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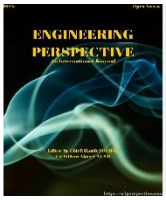

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Research Paper

Investigation of Natural Frequency Values of Composite Cover Design with Different Laying Angles

Mehmet Can Katmer[1,2], Adnan Akkurt[2], Tolga Kocakulak[3*]

[1]*Hidromek A.Ş., Sincan Organized Industrial Zone, Ankara, TURKEY*
[2]*Gazi University, Faculty of Technology, Department of Industrial Design Engineering, Ankara, TURKEY*
[3]*Burdur Mehmet Akif Ersoy University, Technical Sciences of High Vocational School, Burdur,TURKEY*

ABSTRACT

In In this study, the effect of composite laying angle on the natural frequency values of a long and flexible cover made of laminated composite material was investigated. Investigation of the effect of the laying angle, a composite cover with rib design with the topography optimization method was used. The cover design used in the study is an industrial design product and has producible features. A design with a total of 20 different laying angles has been made on the ribbed and ribless parts of the composite cover. Care was taken that the selected laying angles do not interfere with manufacturability. Designs with different laying angles are modeled with the ANSYS ACP module. The modal analysis of the created designs was carried out with the finite difference method in the ANSYS program environment. As a result of the modal analysis, natural frequency values of mode 1, mode 2, mode 3, mode 4, mode 5 and mode 6 of these designs were obtained. It was concluded that the best mode 2 natural frequency values (45°,-45°,45°,-45°,45°,-45°,45°) were obtained by using the degree of laying angles. In this design, mode 2 has a natural frequency value of 12.2 Hz, mode 3 33 Hz, mode 4 40.9 Hz, mode 5 57.8 Hz and mode 6 82.7 Hz. In this design, mode 2 has a natural frequency value of 12.2 Hz, mode 3 33 Hz, mode 4 40.9 Hz, mode 5 57.8 Hz and mode 6 82.7 Hz.

Keywords: Laying angle, Composite, Natural frequency, Design, Modal analysis

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Author Contacts
**Corresponding Author*
e-mail addresses : mehmet.katmer@hidromek.com.tr, aakkurt@gazi.edu.tr, tkocakulak@mehmetakif.edu.tr*
Orcid numbers : 0000-0002-4610-8178, 0000-0002-0622-1352, 0000-0002-1269-6370

1. Introduction

Composite materials are widely used in sectors such as the automotive industry, aerospace and defense industry due to various advantages [1,2]. Composite is defined as a material with different new properties by combining two or more materials [3,4]. With the use of composite materials increasing day by day, the studies have gained intensity. The most basic common goal in these studies can be said to reduce design weight and achieve better mechanical performance [5,6,7]. One of the most basic methods of achieving this goal is the use of layered type composite structures [8,9]. Although it has these features, studies are continuing to improve it and eliminate some of the problems it carries [9]. The most important of these problems aimed to be solved is the vibration behavior of composite materials [10].

Vibratory motion can be defined as the repeated motion of a structure around its equilibrium position. In many systems used in engineering and daily life, vibrations occur due to environmental or undetected reasons. Long-term vibration can cause fatigue in the machine elements and cause breakage and damage. In particular, the determination of vibrations and values of structures used in critical functions are important for natural frequency values and resonance issues. The modal analysis method is widely used to predict the vibration properties of a designed structure. The purpose of the modal analysis is to determine the natural frequencies and the corresponding mode behaviors [11,12,13,14].

Studies aiming to improve the characteristic properties of layered type composite materials are available in the literature. Şakar et al. observed the effect of orientation angles and a number of layers on the dynamic behavior of the composite structure in the sandwich panels they prepared. The mode shapes and natural frequencies of the produced panels were determined both experimentally and numerically with the ANSYS program [15]. Atlıhan studied computational and experimental modal analysis on delaminated composite structures with different orientation angles consisting of 16 paves. He observed the dynamic behavior of the structures according to the orientation angle change and delamination status. He used ANSYS software for analysis studies [16]. R. Gibson explained the modal analysis methods used to determine the dynamic behavior of fiber-reinforced composite materials, the determined parameters and basically what factors will change these parameters [17]. Yeşilyurt et al. in their study, applied modal analysis to a bar produced as a unidirectional composite and approached to determine the mechanical properties of the material with the data obtained [18]. Soni et al. made the most appropriate design study by changing the orientation angles for low displacement and high strength in laminated composite plates. The layer placements were examined as an angled layer, unsymmetrical and symmetrical angled layer [19]. In the second stage of his study, Vatangül numerically investigated the behavior and strength of composite samples with different orientation angles under load. They used ANSYS software in their studies [20]. Baba examined the effects of parameters such as boundary condition, delamination size, location of delamination and fiber orientation angles on plate buckling behavior in composite plates [21]. It has been observed in the literature that many studies have been made and are still being done for the appropriate design of layered composite materials. In these studies, the behavior of the layered composite material; has been observed that fiber orientation angle, layer thickness and number, delamination, temperature, symmetric or non-symmetrical array are examined depending on many different parameters. As a result of the research; In many of the studies on both structural optimization and composite material, it has been determined that the modal analysis method is used to examine the behavior of the part.

In the literature, no study has been found in which the laying angles of the lid, which is an industrial design product and can be produced, and which has a long and flexible design, are examined. In this study, the optimum laying angle design was determined by examining the natural frequency values in case the composite material used in the cover design with a long and flexible structure has different winding angles. Natural frequency values were obtained by the modal analysis method in ANSYS environment.

2. Material and Method

The effect of the laying angles on the natural frequency value of the long and flexible composite cover, of which rib design was made with the topography optimization method, was investigated. The macro mechanics of laminated composite plates are discussed in detail and formulated. Information about the materials and layers of the composite cover is given. 20 different designs were created by applying different laying angles to the ribbed composite cover. A finite element model of designs with different laying angles was created in ANSYS environment. The mesh spacing value was chosen as 5 mm in order not to prolong the processing time more than necessary and to obtain results close to the real values. In addition, analyzes were made at several different mesh spacing values and it was observed that the results differed negligibly at mesh sizes below 5 mm. By applying modal analysis to all designs, natural frequency values of mode 1, mode 2, mode 3, mode 4, mode 5 and mode 6 were obtained.

2.1 Macro Mechanics of Laminated Composite Plates

The representation of a layered composite plate is shown in Figure 1. In Figure 2 and Figure 3, the forces and displacements occurring in the plate are expressed [22].

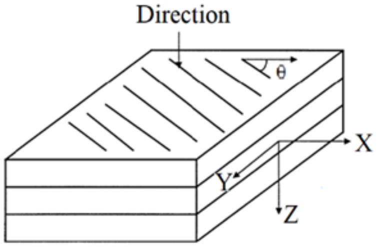

Figure 1. Schematic representation of the laminated composite plate

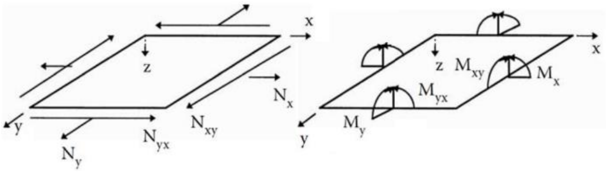

Figure 2. Forces and moments in the laminated composite plate

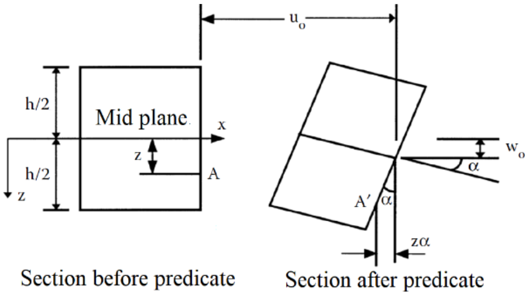

Figure 3. The relationship between displacement and curvature before and after loading

u_0, v_0 and w_0 show the mid-plane (z=0) displacements of the layered composite material in the x, y and z directions. Equations 1,2 and 3 show the displacements of the u, v and w layered composite material in the x, y and z directions of any point on the cross section.

$$u = u_0 - z\alpha \tag{1}$$

$$\alpha = \frac{\partial w_0}{\partial x} \rightarrow u = u_0 - z\frac{\partial w_0}{\partial x} \tag{2}$$

$$v = v_0 - z\frac{\partial w_0}{\partial y} \tag{3}$$

The unit strain-displacement relations are given in equations 4, 5 and 6.

$$\varepsilon_x = \frac{\partial u}{\partial x} = \frac{\partial u_0}{\partial x} - z\frac{\partial^2 w_0}{\partial x^2} \tag{4}$$

$$\varepsilon_y = \frac{\partial v}{\partial y} = \frac{\partial v_0}{\partial y} - z\frac{\partial^2 w_0}{\partial y^2} \tag{5}$$

$$\gamma_{xy} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} = \frac{\partial u_0}{\partial y} + \frac{\partial v_0}{\partial x} - 2z\frac{\partial^2 w_0}{\partial x \partial y} \tag{6}$$

The unit strains in the midplane and the global strains in terms of curvatures are shown in equation 7.

$$\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} = \begin{Bmatrix} \dfrac{\partial u_0}{\partial x} \\ \dfrac{\partial v_0}{\partial y} \\ \dfrac{\partial u_0}{\partial y} + \dfrac{\partial v_0}{\partial x} \end{Bmatrix} + z \begin{Bmatrix} -\dfrac{\partial^2 w_0}{\partial x^2} \\ -\dfrac{\partial^2 w_0}{\partial y^2} \\ 2\dfrac{\partial^2 w_0}{\partial x \partial y} \end{Bmatrix} = \begin{Bmatrix} \varepsilon_{x0} \\ \varepsilon_{y0} \\ \gamma_{xy0} \end{Bmatrix} + \begin{Bmatrix} K_x \\ K_y \\ K_{xy} \end{Bmatrix} \tag{7}$$

Since $\bar{Q}$ varies depending on the mechanical properties and angle of each layer, the stress does not change linearly across the plate, it remains linear only within the layer. In other words, if the elongation and curvature values of the midplane are known, the values of the global stresses (σx, σy, τxy) can be found depending on the position (z) as above. Therefore, local stresses and strains can be found for each layer using the transformation matrix and damage criteria can be applied. In Figure 4, the stress and strain variation of the laminated composite plate for the mid-plane, and in Figure 5, the coordinate positions of the layers in the laminated composite plate are given according to the midplane [22].

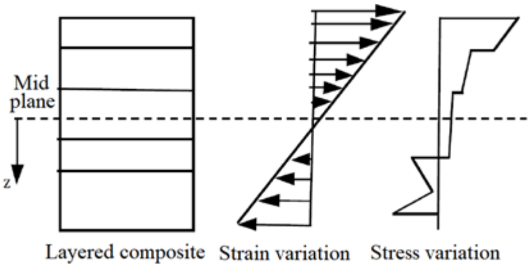

Figure 4. Stress and strain variation along with the thickness of the laminated composite plate

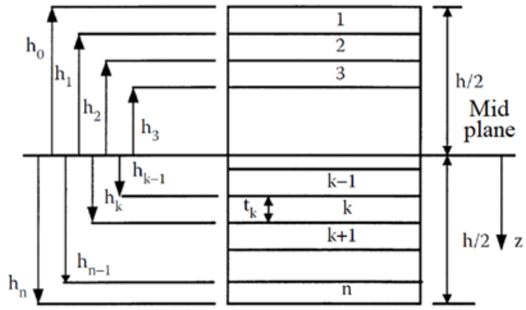

Figure 5. Coordinate positions of the layers in the laminated composite plate

Writing the elongation and curvature values of the midplane in terms of forces and moments is expressed by Nx, Ny and Nxy. In-plane normal and shear forces for unit length are shown in equation 8.

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} \\ A_{12} & A_{22} & A_{26} \\ A_{16} & A_{26} & A_{66} \end{bmatrix} \cdot \begin{bmatrix} \varepsilon_{x0} \\ \varepsilon_{y0} \\ \gamma_{xy0} \end{bmatrix} + \begin{bmatrix} B_{11} & B_{12} & B_{16} \\ B_{12} & B_{22} & B_{26} \\ B_{16} & B_{26} & B_{66} \end{bmatrix} \cdot \begin{bmatrix} K_x \\ K_y \\ K_{xy} \end{bmatrix} \tag{8}$$

Bending and torsional moments for Mx, My and Mxy unit length are given in equation 9.

$$\begin{bmatrix} M_x \\ M_y \\ M_{xy} \end{bmatrix} = \begin{bmatrix} B_{11} & B_{12} & B_{16} \\ B_{12} & B_{22} & B_{26} \\ B_{16} & B_{26} & B_{66} \end{bmatrix} \cdot \begin{bmatrix} \varepsilon_{x0} \\ \varepsilon_{y0} \\ \gamma_{xy0} \end{bmatrix} + \begin{bmatrix} D_{11} & D_{12} & D_{16} \\ D_{12} & D_{22} & D_{26} \\ D_{16} & D_{26} & D_{66} \end{bmatrix} \cdot \begin{bmatrix} K_x \\ K_y \\ K_{xy} \end{bmatrix} \tag{9}$$

The matrices $[A]$, $[B]$ and $[C]$ in the equations represent the axial/extension, coupling, and bending stiffness matrices.

$$A_{ij} = \sum\nolimits_{k=1}^{n} \left[\bar{Q}_{ij}\right]_k (\mathrm{h}_k - \mathrm{h}_{k-1}), \mathrm{i} = 1,2,6 \text{ ve } \mathrm{j} = 1,2,6 \tag{10}$$

$$B_{ij} = \frac{1}{2}\sum\nolimits_{k=1}^{n} \left[\bar{Q}_{ij}\right]_k (\mathrm{h}_k^2 - \mathrm{h}_{k-1}^2), \mathrm{i} = 1,2,6 \text{ ve } \mathrm{j} = 1,2,6 \tag{11}$$

$$D_{ij} = \frac{1}{3}\sum\nolimits_{k=1}^{n} \left[\bar{Q}_{ij}\right]_k (\mathrm{h}_k^3 - \mathrm{h}_{k-1}^3), \mathrm{i} = 1,2,6 \text{ ve } \mathrm{j} = 1,2,6 \tag{12}$$

For symmetrical composite plates, the value $[B]$ is equal to zero. In this case, when equations 8 and 9 are arranged, equations 13 and 14 are obtained.

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} \\ A_{12} & A_{22} & A_{26} \\ A_{16} & A_{26} & A_{66} \end{bmatrix} \cdot \begin{bmatrix} \varepsilon_{x0} \\ \varepsilon_{y0} \\ \gamma_{xy0} \end{bmatrix} \tag{13}$$

$$\begin{bmatrix} M_x \\ M_y \\ M_{xy} \end{bmatrix} = \begin{bmatrix} D_{11} & D_{12} & D_{16} \\ D_{12} & D_{22} & D_{26} \\ D_{16} & D_{26} & D_{66} \end{bmatrix} \cdot \begin{bmatrix} K_x \\ K_y \\ K_{xy} \end{bmatrix} \tag{14}$$

There is no coupling effect and no curvature due to axial loads and no normal deformations due to moments that occur in the midplane. Composite plates with various laying arrangements, which are of great importance according to the place they will be used, have different characteristics. These characteristics are known as symmetrical, equilibrium, angle fold, cross fold and semi-isotropic. The distance of both sides of the symmetrical sheet from the sheet midpoint should be equal. With symmetrical layer (0°, -45°, +45°, 90°, 90°, +45°, -45°, 0°) or simply (0°, -45°, +45°, 90°) can be sampled. Opposite angles of θ=90° and θ=0° fiber angles are θ=0° and θ=90° degrees, respectively. There must be a plate with a certain material property, fiber direction and thickness of a layer in equilibrium and a separate plate within that composite layer with the same material properties and thicknesses, but with the opposite fiber direction. The equilibrium layer can be sampled with (90°, -45°, 0°, 45°) and (90°, 60°, 30°, -30°, 0°, -60°). In the angle layer composite plate, the fibers of each layer are located at angles -θ and θ. The angle can be exemplified by layer 2 (60°, -60°, 60°, -60°) or briefly (60°, -60°). In the cross layer composite layer, the fiber angles of each layer are θ=0° and θ=90°. The cross layer can be sampled by layer (0°, 90°, 0°, 90°) or simply (0°, 90°). The fiber angles (θ) of the layers forming the semi-isotropic composite layer are at 0°, -45°, +45°, 90° angles and are symmetrical. These layers also have a balancing feature. Semi-isotropic layer (0°, 90°, +45°, -45°)s, (-45°, 90°, +45°, 0°)s and (90°, -45°, 0°, +45) °)s [23,24,25,26,27].

2.2 Cover Design and Material

The composite cover has a width of 354 mm, a length of 1710 mm and a height of 234 mm. The composite valve consists of two combined structures, with and without ribs. The visual figure of the composite cover can be found in Figure 6.

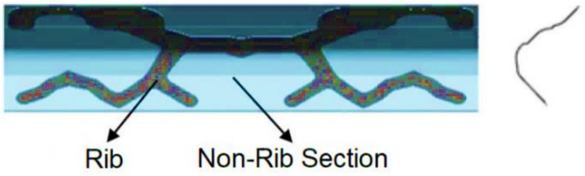

Figure 6. Ribbed and ribless portions of the composite door design

According to the usage conditions of the part, different laying angles were determined in each paving layer by using resin-impregnated unidirectional carbon fiber (prepreg) materials in order to reduce the effect of vibration loads on the part. Laying angle sequences were made using the rules in the literature under the main heading of design rules of layered composites. In this way, it is aimed to increase strength. The mechanical properties of the materials are given in Table 1.

Tablo 1. One way carbon/epoxy prepreg material properties

Parameter	Symbol	Carbon prepreg
Elasticity Module (0°)	GPa	121
Elasticity Module (90°)	GPa	8.6
Slip modulus	GPa	4.7
Poisson's ratio	-	0.27
Density	g/cc	1.49

The multi-layer composite plate is formed by overlapping orthotropic single-layer composite plates with different fiber directions in a symmetrical manner as in Figure 7. In the study, a composite cover design with 20 different laying angles was carried out.

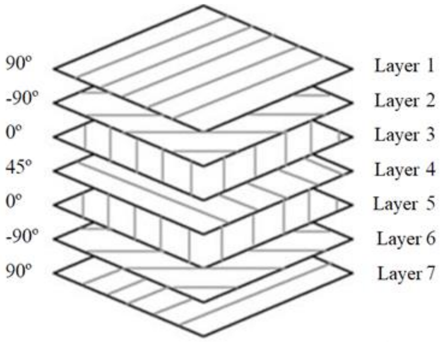

Figure 7. Composite material laying angles

2.2 Composite Orientation Angles

Fiber orientations angles, which is one of the design variables for the designed composite cover, are changed in each laying layer, and it is aimed to reduce the effect of vibration loads on the part according to the usage conditions of the part. Manufacturability was taken into account in determining the laying angles. Laying angles, which are frequently used in practice, were preferred for layered composites in the study. The arrays with different orientation angles that make up the designs are given in Table 2. Laying sequences were modeled and analyzed with the ANSYS ACP module.

Table 2. Arrays with different orientation angles

Design no	Orientation angles
1	(45°,-45°,45°,-45°,45°,-45°,45°)
2	(0°, 45°, -45°, 0°, -45°, 45°, 0°)
3	(0°, 45°, 90°, 0°, 90°, 45°, 0°)
4	(0°, 45°, 90°, 0°, -90°, -45°, 0°)
5	(-45°, 0°, 45°, 90°, 45°, 0°, -45°)
6	(45°,-45°,45°,-45°,45°,-45°,45°)
7	(90°,-90°,90°,-90°,90°,-90°,90°)
8	(45°,90°,45°,90°,45°,90°,45°)
9	(90°,-90°,0°,90°,0°,-90°,90°)
10	(90°,-90°,45°,90°,45°,-90°,90°)
11	(0°,-90°,45°,90°,45°, 90°,0°)
12	(90°,-90°,0°,0°,0°,-90°,90°)
13	(0°,45°,90°,0°,0°,-90°,90°)
14	(90°,-90°,45°,90°,0°,-90°,90°)
15	(90°,-90°,90°,0°,90°,-90°,90°)
16	(45°,-45°,0°,0°,0°,-45°,45°)
17	(45°,-45°,45°,0°,45°,-45°,45°)
18	(45°,-45°,0°,45°,0°,-45°,45°)
19	(45°,-45°,0°,90°,0°,-45°,45°)
20	(90°,0°,90°,0°,90°,0°,90°)

3. Results and Discussion

All created designs were modeled and analyzed with the ANSYS ACP module. In the first column of the table, it gives the laying angles of the ribless section in the top row and the ribs in the bottom line. As a result of the analysis, mode 1, mode 2, mode 3, mode 4, mode 5 and mode 6 natural frequency values were obtained for each design. Obtained values are shown in Figure 8. Since the mode 1 natural frequency value is found to be zero for all designs, it is not included in the graph.

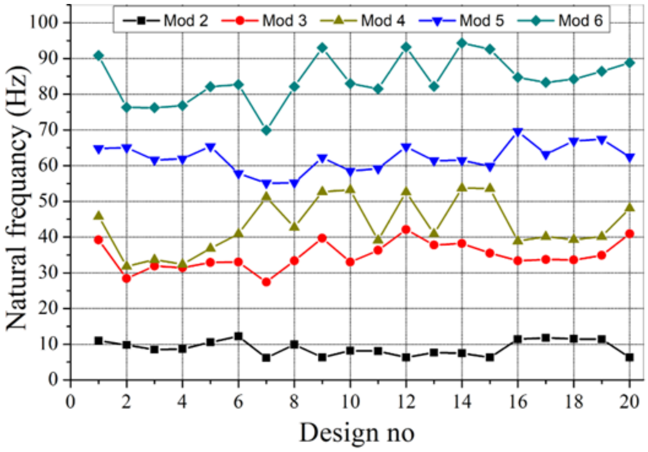

Figure 8. Natural frequency values in different laying sequences

When the analysis results were examined, it was seen that the best mode 2 natural frequency value of the structure was obtained in the 6th design. It is seen that this design has (45°, -45°, 45°, -45°, 45°, -45°, 45°) degree, angular and symmetrical arrangement. In this design, it was determined that mode 2 has 12.2 Hz, mode 3 33 Hz, mode 4 40.9 Hz, mode 5 57.8 Hz and mode 6 82.7 Hz natural frequency values. Good results were also obtained for the pavings made with 45°, -45° angles on the top and bottom layers and 0° angles in the center. The lowest mode 2 values were obtained with layer arrays with 0 and 90 degree laying angles. This result was reached with the natural frequency values obtained from designs 7, 9, 12, 15 and 20. When these results are evaluated, it is seen that it is possible to improve the mode 2 behavior of these and similar structures by designing the first layer by preferring 45°, -45° angle layers and symmetrical arrangement.

The best mode 3 natural frequency value of the structure was obtained with design number 12. This design is constituted by a layer arrangement with equilibrium conditional laying angles of (90°, -90°, 0°, 0°, 0°, -90°, 90°). The second design with a high mode 3 natural frequency value was determined as design number 20. This design has diagonal ply laying angles of (90°, 0°, 90°, 0°, 90°, 0°, 90°). It has been concluded that the lowest mode 3 values occur in layer arrays with 45 and 90 degree laying angles. These laying angles are available in designs 2, 3, 4, 6 and 7. When the results are evaluated, it is seen that it is possible to improve the mode 3 behavior of these and similar structures by designing 90° and 0° equilibrium arrays or 90° and 0° cross-floor pavements.

4. Conclusions

In the study, it was observed that with the increase of mode 2 and mode 3 natural frequency values, the other mode values increased. In this study, more focused on mode 2 and mode 3 natural frequency values, which are seen as critical for the structure. It has been concluded that the examined cover design gives the best mode 2 value (45°, -45°, 45°, -45°, 45°, -45°, 45°) if it has a degree, angular and symmetrical arrangement. In this design, mode 2 has a natural frequency value of 12.2 Hz, mode 3 33 Hz, mode 4 40.9 Hz, mode 5 57.8 Hz and mode 6 82.7 Hz. In this cover design, the best mode 3 natural frequency values (90°, -90°, 0°, 0°, 0°, -90°, 90°) degrees have been achieved with a layer arrangement with balance conditional laying angles. In this design, mode 3 has a natural frequency value of 6.3 Hz, mode 3 42.1 Hz, mode 4 52.6 Hz, mode 5 65.3 Hz and mode 6 93.2 Hz. It has been determined that in case the Mode 3 natural frequency value is aimed to be high (90°, 0°, 90°, 0°, 90°, 0°, 90°) it can be preferred in its structure with diagonal floor laying angles of 5°. In this design, it was determined that mode 3 has 6.3 Hz, mode 3 40.9 Hz, mode 4 48.1 Hz, mode 5 62.5 Hz and mode 6 88.8 Hz. The general results obtained in this study are given below.

•The best mode 2 behavior was obtained by choosing the 45°, -45 angle fold and symmetrical arrangement of the first layer in the laying arrangements.

•The lowest mode 2 values were obtained with layer arrays with 0 and 90 degree laying angles.

•The best mode 3 behavior is obtained by choosing the 90° and 0° balance arrays in the laying arrays.

•It has been observed that the mode 3 behavior gives close to the best value in case of 90° and 0° diagonal floor layings.

•It has been concluded that the lowest mode 3 values occur in layer arrays with 45 and 90 degree laying angles.

Conflict of Interest Statement

The authors declare that there is no conflict of interest in the study.

CRediT Author Statement

Mehmet Can Katmer: Conceptualization, Methodology, Software, Writing - original draft

Adnan Akkurt: Conceptualization, Supervision, Writing - original draft

Tolga Kocakulak: Writing - review & editing, Writing - original draft

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