Effect of moisture absorption on dimensional stability in carbon/epoxy composites

[Yoshihiko Arao[a]], Jun Koyanagi[b], Hiroshi Hatta[b], Yuichiro Aoki[b], Hiroyuki Kawada[c]

[a]Graduate School of Waseda University, [b]Japan Aerospace Exploration Agency, [c]Department of Mechanical Engineering, University of Waseda

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Abstract

In order to quantify the dimensional stability in CFRPs at humidity environment, the water diffusion considering an anisotropy and moisture expansion behavior are investigated. Water diffusivity coefficients were determined by measuring the specimen weight during the moisture absorption test. The diffusivity coefficients of three main axial directions are obtained from three shapes specimen's result and solving simultaneous equations. A 3-dimensional locator using laser-displacement measurement was employed to measure micro deformation of the CFRP specimens caused by moisture absorption.

The curvature of surface was observed due to the distribution of moisture contents. The coupling analysis which includes mechanical deformation and thermal diffusion was conducted. The numerical results are in good agreement with the test results.

1. Introduction

Application field of carbon fiber reinforced polymer matrix composites (CFRPs) is still limited due to their dimensional instability regard less of the facts, that of high T_g polymeric materials has been developed, and that carbon fiber has excellent low coefficient of liner expansion [1]. Especially for antenna, mirror and so on, micro-dimensional stability is required. Moisture expansion is one of the potential factors dominating time-dependent deformation of CFRPs.

Moisture diffusion behavior for FRP is investigated by Springer et al. [2]. In this research, moisture content was quantified by measuring weight of FRPs, and the moisture concentration in the material was determined by means of Fick's law. The diffusion coefficients were important parameter in the diffusion behavior. Loots et al. confirmed the temperature dependent for diffusion coefficient, and brought out that moisture diffusion phenomenon was composed of Arrhenius equation [3]. Moisture diffusion into polymer is so slow that it takes long time until the material gets to saturated condition. So FRPs are in the unsaturated condition and the distribution of moisture content generates stress. The stress due to moisture gradient was studied well with the aid of numerical analysis, but it comes short of experimental demonstration [4]～[6]. Meanwhile the strain due to moisture uptake is organized with CME (Coefficient of Moisture Expansion). Collings et al. examined CME by use of asymmetric laminates. They acquired CME by measuring the change of curvatures caused by moisture absorption. For this technique the distribution of moisture content wasn't considered and the expansion for fiber direction was disregarded [7]. For this reason the accurate CME wasn't obtained.

The aim of this study is twofold. First, To determine the moisture diffusion coefficient taking into consideration the anisotropy of material. In this work three direction's coefficients were obtained to get three results of the change of moisture content with the square root of time, and solving these three equations. Second, the dimensional change due to moisture uptake was measured using a 3-dimensional locator with a laser-displacement measurement. The dimensional change for the material under unsaturated condition was investigated. In the simulation, and couple analysis which includes mechanical analysis and thermal analysis was conducted in consideration of the anisotropy of moisture diffusion. The accurate CME was determined by fitting the numerical data into experimental data, and the numerical results which depend on the time were compared with the experimental results of arbitrary time.

2. Experimental procedure

2.1 Moisture absorption test

In order to predict the moisture content of a

material the maximum moisture content M_m and the diffusivity D must be known. In this study of moisture absorption behavior, all specimens would be placed for a long specified time in a humidity-controlled chamber at 80° and 90% relative humidity (RH). The specimen's size is as shown in Fig.1. One is the thin plate (50×50×1[mm]) which is easy to saturate, and the other is bar with square cross section (90×10×10[mm]) which is used for measuring dimensional change. Unidirectional and Quasi-isotropic laminates were fabricated from the high elastic prepreg tape (Hye-34M-65D, Mitubishi Chemical), and woven fabric were made from the prepreg tape (T300/#2500, TORAY). Specimens were dried at 100˚ for 72 hours using vacuum chamber. The size and weight of the specimens were measured as a function of time immediately after removing the water on the specimen surface.
The percent moisture content M defined as

$$M = \frac{W - W_d}{W_d} \times 100 \qquad (1)$$

Where W is the weight of moist material and W_d is the weight of dry material.

2.2 Measuring dimensional change

Specimens were placed on the 3-dimensional locator after leaving them at 20˚ for an hour. The laser finder which has 0.1μm accuracy was attached to a 3-dimensional locator with x-y stage which control displacement in 1μm accuracy. The schematic of measuring is shown as in Fig.2. The displacements of straight side direction and thickness direction were measured. CME (Coefficient of Moisture Expansion) is defined as follow equation.

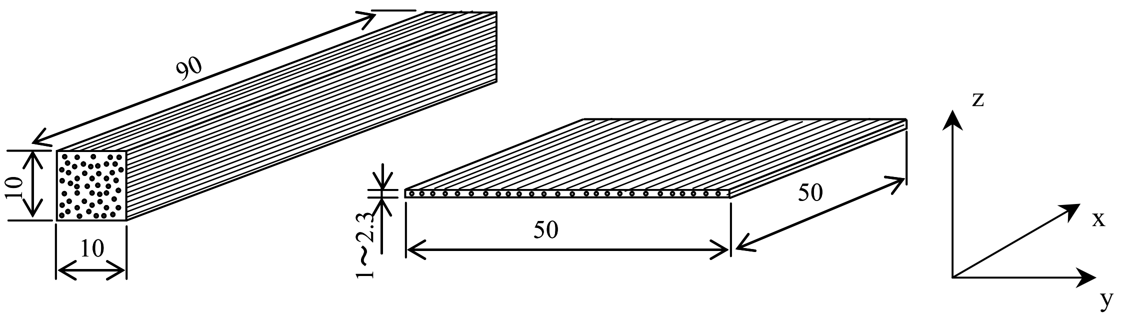
$$\beta = \frac{\varepsilon^M}{M} \qquad (2)$$

ε^M is the strain induced by moisture absorption. To get the CME for fiber direction is difficult to obtain experimentally, so Schapery's equation involving thermal expansion was applied to get it. In this equation, thermal expansion is replaced by moisture expansion, and it is assumed that fibers don't expand by moisture absorption.

$$\beta_T = \beta_m V_m (1 + \nu_m) \qquad (3)$$

$$\beta_L = \frac{E_m V_m \beta_m}{E_m V_m + E_f V_f} \qquad (4)$$

Where β_m is CME (Coefficient of Moisture expansion) of matrix, β_L is that of CFRP along fiber direction, and β_T is transverse direction against fiber.



(a) Bar (UD0°) (b) Thin plate (UD)

Fig. 1. Specimen geometry and direction

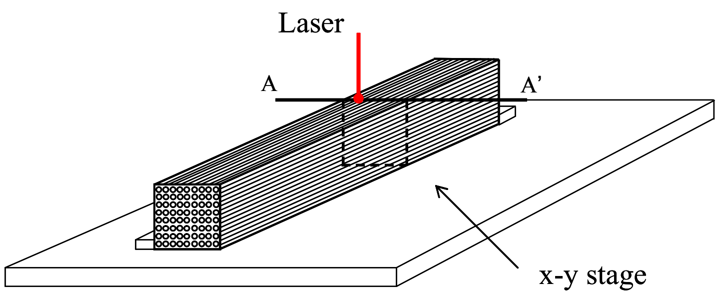


Fig. 2. Measuring the displacement of thickness direction and straight side direction

3. Diffusion coefficient in considering of anisotropy

3.1 Fick's second law of 3-dimension diffusion

For a relatively large and thin composite plate, the water concentration in the thickness z-direction may be governed by the one-dimensional diffusion equation of Fick's second law, viz

$$\frac{\partial c(z,t)}{\partial t} = D_z \frac{\partial^2 c(z,t)}{\partial^2 t} \quad (0 \le z \le L, t > 0) \quad (5)$$

$$c = c_i \quad (0 < z < L, t \le 0) \quad (6a)$$

$$c = c_\infty \quad (z = 0, L, t > 0) \quad (6b)$$

Where t is time; L, thickness of specimen; z,distance measured from the bottom surface; subscript 'i' and '∞' represent 'initial' and 'full saturated' states, respectively; and D_z, moisture diffusion coefficient in the z-direction. The approximation solution of equation (5) and (6) is given

$$\frac{M}{M_m} = \frac{4}{L\sqrt{\pi}}\sqrt{D_z t} \quad (7)$$

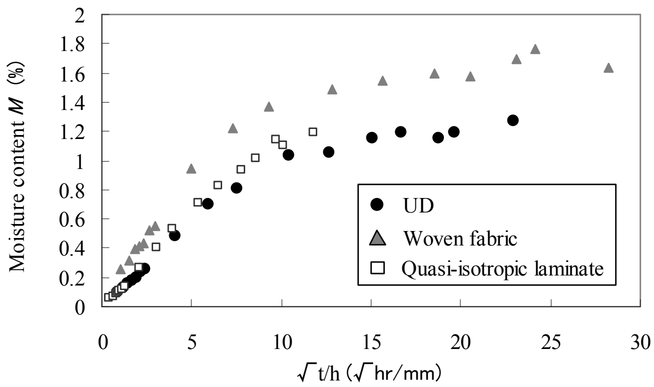
M_m is the maximum moisture content which can be attained the given environmental conditions. From above equation, it is noticed that moisture diffusion coefficient is in proportion as square root of time. In the early stages of the process the interaction of the different sides may be neglected and equation (7) can be applied to each side independently. Thus extended form of equation (7) described as follow

$$M = 4M_m\left(\frac{1}{l}\sqrt{D_x} + \frac{1}{w}\sqrt{D_y} + \frac{1}{h}\sqrt{D_z}\right)\sqrt{\frac{t}{\pi}} \quad (8)$$

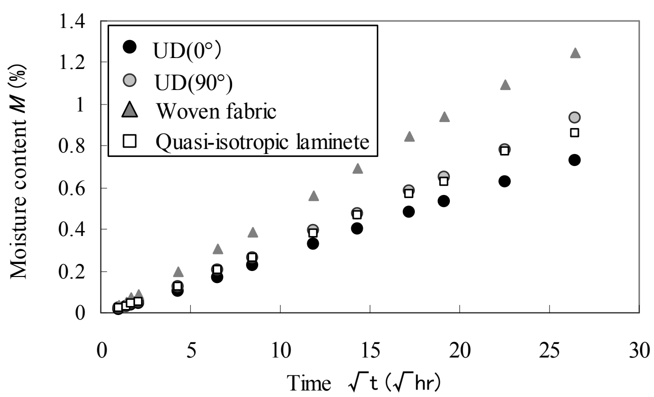
In this work it is considered that the independent diffusion coefficient is three in a narrow sense, so diffusion coefficients of three axial directions are determined for unidirectional laminates. In the case of woven fabric and Quasi-isotropic laminate, it is considered that the diffusion coefficients of in-plain direction are the same value, so two directions (in-plain and thickness direction) were investigated.

3.2 Result of moisture absorption test

Fig. 3 shows the percent weight of the composite specimens as a function of the square root of time. It is observed that the moisture absorption is exhibiting a linear relation in the initial stages of absorption. Fig. 3(a) shows the results of thin plate, it is observed



(a) Moisture uptake for thin plates



(b) Moisture uptake for bars

Fig. 3. Moisture content with the square root of time for CFRP composites

Table 1. Comparison of diffusivities

Material	Diffusivities D_x mm^2/h	Diffusiviteis D_y mm^2/h	Diffusiviteis D_z mm^2/h
UD	0.00555	0.00244	0.00131
Qusasi-isotropic Laminate	0.00459	0.00459	0.00133
Woven fabric	0.00482	0.00482	0.00227

that the specimens were saturated after 400 hours. On the other hand, specimens of bar weren't saturated for 1 month, because they were thick.

The diffusion coefficient can be determined by Equation (8) from the initial slopes of the linear relation and solving simultaneous equation. The results are shown in table 1. D_x and D_y are the diffusion coefficient of in-plain direction. The diffusivity of thickness direction is described as D_z. The definition of *x*, *y*, *z* direction is shown in Fig. 1. From Table 1, it is apparent that D_x is 2～4 times larger than D_y and D_z. It is due to the diffusion behavior that the fibers imbedded in the matrix were assumed to act as a barrier to the penetrating water molecules [8]. In the though-thickness direction, the laminate thickness or lay-up sequence does not affect the diffusion rate.

4. Determination of the Coefficient of Moisture expansion

4.1 Distribution of dimensional change

Fig.4 shows the distribution of thickness directions displacement. The curve lines shown in Fig.4 represent FEM result which was explained later. Horizontal axis is the normalized distance of specimen's width, and vertical axis is dimensional change from dry condition. It is clear that all specimens' edges swell bigger than the other position. The water diffusion into CFRP is very slow, so the moisture concentration near the surface is much higher than that at the middle of specimen. The distribution of moisture content generates stress and deterioration of surface accuracy. In regard to the woven fabric, the surface accuracy is gradually getting worse along the woven structure. It is easy to

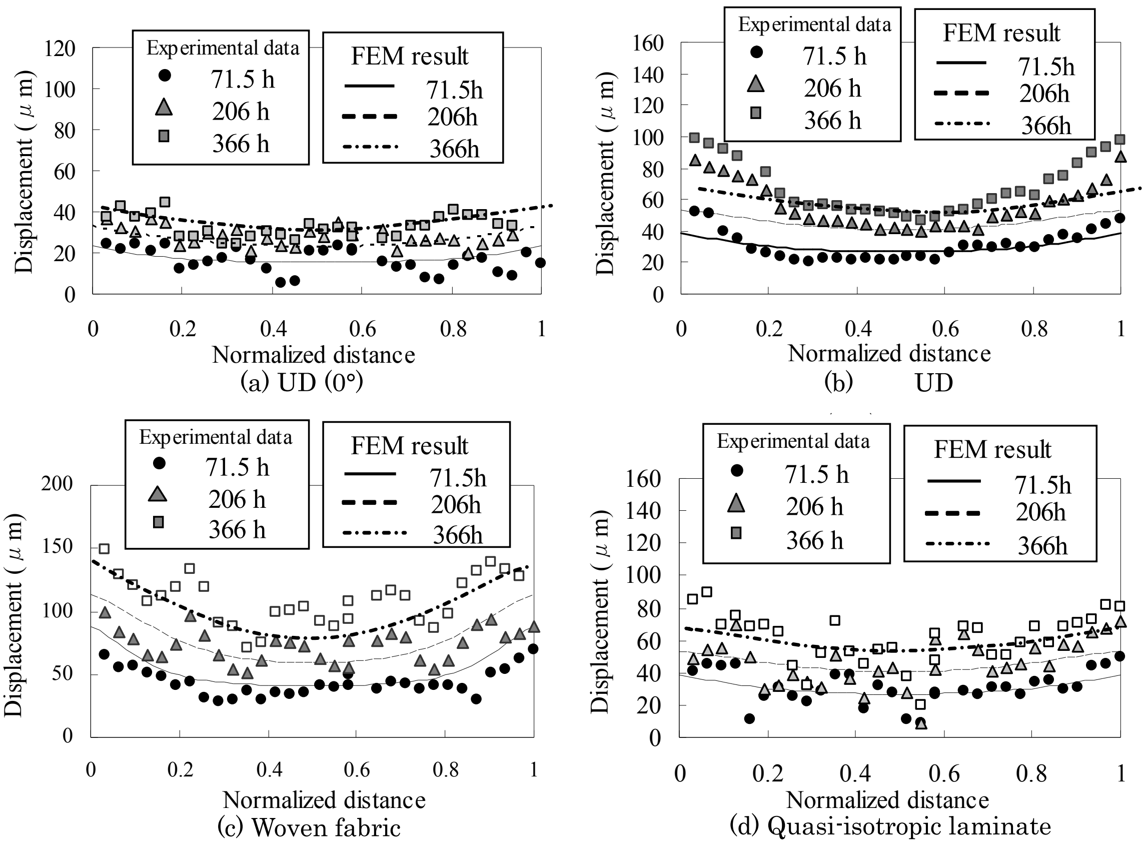


Fig. 4. Distribution of thickness direction's displacement

understand that if we measure CME at the edge using like a strain gage, CME is estimated too large. Therefore it is important to consider surface curvature when we get exact CME in these specimens.

4.2 Determination of CME by means of FEM

To investigate the dimensional change under unsaturated condition, finite element analysis was conducted. Finite element model is shown in Fig. 5. To avoid rigid body move and spin, four nodes are fixed in z direction and y direction as shown in Fig. 5. Boundary condition of surrounding area gave M_m which means maximum moisture content. M_m was obtained from the results of Fig. 3, more specifically M_m for unidirectional is 1.3% and M_m for woven fabric is 1.7%. Material properties are listed in Table 2, and moisture coefficient is the value of Table 1. CME listed in Table 3 is determined to fit the experimental date. In this analysis, quadrate eat conduction element and quadrate plain strain element were applied. Coupled analysis which includes thermal and mechanical analysis was conducted.

Fig. 4(a)-(d) present comparisons between the experimental and numerical data of dimensional change. Observing the numerical data for all specimens, we can see that calculated distribution of dimensional change is in good agreement with the experimental result except for unidirectional laminate which the direction of fiber is perpendicular to straight side of specimen. This indicates that the deformation caused by moisture absorption can be predicted under constant condition when the maximum moisture content, the diffusion coefficient for each direction, and CME are known and coupled analysis was conducted. The discrepancy shown in Fig. 4(b) is ascribed to the neglecting of shear stress relaxation which arises at fiber/matrix interface at the edge of specimen.

CMEs for each direction are shown in Table 3. CMEs for fiber direction are difficult to obtain, so they were calculated using equation (4). It was

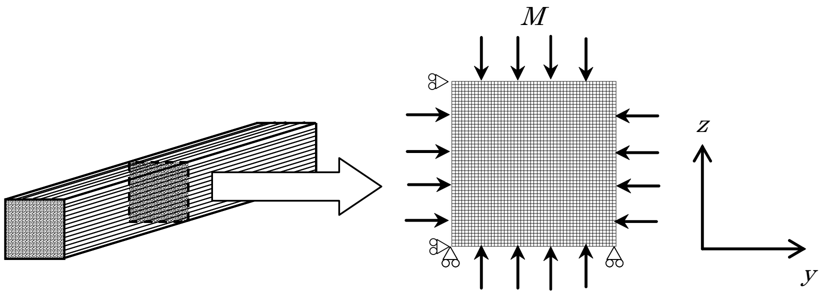


Fig. 5. FEA model

Table 2. Material properties

	UD(0°)	UD(90°)	Woven fabric	Quasi-isotoropic laminate
E_y [GPa]	5	350	54	130
E_z [GPa]	5	5	5	5
ν_{yz}	0.3	0.3	0.3	0.3
G_{yz} [GPa]	4	4	4	4

Table 3. Coefficient of moisture expansion

Material	direction	CME [/%]
Unideirectional laminate	$\beta_{0°}$	0.32×10^{-4}
	$\beta_{90°}$	33×10^{-4}
	$\beta_{thickness}$	67×10^{-4}
Woven	$\beta_{0°}$	2.1×10^{-4}
	$\beta_{thickness}$	110×10^{-4}

observed that the CME for thickness direction is 2 times higher than that of 90˚ direction, despite of both directions are perpendicular to fiber direction. It is considered that this discrepancy is due to the distribution of carbon fibers.

5. Conclusion

1) The diffusion coefficients for three main axes were determined to get the percent weight of the composite specimens as a function of the square root of time for three shapes of specimens.
2) The micro-deformation caused by the gradient of moisture content can be predicted under constant condition when the maximum moisture content, the diffusion coefficient for each direction, and CME are known and coupled analysis was conducted.
3) CME for thickness direction is 2 times higher than that of 90˚ direction, despite of both direction is perpendicular to fiber direction.

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