M_i is relative weight gain, %; W_i is current specimen mass, g; W_b is oven-dry specimen mass, g. Finite element analysis was carried out using the finite element software ABAQUS. The mass diffusion analysis and static stress analysis were employed to model transient moisture diffusion and compression test respectively.

3 Result

3.1 Water-sorption tests result

Both experimental and theoretical water-sorption curves versus the square root of time are plotted in

the Fig. 1. The solid line is the theoretical Fickian diffusion curve obtained by calculating the equation (2) proposed by Shen and Springer [5]. The experimental data shows a similar trend to the solid curve, which suggests the water-sorption behaviour of this material followed Fickian diffusion. The theoretical result exhibits a lower rate than the experimental data. This is because the thickness of plates in the equation (2) is small enough to neglect edge effects and only the faces perpendicular to z direction are concerned. However, the thickness of specimens in this study can't neglect and water can diffuse into the specimens from all the faces of specimens, which leads to greater experimental results.

$$G = \frac{m - m_i}{m_m - m_i} = 1 - \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{\exp\left[-(2n+1)^2 \pi^2 \left(\frac{D_z t}{h^2}\right)\right]}{(2n+1)^2} \quad (2)$$

Where: m_b is the initial weight of the moisture in the material, g ; m_m is the weight of moisture in the material when the material is fully saturated, g ; D_z is the diffusivity of the material in the direction normal to the surface, mm^2/h ; h is the thickness of specimens, mm ; t is time, h .

3.2 Open-hole compression tests result

The results of compressive tests are given in Fig. 4. After immersed in hot water for 344 hours, considerable reduction in the strength has been measured. With a relative weight gain of 0.718%, the average strength decreased about 6% and the dispersion degree of compressive strength aggravated. Same failure mode which was shear crippling damage can be observed in both dry specimens and immersed specimens.

3.3 Water diffusion modelling

In the mass diffusion analysis of ABAQUS, the governing equations are an extension of Fick's equations [6]:

$$J = -D \cdot \left(s \frac{\partial \phi}{\partial z} + \phi \frac{\partial s}{\partial z} \right) \quad (3)$$

Where D is the diffusivity, s is the solubility of the diffusing material in the base material, ϕ is the "normalized concentration", $\phi = c/s$, where c is the mass concentration of the diffusing material, J is the flux of concentration of the diffusing phase.

Considering each laminate of the specimen as orthotropic material, the values of diffusivity and solubility were calculated by the combination of experimental results and the method of interpolation to provide the appropriate solution for transient moisture diffusion. After computing and simulating repeatedly, the material parameters were estimated as $D_{11} = 0.0147 mm^2/h$, $D_{22} = D_{33} = 0.0038 mm^2/h$, $s = 1.02$, where D_{11} is the diffusivity in the direction parallel to the fibers, and D_{22} and D_{33} are the diffusivities in the directions normal to the fibers[5].

Because water diffuses into the specimen from all the faces, a solid element model within the piles to model the sequence of laminate was employed. The maximum moisture content was specified as the boundary condition on the faces contacting the water environment. The entire specimen had zero moisture content at the beginning of mass diffusion procedure. Fig. 2 shows that the simulated result provides a good agreement with the experimental data. The water diffusion model with the same diffusivity and solubility is also conducted on the open-hole compressive specimens. And the water content distribution at different local regions at $t = 344h$ is illustrated in Fig. 3. Non-uniform water distribution can be observed and the specimen was not saturated. The surface of specimen and the edge of hole have higher water concentration.

3.4 Open-hole compression test modelling

The simulation of open-hole compression test was carried out after mass diffusion analysis.

It has been reported that the properties of the composites are not dependent on the duration of exposure but mainly on the water content [2]. The influence of hydrothermal environment on mechanical properties can be considered as the decrease of rigidity due to water uptake. It is difficult to introduce the water distribution directly into the static stress analysis model. In addition, temperature and water concentration have the same degree of freedom in ABAQUS. Thereby, the water distribution was introduced into the mechanical analysis model as the temperature initial condition and a sequentially coupled thermal-mechanical analysis was carried out. In this way, hydrothermal effects can be simplified as the influence of temperature in the analysis.

The user subroutine UMAT was employed to predict the compressive strength and the failure patterns of

fiber and matrix within the fiber-reinforced epoxy layer which is described using the model proposed by Linde [7]. The relation of variations of mechanical properties as a function of water content, which was obtained from equilibrium conditioning water-sorption tests and mechanical tests, was also implemented in user subroutine UMAT.

Because the diffusion didn't reach the equilibrium, the water distribution within the specimen was non-uniform and each element in the model has different water concentration. By determining the overall characteristics from the local properties in each element, it is possible to predict the mechanical behaviour during aging. The decrease of element rigidity due to the water-sorption can be simply expressed as follows [8]:

$$\tilde{C} = \tilde{C}^0 - \tilde{C}^H \cdot C_e \quad (4)$$

Where, \tilde{C} is rigidity of immersed specimens; \tilde{C}^0 is rigidity of dry specimens; \tilde{C}^H is decrease of rigidity due to hydrothermal effect, identified from experiments; C_e is water concentration (%).

Table 2 shows the comparison of the maximum load between experimental results and simulation results. Similar reduction can be observed. Fig. 5 and Fig. 6 show the failure patterns of fiber and matrix within the fiber-reinforced epoxy layer separately. SDV is a solution dependent state variable which is used to describe the failure pattern. Damage occurs when SDV reached 1. It can be seen that the fiber damage only occurs in the 45°, -45° and 90° fiber reinforced epoxy layers, and propagates orthogonally the loading direction. Fig. 6 shows the matrix damage occurs in each layer and the damage patterns relate to the fiber orientation.

4 Conclusions

Based on the results obtained, the following general conclusions can be made concerning the diffusion behaviour and mechanical behaviour of T700/9916 CFRP composite.

The T700/9916 laminates exhibited more complex water absorption behaviour than the Fickian diffusion model proposed by Shen and Springer [5]. Finite element model was employed to simulate the water diffusion process under the exposure condition investigated and good agreement between the

simulated results and the experimental results can be observed.

The water sorption implied a clear drop of compressive property. With a relative weight gain of 0.718%, the average strength decreased about 5% after 344 hours immersion. Static stress analysis which takes into account hydrothermal influence has been proposed. It is possible to predict hydrothermal-mechanical degradation at all times during water absorption during which the water concentration profile is non-uniform within the material.

Table 1 The dimensions of specimens

	Length/ mm	Width/ mm	Thickness/ mm
Type A	300	36	5
Type B	40	12	7

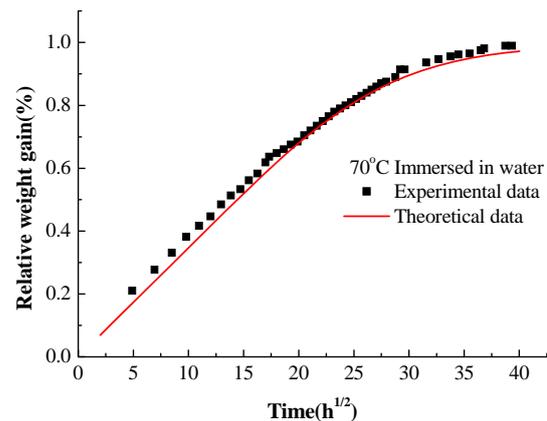


Fig. 1. Comparison of water-sorption curves versus the square root of time between experimental data and theoretical data.

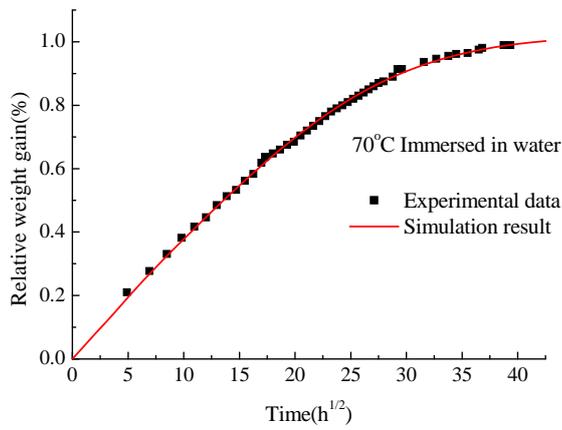


Fig. 2. Comparison of water-sorption curves versus the square root of time between experimental data and simulated result.

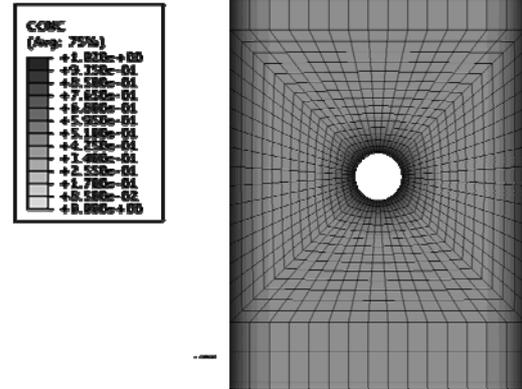


Fig. 3. The water content distribution within specimen at different local regions

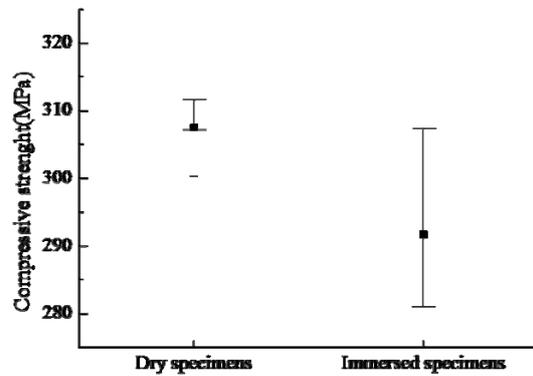
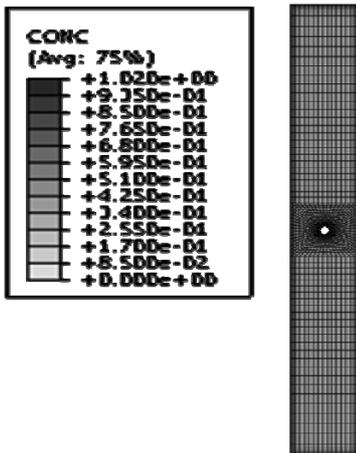


Fig. 4. Comparison of compressive strength between dry specimens and immersed specimens

Table 2 Comparison of the maximum load between experimental results and simulation results

Load/kN	Experimental results	Simulation results
Dry specimens	57.37	55.96
Immersed specimens	53.97	52.04

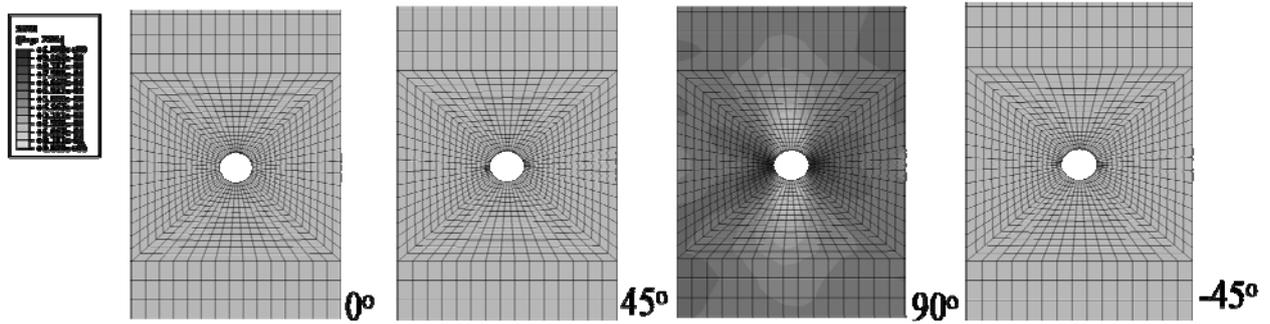


Fig. 5. Fiber damage pattern of the open-hole compression test model after hydrothermal exposure

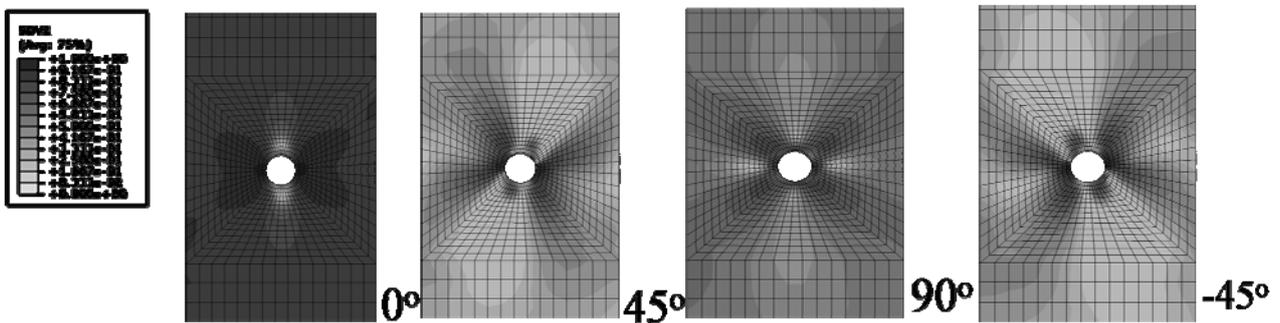


Fig. 6. Matrix damage pattern of the open-hole compression test model after hydrothermal exposure

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