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Effect of moisture absorption on damping and dynamic stiffness of carbon fiber/epoxy composites [†]

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Abstract

In this paper, the damping and dynamic stiffness of UHN125C carbon fiber/epoxy composite beam was experimentally measured. The effect of fiber orientation angle and stacking sequences on damping, resonance frequency, and dynamic stiffness was discussed with a focus on the effect of moisture absorption. Dried specimens were immersed in distilled water for a certain period to absorb water for 8, 16, and 24 d, respectively, and the moisture content absorbed in the specimen was measured. Furthermore, using the impact hammer technique, the measurements of dynamic responses were conducted on a cantilever beam specimen with one end clamped by bolts and metal plates. The damping properties in terms of loss factor were approximated by half-power bandwidth technique. The dynamic stiffness was evaluated using resonance frequency as a function of moisture content. The damping increased with the increase of moisture content; however, the dynamic stiffness reduced with the reduction of resonance frequency. The results of the dynamic stiffness were aided by measuring the dynamic strain using DBU-120A strain-indicating software. The increment in the dynamic strain strengthened the results obtained for dynamic stiffness.

Keywords**:** Damping; Dynamic stiffness; Staking sequence; Moisture content; Fiber orientation

1. Introduction

Carbon/graphite fibers are widely used reinforcing materials with high strength and high modulus in the fabrication of high-performance polymeric composite structures [1]. Carbon fiber is made up of extremely thin fibers about 0.0002-0.0004 in (0.005-0.010 mm) in diameter and is composed mostly of carbon atoms bonded together in microscopic crystals that are more or less aligned parallel to a long axis. The crystal alignment makes the fiber incredibly strong for its size. Carbon fiber can be combined with epoxy and wound or molded to form composite materials such as carbon fiber reinforced plastic (also referred to as carbon fiber) to provide high strength to weight ratio material. The need to develop and use lightweight structural components in the design of aircraft, automotive, and various sporting goods has brought about increasing applications of the composite material. Reliable performance of the advanced, high-strength material in critical applications depends on the assurance that each part placed in service satisfies the conditions selected for the design. Thus, it is of paramount importance to ensure the quality of materials used and the integrity of the product during the various stages of manufacturing until the final product is achieved.

Damping is an important parameter of structural design in which vibration control and dynamic loading are critical. Various studies have been reported on the damping properties of fiber-reinforced composites [2-9], proposing that damping properties can be im-

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proved by optimizing the fiber orientation angle and stacking sequence [10-11]. Damping is also a significant factor in the fatigue life and impact resistance of structures. Aside from the direct relation of damping to the vibration characteristics of the material, supreme consideration should also be given to selecting material with the desired strength. Different environmental actions such as frequency, amplitude of stresses, humidity, and temperature significantly affect the performance of the advanced composites during service [12-14]. These factors can limit the application of composites by reducing the mechanical properties over a period of time. It is very important to understand the response of polymeric composite material in different conditions. More than the conventional materials, the strength, stiffness, damping, and eventually the life of composite materials are affected by the presence of moisture and temperature.

This paper reports an experimental study of the damping and dynamic stiffness of UHN125C carbon fiber/epoxy composite with different fiber orientation angles and stacking sequences. There is considerable amount of moisture absorption by carbon/epoxy composite at 80^0C, and its damping and dynamic stiffness changes with the moisture content. Thus, it is necessary to analyze the response of the composites under a hygrothermal environment.

2. Theoretical analysis

2.1 Damping

The damping properties were determined by half-power bandwidth technique in terms of loss factor. The more damping is present the larger the separation will be between the two consecutive frequencies associated to the half power point used herewith as a measure of damping.

In Fig. 1, *FR* is the resonance frequency representing the maximum amplitude of vibration; *FL* is the frequency below the resonance frequency; and *FH* is the frequency above the resonance corresponding to half power points. The loss factor η can be obtained using these frequencies [15].

$$\eta = \frac{FH - FL}{\sqrt{3}FR} \qquad \because \eta = 2\xi \tag{1}$$

Another quantity called "Quality factor" denoted by Q is known as the internal friction of a material. The bandwidth of a resonant peak is determined by the internal friction and the natural frequency of the oscillating system. Q can be obtained from the damping ratio ξ as given in Eq. (2):

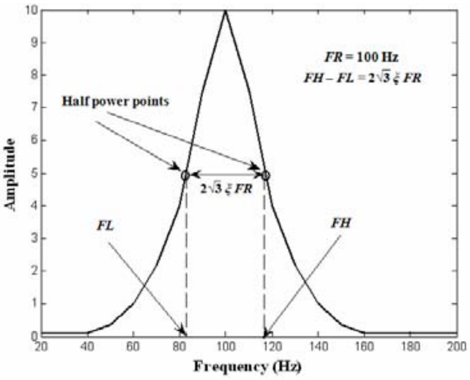

Fig. 1. FFT plot of response of a system.

$$Q^{-1} = 2\xi = \frac{FH - FL}{\sqrt{3}FR} \quad . \tag{2}$$

The relations between loss factor η, quality factor Q, and damping ratio ξ can be summarized as

$$\eta = Q^{-1} = 2\xi \tag{3}$$

2.2 Dynamic stiffness

The dynamic stiffness or dynamic storage modulus is evaluated based on the resonant frequency [4, 16], which is the estimated stiffness value for strength comparison of the different specimens of composite material given in Eq. (4).

$$E' = (38.24)\left(\frac{\rho L^4}{t^2}\right)\omega_n{}^2 , \tag{4}$$

where E' is the dynamic storage modulus; ρ is the density; L is the length; t is the thickness; and ω_n is the natural frequency. The dynamic stiffness is aided by calculating the dynamic strain value at a fixed end using dynamic strain gauges and the DBU-120A strain-indicating software.

3. Specimen preparation

3.1 Processing of laminates

Six laminates of different stacking sequences were produced using a unidirectional carbon/epoxy prepreg

Table 1. Specimen layup sequence.

Specimen number	Specimen Layup sequence
1	$[0_{12}]$
2	$[\pm 45]_{3s}$
3	$[90_{12}]$
4	$[0_2/\pm 45/90_2]_S$
5	$[\pm 45/90_2/0_2]_S$
6	$[90_2/0_2/\pm 45]_S$
7	Al

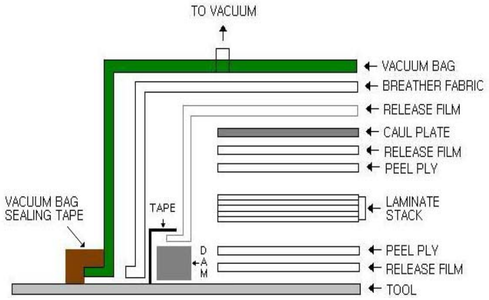

Fig. 2. Vacuum bagging process for graphite/epoxy composites.

tape of 0.113 mm thickness. They were manufactured using high-strength carbon fiber with UHN125C grade, 39.32 GPa tensile modulus, 4.61 GPa tensile strength, $1.82\text{x}10^{-3}$ g/mm^3 fiber density, and $1.2\text{x}10^{-3}$ g/mm^3 resin density. Three different angles of 0, 45, and 90 unidirectional prepreg were selected for the fabrication of the specimens presented in Table 1. For specimens No. 1, 2, and 3, simple unidirectional specimens of 0, 45, and 90 degree angles were prepared. For the cases of 4, 5, and 6, the combination was intended to investigate the effect of position (outermost or innermost) change of a particular layer.

Before putting the prepreg layup into the autoclave for curing, a vacuum bagging process for the graphite epoxy laminates was required (Fig. 2). Once the vacuum was achieved, the laminates were simultaneously cured in autoclave at 125^0C, under a pressure of 0.49 Mpa according to the curing cycle (Fig. 3). Initially, a rectangular plate was fabricated with a width and length of 150 mm and 280 mm, respectively. It was later cut using a low-vibration wheel cutter for carbon fiber reinforced plastic (CFRP) to obtain the beams with the desired dimensions. The composite laminates were composed of 12 plies resulting in a nominal thickness of 1.4 mm. The width and length of the specimen were 30 mm and 225 mm, respectively.

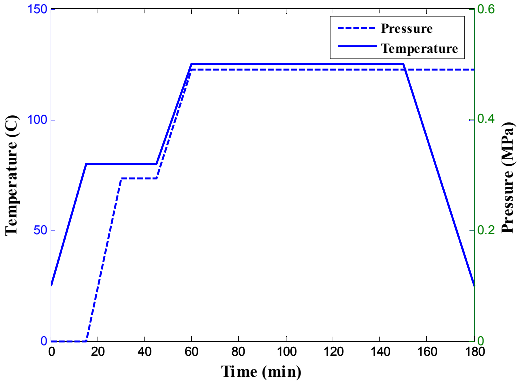

Fig. 3. Curing cycle.

3.2 Hygrothermal effect

To investigate the hot-wet environmental effect, the specimens were exposed to a combination of temperature and moisture for a hygrothermal effect using a refrigerating bath circulator (CW-20G) following the steps below:

(1) Dry the specimens in the oven at 50°C to remove all moisture.
(2) Immerse the specimens in distilled water at 80°C for 8, 16 and 24 d for different moisture content calculated using Eq. (5).
(3) Dry the samples for a short period before taking the data.

$$M\,\% = \frac{W_m - W_d}{W_d}\cdot 100 \qquad (5)$$

where M% is the moisture content (%) absorbed in the specimen, and W_m , W_d are the weights of the wet and dry specimens, respectively.

4. Experimental setup

The schematic experimental setup and block diagram are shown in Fig. 4 and Fig. 5. The impulse technique involved the application of impact force at one point on the structure and the measurement of the response at another. The impact force was calculated through the force transducer attached at the tip of the hammer, while the response of the signal was measured through the gap sensor using two channels, FFT analyzer and DASY LAB software. The input force and corresponding response signal were digitally processed by the analyzer to form the frequency

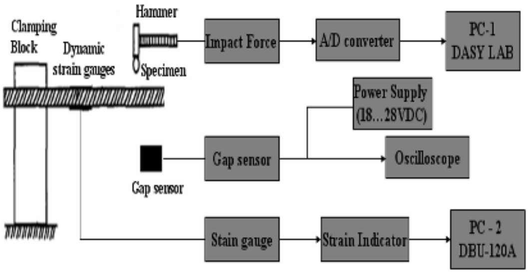

Fig. 4. Block diagram of the complete experimental setup.

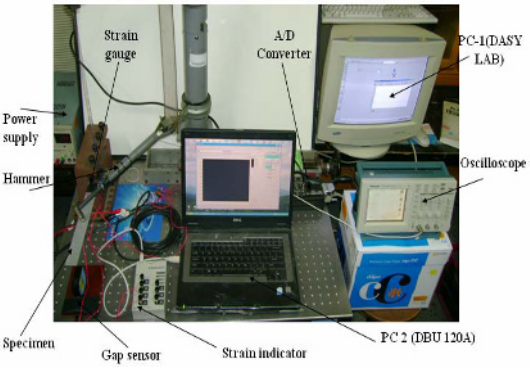

Fig. 5. Complete experimental setup.

response function. Damping, stiffness, and natural frequency were then extracted from the output of the analyzer using the approaches mentioned in Section 2. With regard to the dynamic stress, two dynamic strain gauges were attached at the fixed end of the beam. The dynamic strain response was measured using the setup of the strain indicator and DBU – 120A software. A half bridge with two strain gages was used to compensate for the temperature error in the strain measurement.

5. Results and discussion

Eq. (4) indicates that the resonant frequency is proportional to the square root of the dynamic storage modulus of the beam. For a unidirectional carbon/epoxy laminated structure, the dynamic storage modulus decreases by increasing the fiber off-axis angle to as much as the resonance frequency. This is proven in the experimental results presented in Table 2.

Data in Table 2 indicate that the decay rate and damping coefficient decrease with the increasing fiber off-axis angle. Although the fiber off-axis angle was up to 90 degrees, the loss factor was still more than that of the aluminum (Al 2024-T3) beam, with the resonance frequency being higher. This was due to the laminated structure of the carbon/epoxy composites; epoxy resin plays the role of a damping layer. As for the aluminum beam, the only way to have energy loss was through internal friction. To obtain a good damping effect, high loss factor and dynamic storage modulus are required. Hence, we obtained a decreasing damping property by increasing the fiber off-axis angle.

Table 2. Experimental results of the damping properties of the fiber composite cantilever beam (Dry specimens).

Specimen types	FR (Hz)	Loss factor	Decay Rate	Dynamic Storage Modulus E'(Gpa)	Max. dynamic strain (με)
$[0_{12}]$	48.82	0.0597	0.1876	216.54	750
$[\pm 45]_{3s}$	32.71	0.0303	0.0952	96.92	1120
$[90_{12}]$	11.95	0.0130	0.0408	13.03	1995
$[0_2/\pm 45/[90_2]_S$	33.00	0.0272	0.0855	98.01	950
$[\pm 45/90_2/0_2]_S$	23.43	0.0219	0.0688	48.92	1410
$[90_2/0_2/\pm 45]_S$	18.55	0.0181	0.0569	31.31	1640
Al	31.25	0.0124	0.0390	-	-

For the laminated structure of the different stacking sequences (Table 2), the resonance frequency depends on the position of the 0 degree layer. For $[0_2/\pm 45/90_2]_S$, we had the highest dynamic storage modulus compared with $[90_2/0_2/\pm 45]_S$ and $[\pm 45/90_2/0_2]_S$. It was found that the dynamic storage modulus decreased with the changing the position of the 0 degree layer. The closer to the outer layer it is, the more the resonance frequency and the damping.

Fig. 6 shows the weight increase as a function of the exposed time of the different intervals for carbon fiber/epoxy composites specimens exposed at 80°C. Like any other polymer, epoxies absorb moisture when exposed to humid environments. Moisture absorption takes place through a diffusion process governed by Fick's law, in which water molecules are transported from areas with higher concentration to areas with lower moisture concentration [12, 17].

It was found that the moisture absorption was not uniform so that the unidirectional composites led to higher absorption, as was the case for $[0_{12}]$ specimen (5.3%) and $[90_{12}]$ specimen (4.9%) compared with $[\pm 45]_{3s}$ specimen (4.5%), which was a cross-ply composite. Moreover, the other specimen also had a lower percentage of weight increase due to different lamina directions; the maximum was absorbed in $[90_2/0_2/\pm 45]_{S,}$ compared with $[0_2/\pm 45/90_2]_S$ and $[\pm 45/90_2/0_2]_S$.

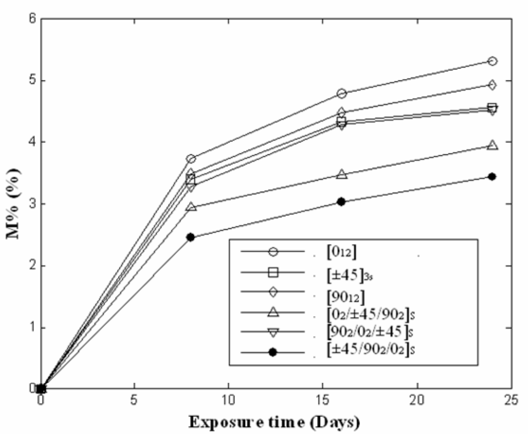

Fig. 6. Weight increase in terms of moisture content for the six specimens.

Fig. 7 shows experimental results for the variation in loss factor with increasing moisture content. The addition of moisture significantly affected the material damping. Initially, there was a rapid increase in loss factor with moisture content for an exposure time of 8 d and slowly afterwards with the further increase in moisture content. Fig. 8 gives a clear idea of the percentage of damping increase with the percentage of moisture content. Maximum increment was in $[0_{12}]$ laminate, which was about 40%, caused by the maximum percentage of moisture absorption, and the lowest was $[\pm45/90_2/0_2]_S$ (33%). The amount of increment went well in accordance with the percentage of moisture content. The larger the moisture content is, the higher the percentage increment in damping: this is a principle true for all other specimens. Thus, we conclude that when epoxy becomes exposed to moisture, it exhibits plasticization and swelling, which in turn affects the inter-phase reaction between the fiber and the epoxy. Plasticization significantly affects energy dissipation because the damping and deformation properties are very sensitive to the stiffness of the outer layers. Moreover, the moisture that penetrates the free area between the fiber and epoxy increases friction loss. The same holds true with energy dissipation in terms of damping.

The dynamic storage modulus (E') was not affected by moisture as much as the damping (Fig. 9). The dynamic storage modulus E' decreased in moisture content with the decrease in resonant frequency. On the other hand, the density increased with moisture content, reducing overall change. Furthermore, moisture can cause plasticization and swelling, softening

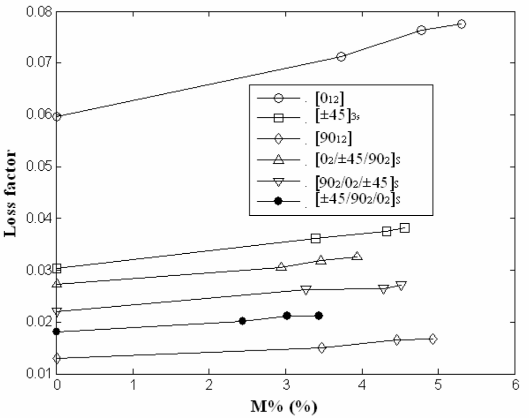

Fig. 7. Variation in loss factor for the six specimens with moisture content.

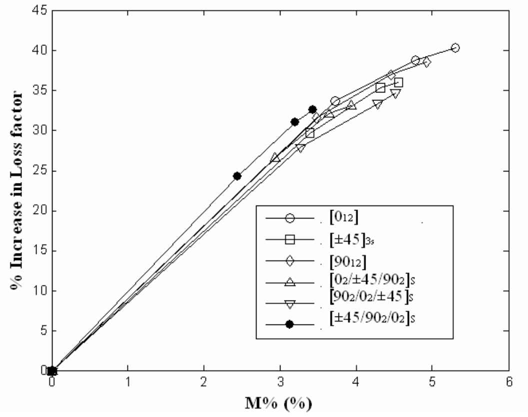

Fig. 8. Percentage of the damping increase as influenced by moisture.

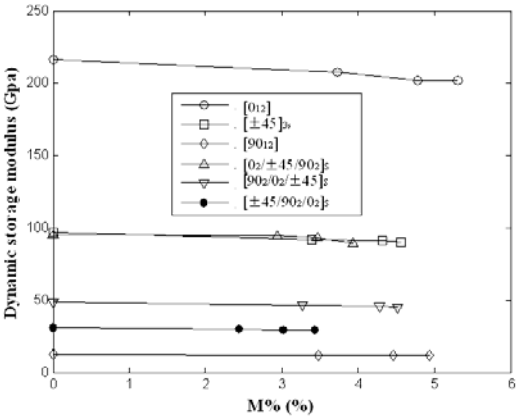

Fig. 9. Variation in *E'* for the six specimens with moisture content.

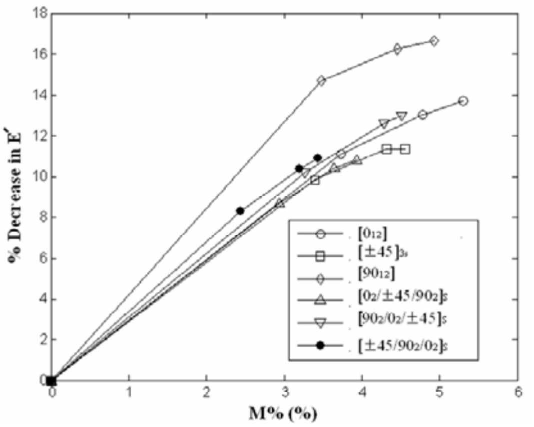

Fig. 10. Percentage of E' decrease as influenced by moisture absorption.

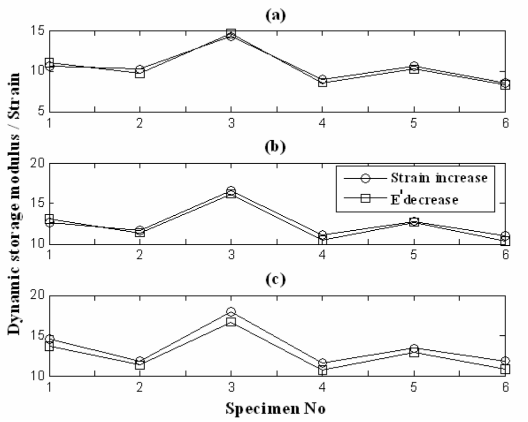

Fig. 11. Variation of dynamic strain and E' with 8 d(a), 16 d (b) , 24 d (c) of water exposure.

the epoxy matrix without affecting the moisture on carbon fiber, as mentioned earlier. E' is a longitudinal modulus that highly depends on the strength of the fiber. Therefore, there were almost three times less changes in E' compared with damping. However, the case was different for the two specimens $[90_{12}]$ and $[90_2/0_2/\pm45]_S$ (Fig. 10). It was observed that the decrease in E' was almost twice for these specimens.

To investigate this influence, the dynamic strain was measured along with moisture content. The results shown in Fig. 11 indicate that the strains developed in both these specimens were relatively higher than those in the other four cases. Thus, the laminates with 90 degree outer layers were highly affected by moisture. Strain development highly depends on E'. The percentage increase in strain quite agreed with the percentage decrease in E'. Moreover, higher pecks at $[90_{12}]$ and $[90_2/0_2/\pm45]_S$ specimens were noted. This effect was reduced by reducing the fiber off-axis angle of the outer layer (See Table 1 for the corresponding layup sequence against their specimen number.)

6. Conclusion

The following conclusions are obtained by analyzing the hygrothermal effect on fiber-reinforced composites:

(1) For dry specimen resonant frequency, loss factor and dynamic storage modulus (E') increases with the fiber off-axis angle.

(2) For the laminated structure of different stacking sequences, the properties depend on the position of the 0 degree layer. The closer it is to the outer layer, the more the resonance frequency as well as the damping.

(3) Unidirectional composites absorb more water than cross-ply laminates.

(4) Loss factor reaches a maximum of 40% depending on the moisture content.

(5) Resonance frequency and E' decrease with the moisture content, but the change is much smaller (1/3) compared with the loss factor.

(6) $[90_{12}]$ and $[90_2/0_2/\pm45]_S$ specimens are exclusive. The effect of moisture is larger for these two cases due to the 90-degree outer layer.

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References

[1] B. D. Agarwal, L. J. Broutman and K. Chadrashaekhara, *Analysis and Performance of Fiber Composites,* John Wiley & Sons. Third edition.
[2] R. D. Adams and D. G. Bacon, *ibid.* 7 (1973) 402.
[3] Y. A. Willway and R. G. White, *ibid. 36* (1989) 77.
[4] Djumaev and K. Takahashi, Effect of moisture absorption on damping performance and dynamic stiffness of NY-6/CF commingled yarn composite, *Journal of Materials Science* 29 (1994) 4736-4741.
[5] A. B. Shultz and S. W. Tsai, Dynamic moduli and damping ratios in fiber reinforced composites,

Journal of Composite Materials 2 (1968) 368-379.

[6] R. F. Gibson, S. K. Chaturvedi and C. T. Sun, Complex moduli for aligned discontinuous fiber reinforced polymer composites, *Journal of Material Science* 17 (1982) 3499-3509.

[7] V. Tita, J. de Carvalho and J. Lirani, Theoretical and Experimental Dynamic Analysis of Fiber Reinforced Composite Beams, *Journal of Brazilian Society of Mechanical Science and Engineering* 25 (3) (2003) 306-310.

[8] S. A. Suarez, R. F. Gibson, C. T. Sun and S. K. Chaturvedi, The influence of fiber length and fiber orientation on damping and stiffness of polymer composites, *Experimental Mechanics*. 26 (2) (1986) 175-184.

[9] R. M. Grane and J. W. Gillespie, Characterization of vibration damping loss factor of glass and graphite fiber composite, *Compos.Sci. Technol*. 40 (1991), 355-361.

[10] G. X. Sui, G. H. He, L. Y. Bai and B. L. Zhou, Effects of fiber orientation on the vibration damping characteristics of virall laminates, *Journal of Material Science Letters* 14 (17) (1995), 1218-1219.

[11] Y. Aoki, O-Il Byon and K. Hasumi, Damping analysis and experiment of carbon fiber/PEEK laminates, *Journal of Japan Society of Material Science* 41 (466) (1992) 1121-1125.

[12] E. C. Botelho, L. C. Pardini and M. C. Rezende, Hygrothermal effect on the shear properties of carbon fiber/epoxy composites, *Journal of Material Science* 41 (21) (2006) 7111-7118.

[13] R. Selzer and K. Friedrich, Mechanical properties and failure behavior of carbon fiber-reinforced polymer composite under the influence of moisture, *Composite* 28A (1997), 595-604.

[14] C. Mehmet OLAKO˘GLU, Damping and Vibration Analysis of Polyethylene Fiber Composite under Varied Temperature", *Turkish J. Eng. Env. Sci.* 30 (2006), 351-357.

[15] C. Y. Wei and S. N. Kurkureka, Evaluation of damping and elastic properties of composites and composites structure by the resonance technique, *Journal of Material Science* 35 (15) (2000), 3785-3792.

[16] L. E. Nielsen, *Mechanical Properties of Polymers and Composites,* Vol. 1 Dekker, New York, (1974).

[17] H. S. Choi, K. J Ahn, J.-D. Nam and H. J. Chun, Hygroscopic aspect of epoxy/carbon fiber composite laminates in aircraft environments, *Composites* 32 (2001), 709-720.

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