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Original Article

Effects of Fiber Type and Number of Layers on Modal Analysis of Laminated Composite Plates

Savaş Evran[1*], Yasin Yılmaz[2]
[1]Canakkale Onsekiz Mart University, Canakkale Faculty of Applied Sciences, Department of Energy Management, Canakkale, Turkey.
[2]Pamukkale University, Faculty of Engineering, Department of Mechanical Engineering, Denizli, Turkey.
**sevran@comu.edu.tr*

Abstract

The goal of this study is to examine the effects of fiber type and number of layers on modal analysis of laminated composite plates using finite element and Taguchi methods. Modal analysis was carried out by finite element software ANSYS in accordance with L9 orthogonal array which has two control factors such as fiber types and number of layers. Optimal levels of fiber types and number of layers were determined using analysis of Signal-to-Noise ratio, while importance levels and percentage effects of control factors were performed using analysis of variance at 95% confidence level. According to results obtained from this study, the maximum fundamental natural frequency value was calculated using boron-fiber-reinforced laminated composite plates with three layers. Numerical and statistical results obtained from this study can be useful to select the appropriate fiber types and number of layers for laminated composite plates.

Keywords: Modal Analysis, Laminated Composite, Fiber, Finite Element, Taguchi Method.

Tabakalı Kompozit Plakaların Modal Analizi Üzerinde Tabakaların Fiber Tipi Ve Sayısının Etkisi

Özet

Bu çalışmanın amacı, sonlu elemanlar ve Taguchi yöntemleri kullanılarak tabakalı kompozit plakaların modal analizinde fiber tipi ve katman sayısının etkilerini incelemektir. Modal analiz, fiber türleri ve katman sayısı gibi iki kontrol faktörüne sahip L9 ortogonal diziye uygun olarak sonlu elemanlar yazılımı ANSYS ile gerçekleştirilmiştir. Sinyal-Gürültü oranı analizi kullanılarak optimum lif türleri ve katman sayısı belirlenirken kontrol faktörlerin önem seviyeleri ve yüzde etkileri %95 güven düzeyinde varyans analizi kullanılarak gerçekleştirilmiştir. Bu çalışmadan elde edilen sonuçlara göre, maksimum serbest titreşim değeri üç katmanlı bor lifi takviyeli tabakalı kompozit plakalar kullanılarak hesaplanmıştır. Bu çalışmadan elde edilen sayısal ve istatistiksel sonuçlar, tabakalı kompozit plakalar için uygun fiber tiplerini ve katman sayısını seçmek için faydalı olabilir.

Anahtar Kelimeler: Modal Analiz, Tabakalı Kompozit, Fiber, Sonlu Elemanlar, Taguchi Metot.

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1. INTRODUCTION

Laminated composite plates have been used in different area such as mechanical engineering, civil engineering, ocean, aircraft etc. Modal analyses have been carried out to determine the natural frequencies of a structure and thus modal analysis of plates made of composite materials is important because of the extensive application of composite structures [1]. In literature, there are a lot of studies including modal analysis of laminated composite plates. Thai and Kim [2] calculated the natural frequency of composite plates made of different laminates based on two variable refined plate theories. Benhenni, et al. [3] examined the natural frequency of hybrid laminated composite plates under various boundary conditions using finite element method. Fallah and Delzendeh [4] evaluated the modal behavior of plated made of laminated composites and they used a meshless finite volume in analysis. Tawfik, et al. [5] studied the natural frequency of laminated composite plates and they utilized neural network-based second order reliability technique in analysis. Joshi and Duggal [1] performed the modal analysis of plates made from laminated composites during progressive failure and they used numerical method in analysis. Evran [6] analyzed the free vibration behavior of beams made of laminated composites including glass/epoxy systems using experimental and statistical methods. In analysis, L9 orthogonal array based on Taguchi method was used. Boay [7] reported the modal analysis of plates made of laminated composite and the plates have central circular holes. Sharma and Mittal [8] investigated the natural frequency of plates made of laminated composite materials including elastically restrained sides and they also used finite element approach. Aydogdu and Timarci [9] presented the modal analysis of laminated square plates with cross-ply in accordance with various boundary conditions. Ergun, et al. [10] performed experimental modal and buckling analyses of beams made of impacted composite materials. Aydogdu [11] evaluated the natural frequency behavior of beams made from angle-ply laminated composites under different boundary conditions. A study including the optimization of a hybrid composite laminate fabricated using carbon and E glass fibers were presented [15]. As can be understood, it is possible to see the studies containing of fundamental natural frequency analysis of laminated composite beams and plates. In this study, impact of fiber types and number of layers on modal analysis of laminated composite plates using finite element and Taguchi methods was investigated. In literature, there are many studies regarding natural frequency analysis. But study regarding fundamental natural frequency of laminated composite plates with different fiber types using numerical and statistical methods were limited. With this aspect, a new approach to the literature will be presented. Also, in this study, each level of each control factor on the response were evaluated using signal-to-noise (S/N) ratio and variance analysis (ANOVA). This approach of the study presents the difference from mentioned literature review.

2. MATERIALS AND METHODS

In this study, laminated composite plates for numerical analyses was applied. The laminated composite plates designed from glass/epoxy, boron/epoxy, and carbon/epoxy. Each material has different mechanical properties and densities. The material properties were given in Table 1.

Table 1. Material properties [12]

Materials	E_x (GPa)	E_y (GPa)	E_z (GPa)	v_{xy}	v_{xz}	v_{yz}	G_{xy} (GPa)	G_{xz} (GPa)	G_{yz} (GPa)	ρ (g/cm^3)
Glass/Epoxy	38.5	9.35	9.35	0.22	0.05	0.05	3.47	3.47	3.47	1.89
Boron/Epoxy	202.4	9.87	9.87	0.25	0.01	0.01	3.65	3.65	3.65	1.95
Carbon/Epoxy	112.5	9.77	9.77	0.25	0.02	0.02	3.29	3.29	3.29	1.52

To see the effects of fiber type and number of layers on the response, Taguchi method was used based on numerical data. Analysis design was conducted using L9 orthogonal array. The array has two control factors. Each control factor has three levels. The first control factor was assumed as fiber type whereas the second control factor was considered as number of layer of plates made of composite materials. The levels of the first control factor were determined as glass, boron, and carbon fibers, respectively. Also, the levels of the second control factor were used as one layer, two layers, and three layers, respectively. Control factors and their levels used in the analyses were shown in Table 2.

Table 2. Control factors and levels

Control Factors	Symbol	Levels		
		Level 1	Level 2	Level 3
Fiber Type	A	Glass	Boron	Carbon
Number of Layers	B	1	2	3

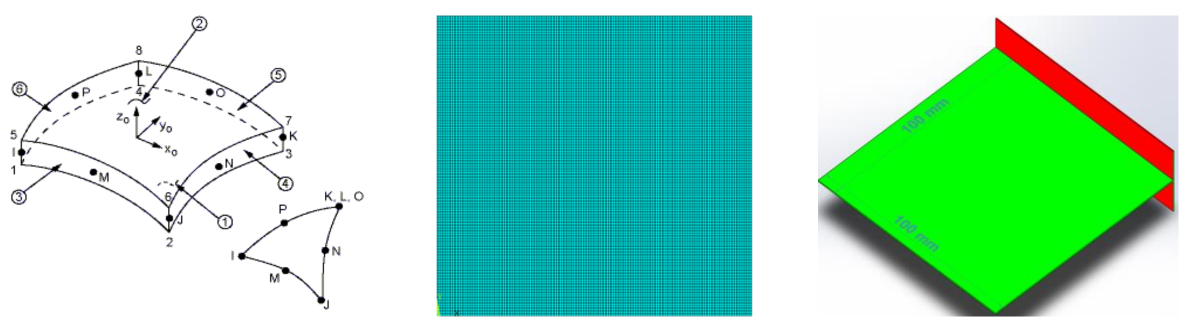
To get the maximum fundamental natural frequency data of laminated composite plates, “larger is better” quality approach presented in Taguchi method was utilized. Equation including this approach was given as [13].

$$(S/N)_{HB} = -10.\log\left(n^{-1}\sum_{i=1}^{n}\left(y_i^2\right)^{-1}\right) \quad (1)$$

where, n is the number of modal analyses in a trial and y_i expressions i^{th} data detected. Statistical analyses and their plots were performed using Minitab software.

3. FINITE ELEMENT ANALYSIS

In the numerical calculations, finite element software ANSYS was utilized to carry out modal analysis of the composite plates with different fibers. In software, each laminate has a thickness of 0.5 mm. The width and length of the plates are same and are 100 mm. In mesh operation, number of element divisions was assumed as 200. The fiber orientation angle of the plates was chosen to be 0 in degrees. In the finite element analysis, SHELL281 element type was utilized, and it contains 8 nodes including six degrees of freedom in accordance with each node: translations for the x, y, and z axes, and rotations based on the x, y, and z axes [14]. Block Lanczos mode was used as extraction method. The laminated composite square plates were selected as the right edge clamped and remaining edges free (C-F-F-F) boundary conditions. Element geometry, mesh size and cantilever laminated composite plates were illustrated in Figure 1.



a) b) c)

Figure 1. a) SHELL281 element geometry, b) mesh size and, c) cantilever laminated composite plates

4. RESULTS AND DISCUSSIONS

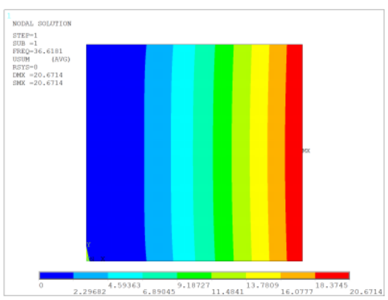
The numerical modal analysis of laminated composite plates was carried out to study the impacts of control factors over the output response characteristic. Nine analyses were performed using Taguchi methodology.

Each test was repeated one time for obtaining S/N ratio values since it depends on numerical calculations. Numerical fundamental natural frequency data for the first mode were given in Table 3.

Table 3. Results for frequency and S/N ratio

Analysis	Designation	Control Factors		Results	
		Type of Fibers	Number of Layers	Frequency λ (Hz)	S/N ratio η (dB)
1	A_1B_1	Glass	1	36.6181	31.2739
2	A_1B_2	Glass	2	73.2196	37.2925
3	A_1B_3	Glass	3	109.789	40.8112
4	A_2B_1	Boron	1	82.3644	38.3148
5	A_2B_2	Boron	2	164.566	44.3268
6	A_2B_3	Boron	3	246.444	47.8344
7	A_3B_1	Carbon	1	69.6246	36.8553
8	A_3B_2	Carbon	2	139.162	42.8704
9	A_3B_3	Carbon	3	208.528	46.3833
Overall Mean ($\bar{T}_\lambda$)				125.591	-

Modal analysis of each laminated composite plate was calculated for the first mode using ANSYS software and visual results obtained were presented in Figure 2. The red zones show the maximum affected edges whereas the blue zones indicate the minimum influenced edges.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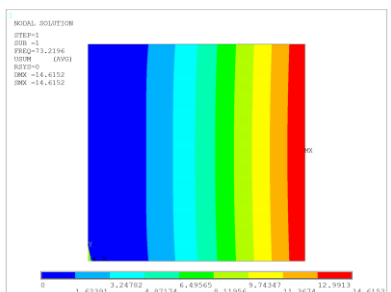
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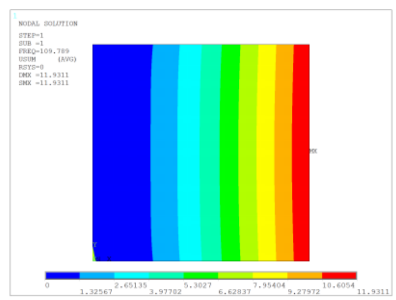
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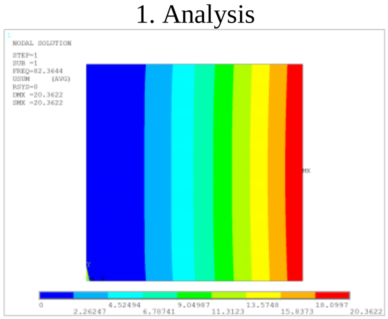
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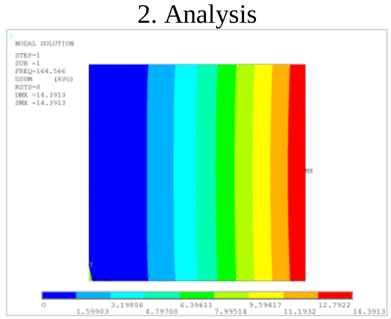
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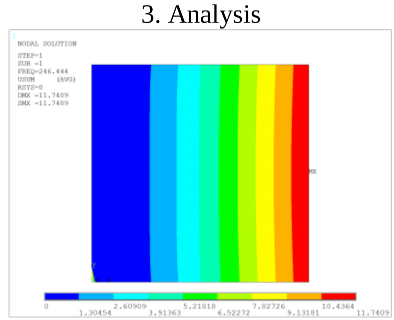
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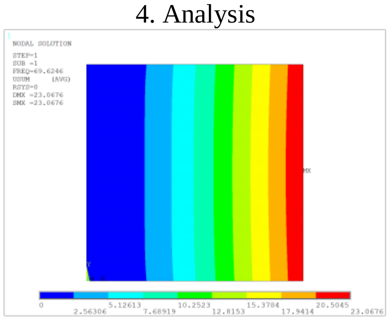
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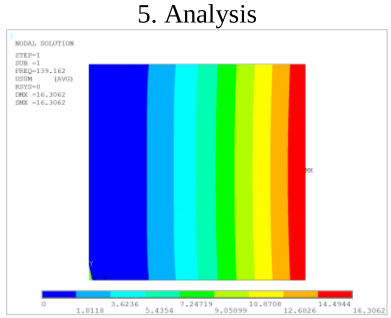
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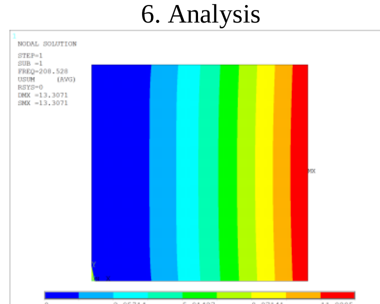
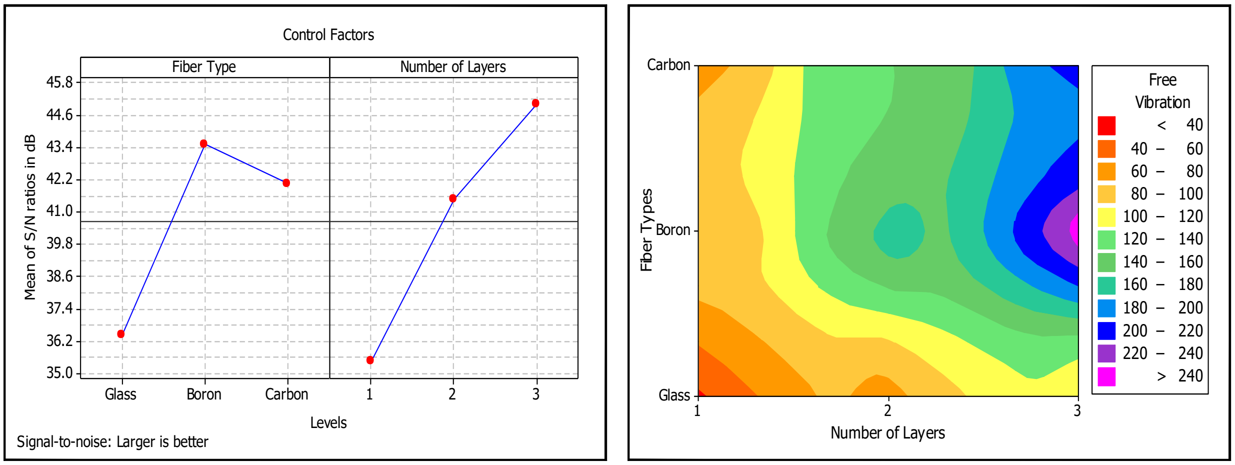

9. Analysis

Figure 2. Numerical results for modal analysis of laminated composite plates

4.1 Effects of Fiber Type and Number of Layers

To determine the effects of fiber type and number of layers on the modal analysis, numerical analyses were conducted in accordance with L9 orthogonal array with two control factors including three levels. The overall data of modal analysis for each control factor at all levels for S/N data were plotted in Figure 3.



a) b)

Figure 3. a) effects of control factors for S/N ratio data and b) contour plot of fundamental natural frequency

Figure 3 shows that fundamental natural frequency data of laminated composite plates were obtained using boron fiber, carbon fiber, and glass fiber, respectively. This is because the mechanical properties such as elasticity modules play the important role on the modal analysis of plates. In addition, fundamental natural frequency increases with increase of number of layers. This situation can be explained that increasing number of layers increases strength of plates.

4.2 Selection of Optimal Levels

To evaluate the significance of the control factors towards fundamental natural frequency analysis, analysis of variance (ANOVA) at 95 % confidence level was carried out. The results for R-Sq = 94.36% and R-Sq(adj) = 88.73% were presented in Table 4.

Table 4. ANOVA result

Source	DF	Seq SS	Adj SS	Adj MS	F	P	% Effect
A	2	13311.50	13311.50	6655.70	12.08	0.020	34.05
B	2	23582.00	23582.00	11791.00	21.41	0.007	60.32
Error	4	2203.20	2203.20	550.80			5.63
Total	8	39096.60					100

It was found that fiber type and number of layers are significant control factors for fundamental natural frequency analysis and thus these control factors affect the mean and variation in the fundamental natural frequency data. Also, number of layers has 60.32 % effect on fundamental natural frequency response whereas fiber type has 34.05 % effect. The overall data and S/N ratio of the modal characteristics for each variable at the various levels were solved from the numerical data. Response table for raw and S/N data was presented in Table 5. In addition, Table 5 demonstrations the average of each modal characteristic for S/N data and means at each level of each control factor. The rank and delta data present that the number of layers has the greatest effect on fundamental natural frequency and is followed by fiber type. As fundamental natural frequency value is the "higher is better" type quality characteristic, it can be seen from Table 5 that the second level of fiber type and the third level of number of layers provide the maximum value of fundamental natural frequency for S/N ratio and means data

Table 5. Response table for modal analysis

Level	S/N ratio (dB)		Mean (Hz)	
	A	B	A	B
1	36.46	35.48	73.21	62.87
2	43.49	41.50	164.46	125.65
3	42.04	45.01	139.10	188.25
Delta	7.03	9.53	91.25	125.38
Rank	2	1	2	1

4.3 Estimation of Optimal Levels

The optimal fundamental natural frequency value of laminated composite plates with different fiber type and number of layers along with their respective confidence intervals was estimated and the result of confirmation analysis was also shown to confirm the optimal fundamental natural frequency data. The optimal result of each fundamental natural frequency response was estimated considering the impact of the powerful control factors only. Thus, the estimated mean of fundamental natural frequency response can be examined as [13].

$$\mu_\lambda = \overline{A_2} + \overline{B_3} - \overline{T_\lambda} \tag{2}$$

where, $\overline{T_\lambda}$ =125.591 Hz and it is the overall mean of in accordance with L9 orthogonal array. $\overline{A_2}$= 164.46 is the average data of fundamental frequency at the second level of fiber type. $\overline{B_3}$= 188.25 is the overall data of fundamental frequency for the third level of number of layers. Thus μ_λ = 246.444 Hz. The 95 % confidence intervals in accordance with confirmation analyses (CI_{CE}) and population (CI_{POP}) were examined based on Equations 3 and 4 [13].

$$CI_{CA} = \left(F_{\alpha;1;n_2} V_{error} \left[\frac{1}{n_{eff}} + \frac{1}{R}\right]\right)^{1/2} \tag{3}$$

$$CI_{POP} = \left(\frac{F_{\alpha;1;n_2} V_{error}}{n_{eff}}\right)^{1/2} \tag{4}$$

$$n_{eff} = \frac{N}{(1 + T_{DOF})} \tag{5}$$

where, $n_2 = 4$ is the error number for degree of freedom and $\alpha = 0.05$ is the risk for 95 % confidence level. Thus $F_{0.05;1;4} = 7.71$ [13] in accordance with F ratio table at 95 % CI (α=0.05). $V_{error} = 550.80$ is error result of variance for ANOVA result. R presents the sample size of confirmation test obtained using numerical analyses. N = 9 is number of analyses for L9 orthogonal array. $T_{DOF} = 4$ is the sum of the degrees of freedom in accordance with important control factors. CI_{CA} and CI_{POP} are computed as ± 48.572 and ± 81.277, respectively. The expected confidence interval for confirmation test obtained using finite element analyses [13] is as follows:

$$\text{Mean } \mu_\lambda - CI_{CA} < \mu_\lambda < CI_{CA} + \text{Mean } \mu_\lambda$$

The population in accordance with the 95 % confidence interval [13] is as follows:

$$\text{Mean } \mu_\lambda - \text{CI}_{\text{POP}} < \mu_\lambda < \text{CI}_{\text{POP}} + \text{Mean } \mu_\lambda$$

The overall value of the characteristics was calculated and compared with the estimated variables. The finite element and expected results for fiber type and number of layers at the optimal levels were given in Table 6.

Table 4. ANSYS and predicted results at 95 % confidence level

Optimal Set	ANSYS Result	Predicted Result	Predicted Confidence Intervals at 95% Confidence Level
A_2B_3	246.444 Hz	227.119 Hz	$178.550 < \mu_\lambda < 275.668$ for CI_{POP} $145.847 < \mu_\lambda < 308.391$ for CI_{CA}

5. CONCLUSIONS

This study presents the evaluation of impacts of fiber type and number of layers on the fundamental natural frequency analysis of laminated composite plates according to numerical and statistical approaches. Numerical calculations were used ANSYS software whereas statistical solutions were utilized Minitab software. Design of numerical tests was conducted using Taguchi L9 orthogonal array including two control factors with three levels. To calculate the effects and percent contributions of control factors on the fundamental natural frequency of laminated composite plates, S/N ratio and variance analyses were performed. Finite element and predicted results for the first mode modal analysis were compared with each other in accordance with 95 % confidence level. The conclusions are as follows:

- The maximum fundamental natural frequency value of laminated composite plate was obtained using boron fiber compared to glass and carbon fibers.
- The most effective fiber types on the fundamental natural frequency analysis of laminated composite plates were obtained as boron, carbon, and glass, respectively.
- Increase of the number of layers for laminated composite plates provides the increase of fundamental natural frequency values.
- According to ANOVA at 95 % confidence level, fiber type and number of layers have significant effect. Also, fiber type has 34.05 % impact on fundamental natural frequency whereas number of layers has 60.32 % impact.
- Predicted optimal fundamental natural frequency results of laminated composite plates at the 95 % confidence level were calculated as $178.550 < \mu_\lambda < 275.668$ for CI_{POP} and $145.847 < \mu_\lambda < 308.391$ for CI_{CA}.

6. ACKNOWLEDGEMENTS

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