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EFFECT OF ORIENTATION ANGLES ON VIBRATION PROPERTIES AT CARBON FIBER REINFORCED POLYMERIC COMPOSITES

ABSTRACT

In this study, composite plates with dimensions of 300x300mm were produced by VARTM (Vacuum Assisted Resin Transfer Molding) method using unidirectional carbon fiber fabrics. The composite plates were produced symmetrically at four different orientations ($(0°)_4$, $(60°/-30°)_S$, $(45°/-45°)_S$, $(0°/90°)_S$) and four layered. Required specimens according to three-point bending and vibration tests related ASTM standards for were cut from produced plates. The maximum flexural stresses of the specimens were determined by performing three-point bending tests. Free vibration tests under fixed-free boundary conditions were performed to determine their natural frequencies and damping ratios. As a result of the tests, specimens with $(0°)_4$ directional angles were found to have the highest bending strength. Also, composite specimens with orientation angles $(0°)_4$ have the highest natural frequencies and lowest damping ratios. $(45°, -45°)_S$, the natural frequency values were the lowest while the damping ratio values were found to be the highest.

Keywords: Laminated Composite Structure, Fiber Orientation Angle, Vibration Properties, Damding Ratio, Flexural Stress

1. INTRODUCTION

As a result of the production techniques developed in recent years, composite materials with superior properties compared to conventional materials have been widely used in many fields including aviation, transportation and defense industry. Transportation sector, aircraft, luxury vehicles, racing cars, passenger cars, sports equipment, maritime and construction sector are some of them. By weight, more than half of the new generation aircrafts produced nowadays consist of composite materials. Since the first use of composite materials, many researchers have focused on studies of the static properties of these materials. Since these structures are usually subject to dynamic loads due to their working environment, dynamic properties, as well as static properties, have been

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investigated in recent years. Most of the studies on the dynamic properties of composite materials are in terms of material characterization. Composite materials are known to have higher damping values when compared to metals. The main reason for this is the viscosity of the polymeric matrices. Dynamically loading of modern laminated composites, in addition to the advantage of high stiffness, stability related to weight and lightweight structures, exhibit marvelous damping properties. Rigidity, stiffness, frequency and damping ratios can be changed by making appropriate choices in the structural parameters of the composites such as fiber aspect, orientation angle, width/length ratio, sequence order and properties of components. Unwanted vibrations and resonance ejections can be largely forestalled by the specific selection and placement of reinforcement and matrix material within the composite. However, for most of the time, the optimum ratios found for dynamic properties may not be the best choice ever for rigidity, endurance, and production cost. For these aims, all dynamic material properties must be known for the dynamic design of the structure.

2. RESEARCH SIGNIFICANCE

In the literature survey, it was found that many studies have been carried out on the mechanical properties of laminated composite structures formed by unidirectional fiber fabrics arrayed at different orientation angles. However, very few studies have been come across about vibration properties. Within the scope of this study, composite plates made of unidirectional carbon fibers with VARTM method, as four layered and four different orientations, were produced. Vibration tests (for natural frequency and damping ratio values) and three-point bending tests (for flexural stress values) were performed on the samples obtained from these plates according to ASTM standards, and as the obtained results were interpreted, contributed to the related literature.

3. RELATED WORK

The characteristics of isotropic materials are the same in every direction of the material, whereas in layered composite materials with orthotropic structure, they depend on the parameters such as fiber type, fiber orientation angle and matrix properties. In the literature review, the dynamic properties of layered composites, especially those that affect damping values, are emphasized. At the same time, it has been observed that most of the experimental work is related to unidirectional fibers. Polymeric composites have been studied in a great number of researches in recent years due to their ease of production, low cost and high energy dissipation properties. In fiber reinforced polymers, the polymer's own structure is the main factor for damping. Thermoplastics have higher energy dissipation than thermosets. Thermosets provide high rigidity and good adhesive ratio [1]. Chung has indicated that increasing the matrix/fiber volume ratio will increase the damping ratio [2]. Ni and Adams reported that a parabolic increase in damping was observed in carbon fiber reinforced polymeric composites (CFRP) and glass fiber reinforced polymeric composites (GFRP) at up to 0.6 volume ratio [3].

Maheri and Adams reported that the specific damping capacity (SDC) increases when the fiber directions are parallel to the bending directions [4]. Doebling et al. [5] pointed out that production and use faults such as fiber separation, weakening of adhesion and foliation increase damping. Berthelot and Sefrani compared different fiber materials; kevlar had higher damping values than glass and carbon [6]. In another study, glass and carbon were compared and glass fiber composites had better damping values than carbon fiber composites [7 and 8]. Berthelot et al. [9] determined frequency-dependent loss factors and damping coefficients by analyzing the fiber layer sequences and orientations, and beam length variations on the effect of vibrations. Adam and Bacon modeled and tested unidirectional angular layers and crosswise layers for general situations and they reported that the best damping values were obtained for different angles [10]. The properties of composite materials are also directly related to the geometric properties of reinforcing elements. The length and shape of the fiber are very important for polymeric composites reinforced especially with short fibers. Gibson and et al. found the optimal fiber aspect, width/length ratio for maximum damping in their work [11].

Tsai and Chi have performed experiments with samples in different configurations, and obtained the best damping value in a square-edge configuration with both free-free and fixed-free boundary conditions [12]. In most applications, the frequency range of operation is limited, and the viscoelastic properties of the matrix composing the composite are assumed to be constant. Ungar and Kervin have identified the loss factor in composite materials by means of stored energy. Energy dissipation in composite materials is a consequence of both matrix and fiber addition [13]. In the experiments performed on carbon fiber woven fabrics, Pei and Li observed that as the fiber orientation angle increases at the same fiber volume ratios, the natural frequency values of the layered composites decrease while the damping ratio values increase [14]. Rueppel et al. examined the damping behavior of unidirectional continuous carbon fiber and flax-reinforced polymer (CFRP and FFRP) composites, taking into account different orientation angles. They determined the damping values by using logarithmic decrement method. They reported that the damping values of flax-fiber composites (FFRP) were better than those of carbon fiber composites (CFRP) [15].

Utomo et al. examined the effect of the number of carbon layers and the dynamic characteristics of carbon-glass hybrid composites in their work. Hybrid composite structures were produced by hand lay-up. The results showed that the number and position of the carbon layer affected the natural frequency and damping ratio of the carbon-glass fiber hybrid composite. The increase in the number of carbon layers increased the natural frequency of the composite and reduced the damping ratio. The position of the carbon layer in the outermost layer of the hybrid composite gave the highest natural frequency and the lowest damping ratio [16]. Nagasankar et al. have worked on different fiber angles to obtain better damping values without compromising more than the stiffness/frequency values the dynamic characteristics of the glass fiber reinforced polymer composites. The productions are divided into three different groups in order to select a better order according to the damping and frequency values. The experimental test was carried out by the Impulse technique. For the same conditions, numerical analyzes were performed with FEA (ANSYS® 11) and good agreement with the experimental results was observed [17].

4. MATERIAL AND METHOD

Classification and standardization of the dynamic properties of composite materials is very difficult. The reliability and reproducibility of the results have been increased by the use of equipment using acoustic and optical methods and contactless sensors in experiments. The use of a laser vibrometer in the tests was a suitable choice in this respect. Carbon (C) fiber fabrics used in this study were supplied from Dost Chemical Ind., Istanbul, as a unidirectional fabric with a density of 320gr/m^2. It is manufactured from thermoplastic in the direction of weft, and carbon fiber in the direction of warp. Material data of unidirectional carbon fabric is given in Table 1.

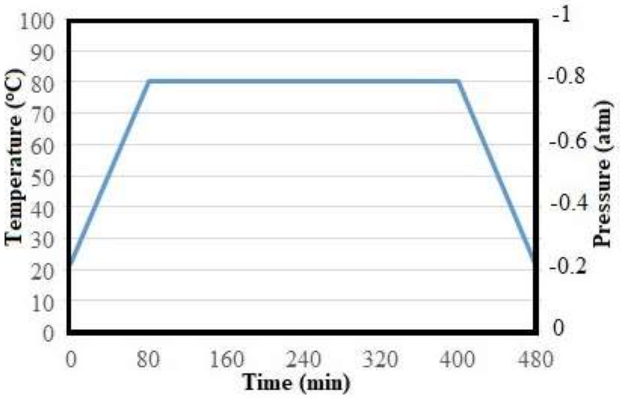
Table 1. Material data of unidirectional carbon fabric

Material Type	320C0
Fiber Orien-tation	0^0
Finenes of Yarn (tex)	3300/68G
Weight Per Layer (g/m^2)	300
Weight of Stitching Tread (g/m^2)	7
Areal Weight (g/m^2)	320
Width (cm)	126/254
Stitching Thread	Polyester yarn

As for the resin system, Huntsman Araldite®LY 1564/Aradur®3487 epoxy resin system was used. The product data of the epoxy resin system is given in Table 2. Production was realized by Vacuum Assisted Resin Transfer Molding (VARTM) method. The curing process of the composites was carried out at -1atm pressure, at 8 hours and 80°C. The curing process is schematically shown in Graphic 1. Composite plates were produced with dimensions of 300mmx300mm, symmetrically with four different orientation angles $[(0^{\circ})_4$, $(60^{\circ}/-30^{\circ})_S$, $(45^{\circ}/-45^{\circ})_S$, $(0^{\circ}/90^{\circ})_S]$ four layers with an average of 1.25mm thickness.

Table 2. Product data of epoxy resin system

Araldite®LY 1564	Aspect (Visual)	Clear Liquid	
	Viscosity at 25°C (ISO 12058-1)	1200-1400	[mPa s]
	Density at 25°C (ISO 1675)	1.1-1.2	[g/cm^3]
	Epoxy index (ISO 3001)	5.8-6.05	[Eq/kg]
Aradur®3486	Aspect (visual)	clear Colourless to Slightly Yellow Liquid	
	Viscosity at 25°C (ISO 12058-1)	10-20	[mPa s]
	Density at 25°C (ISO 1675)	0.94-0.95	[g/cm^3]
	Amine value (ISO 9702)	8.55-9.30	[Eq/kg]



Graphic 1. Schematic representation of curing process of plates produced by VARTM method

5. THREE POINT BENDING TEST

Three point bending tests according to ASTM D790-10 [18] standard were performed with a universal tester (Shimadzu® Corp./Japan). The maximum bending strength is calculated by using the following formula equation 1.

$$\sigma_F = \frac{3}{2}\frac{P_{\max} L}{bh^2} \qquad (1)$$

Here;

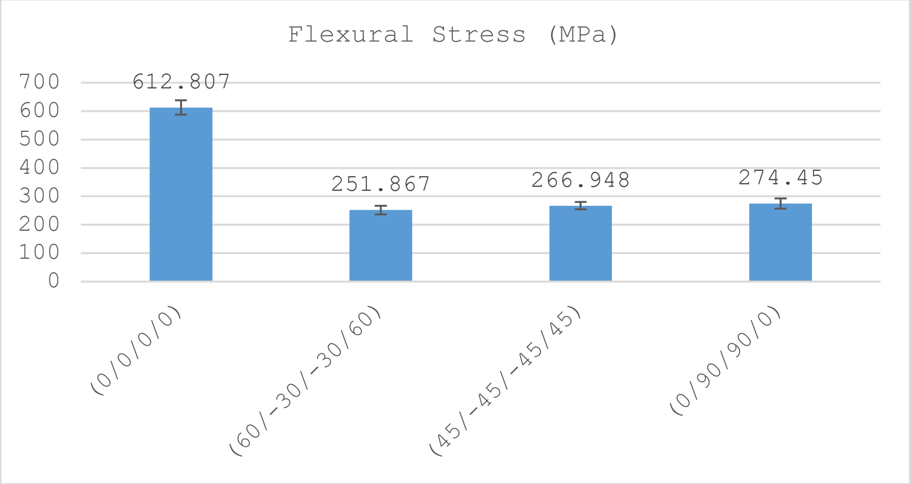
σ_F, Flexural stress MPa;

Pmax, load at a given point on the load-deflection curve (N);
L, support span (mm);
b, width of beam tested (mm);
h, depth of beam tested (mm).

Average dimensions of the samples used in the three-point bending test showed in Table 3 and the maximum flexural stress of composites with different configurations are shown in Figure 2. The average dimensions of the samples used in the three-point bending test are shown in Table 3. The average values of the maximum flexural stress of the composites were obtained at a 95% confidence interval and are shown with the error bars in Graphic 2.

Table 3. Average dimensions of the samples used in the three-point bending test

Sample Types	Width (mm)	Length (mm)	Thickness (mm)
0/0/0/0	11.65	100	1.16
60/-30/-30/60	12.27	100	1.24
45/-45/-45/45	11.06	100	1.46
0/90/90/0	11.35	100	1.15



Graphic 2. Maximum flexural stress of composite samples

6. VIBRATION TESTS

Test samples were obtained by cutting from plates in accordance with ASTM E756-05 [19] standard at lengths of 250mm and widths of 25mm. Free vibration tests of the specimens under fixed-free boundary conditions were performed to determine their natural frequencies and damping ratios. The fixed-free boundary condition is provided by compressing the test specimens of 220mm long with a constant torque value. 5 samples were cut from each plate type and each sample was subjected to 5 tests. In total, natural frequency and damping ratio values were determined by taking 25 values from each sample type. The determination of the vibration characteristics was made with the computer-based analysis system PULSE® vibration measurement system (Brüel & Kjær Sound & Vibration Measurement A/S, Denmark). This system consists of different data collection units and software options. In this study, a driving force was applied with a hammer from a specific point on the material, and the vibration response of the material was measured by means of a laser vibrometer (Figure 3). The transfer function was obtained by means of the Fast Fourier Transform (FRF) on ME'scopeVES® Vibrant Technology, Inc., USA) modal analysis software. The experimental modal parameters (resonance frequency and damping ratio) of the test sample are found based on the fixed-free boundary condition. Thus, the effect on the vibration properties of the orientation angle is investigated. A schematic representation of the testing system was depicted in Figure 1.

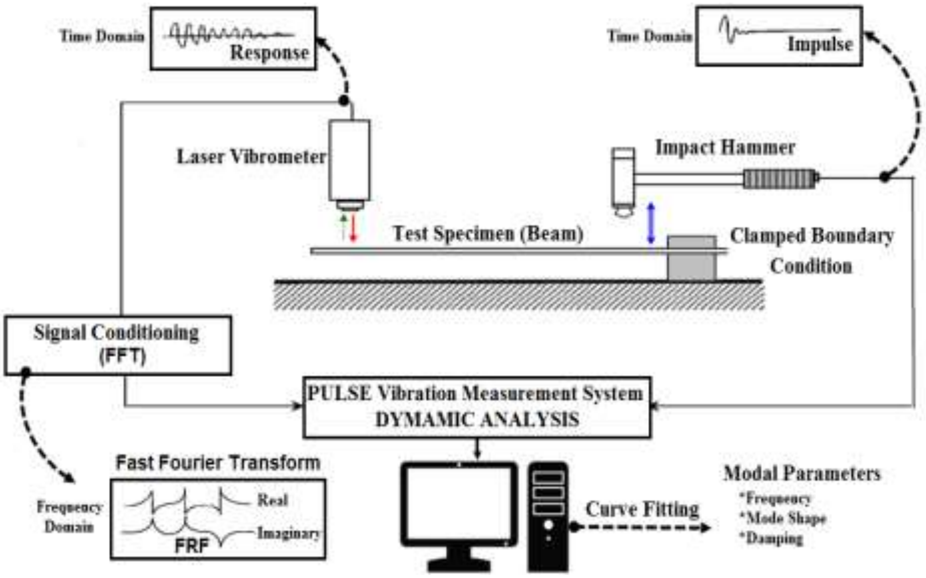
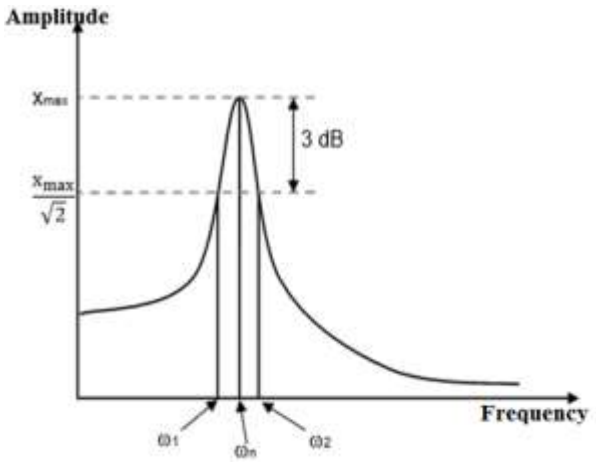


Figure 1. Schematic representation of vibration testing system

This vibration measurement system calculates the damping ratio values by the half-power bandwidth method. As is known, in a vibrating system, each mode has its own damping ratio. The damping ratio can be calculated by using the frequency-base amplitude variation with the half-power bandwidth method, which is used for materials with damping ratios less than 0.05 [16]. Graphic 3 shows the graph for the half-power bandwidth method, which calculates the damping ratio in the frequency domain.

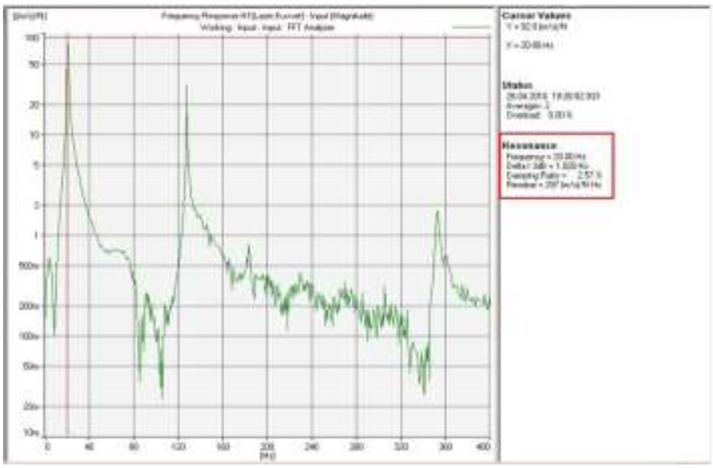


Graphic 3. Half-power bandwidth method

Damping ratio (ζ) for any mode in this method can be calculated by equation 2 using,

$$\frac{\omega_2 - \omega_1}{\omega_n} = 2\zeta \qquad (2)$$

where w_n refers to the resonance frequency while w_1 and w_2 refer to the frequencies corresponding to the values obtained by dividing the amplitude (X_{max}) corresponding to the resonance by $\sqrt{2}$ (Graphic 4). In order to make accurate measurements with this method, the maximum amplitudes of the obtained FRF (Frequency Response Function) functions must be accurately measured. Therefore, the hammer test should be performed at high frequency resolution. Since the test system uses non-contact sensors, it is an appropriate choice. Figure 5 shows a sample screen display obtained by means of the PULSE® vibration measurement system and of which we can directly read the natural frequency and damping ratio values.

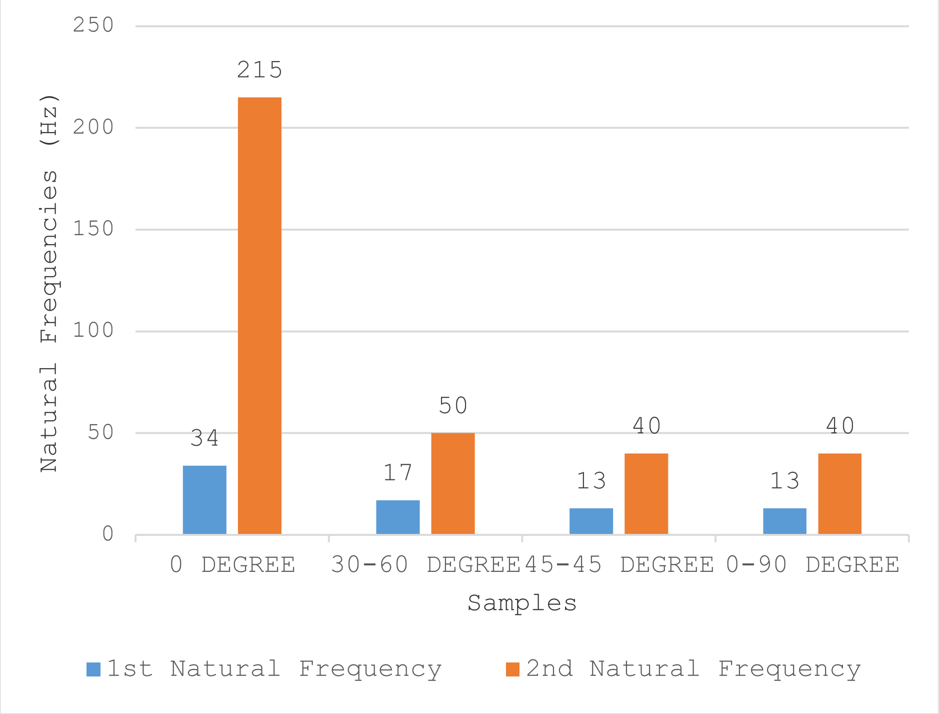


Graphic 4. Schematic presentation of first natural frequency and damping ratio

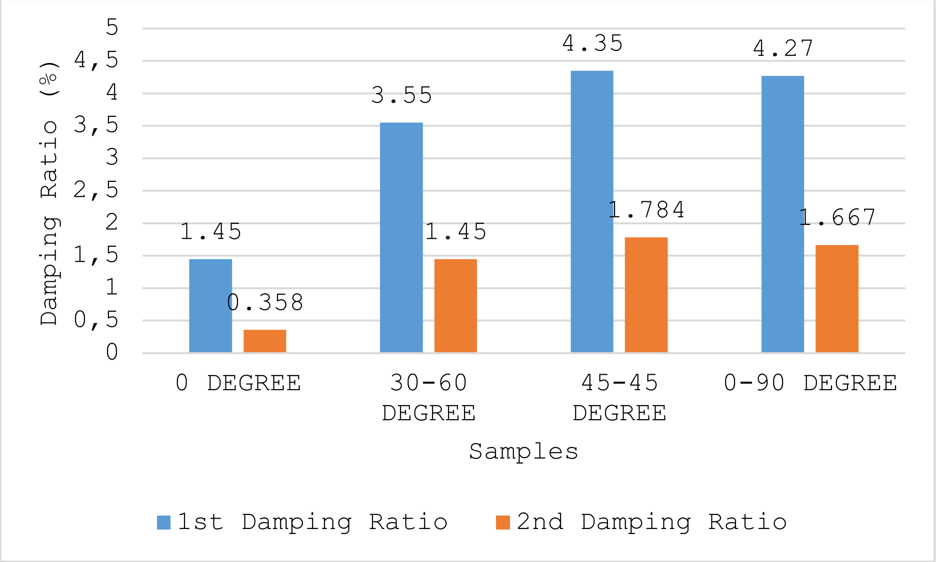
The average values of the results obtained at the end of the study are presented in Table 4, Graphic 5 and Graphic 6.

Table 4. First and Second Natural Frequencies and Damping Ratios for Samples

Natural Frequencies and Damping Ratios of Unidirectional Carbon Fiber Reinforced Layered Composite Samples for Fixed-Free Boundary Conditions				
Orientation Angles	$(0°)_4$	$(60°/-30°)_S$	$(45°-45°)_S$	$(0°90°)_S$
1st Natural Frequency (Hz)	34	17	13	13
1st Damping Ratio (%)	1.45	3.55	4.35	4.27
2nd Natural Frequency (Hz)	215	50	40	40
2nd Damping Ratio (%)	0.358	1.45	1.784	1.667



Graphic 5. First and second natural frequencies of the samples



Graphic 6. First and second damping ratios for the samples

7. RESULTS

In this study, four layer laminated composite plates with 4 different orientation angles [(0° 0° 0° 0°), (60° -30° -30° 60°), (45° -45° -45° 45°), (0° 90 ° 90° 0°)] were produced by using VARTM method using unidirectional carbon fiber fabric. Samples have been obtained according to the relevant ASTM standards for vibration tests of the produced plates. As a result of experimental dynamic tests, the natural frequencies and damping rates of the samples were determined. In the vibration experiments, the first and second natural frequencies and the corresponding damping ratios of each sample. These results are presented in tables and graphs. In the tests performed, the composite sample with (0°)$_4$ orientation angles has the highest natural frequency and the lowest damping ratio. Considering that the natural frequency values are widely related to the flexural rigidity of the material, it is expected that the samples with the 0^0 orientation angle in the axial direction will have the highest flexural rigidity and –thus- the highest natural frequency values. The natural frequency equation for the lateral vibration of the beams is given in equation 3.

$$\omega_n = 1.875^2 \sqrt{\frac{EI}{\rho A L^4}} \qquad (3)$$

Here; *EI* flexural rigidty is directly proportional to the natural frequency [20].

The natural frequency of composite samples with (45° -45°)$_S$ orientation angles is the lowest, while the damping ratio is the highest. These results were found to be compatible with the literature [10 and 14]. According to the results obtained, it is considered that the desired damping and vibration values can be obtained by changing the orientation angles of unidirectional carbon fiber composites. Based on the results of these experiments, it can be inferred that new structures with different vibration properties can be obtained by using the same amount of material, without changing the production period and cost, with different orientation angles in layered composites. Consequently, it is possible to produce advantageous products by producing layered composite structures with different orientation angles, based on the purpose of use. Of course, it should not be forgotten that mechanical properties should be taken into consideration for such a design.

NOTICE

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