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Investigation of effects of fiber orientation angles on deflection behavior of cantilever laminated composite square plates

Ankastre tabakalı kompozit kare plakaların yer değişimi davranışı üzerinde fiber oryantasyon açılarının etkilerinin incelenmesi

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Investigation of Effects of Fiber Orientation Angles on Deflection Behavior of Cantilever Laminated Composite Square Slates

Highlights

- *The deflection response of cantilever laminated composite square plates subjected to the weight of itself was analyzed using finite element and Taguchi methods.*
- *The plates with 12 plies were made of glass fiber reinforced polymer composites (GFRP).*
- *The arrangements and fiber orientation angles of the plies were conducted using Taguchi's L9 (3^3) orthogonal array.*
- *Analysis of signal-to-noise (S/N) ratio was used to evaluate the control factors with the optimum levels for minimum deflection response.*
- *Analysis of variance was carried out to analyze the powerful influential control factors and their percent contributions on responses.*

Graphical Abstract

Finite element analyses of the cantilever laminated composite plates were conducted to investigate the influences of the fiber orientation angles on the response characteristic. The stacking sequences were designed using Taguchi's L9 orthogonal array.

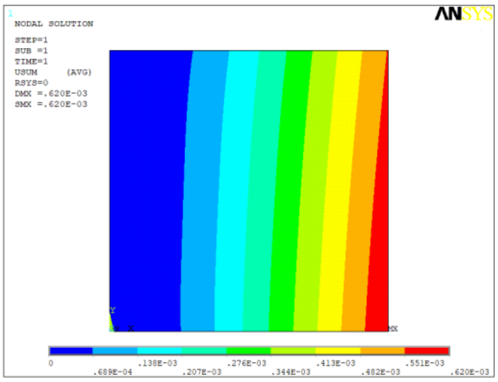

Figure. ANSYS optimal data

Aim

The deflection response of cantilever laminated composite square plates subjected to the weight of itself was investigated.

Design & Methodology

The deflection response was analyzed using Finite Element and Taguchi methods.

Originality

The arrangements and fiber orientation angles of the plies were conducted using Taguchi's L9 (3^3) orthogonal array.

Findings

The most effective plies called as A, B, and C were found to be 97.352 % contribution, 2.152 % contribution, and 0.482 % contribution respectively.

Conclusion

The increase of the fiber orientation angles of plates from 0^0 to 90^0 leads to the increase of deflection values.

Declaration of Ethical Standards

The author of this article declares that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Investigation of Effects of Fiber Orientation Angles on Deflection Behavior of Cantilever Laminated Composite Square Plates

Araştırma Makalesi / Research Article

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ABSTRACT

In this study, the deflection response of cantilever laminated composite square plates subjected to the weight of itself was analyzed using finite element and Taguchi methods. The plates with 12 plies were made of glass fiber reinforced polymer composites (GFRP). The arrangements and fiber orientation angles of the plies were conducted using Taguchi's L9 (33) orthogonal array. Each four plies was assumed to be control factor. Fiber orientation angles were varied from 10 to 90 in degree. Plates were modelled using finite element software ANSYS Parametric Design Language. Analysis of signal-to-noise (S/N) ratio was used in order to evaluate the control factors with the optimum levels for minimum deflection response. Analysis of variance was carried out in order to analyze the powerful influential control factors and their percent contributions on responses.

Keywords: Fiber reinforced composite laminates, finite element analysis, Taguchi method, plate.

Ankastre Tabakalı Kompozit Kare Plakaların yer Değişimi Davranışı Üzerinde Fiber Oryantasyon Açılarının Etkilerinin İncelenmesi

ÖZ

Bu çalışmada, kendi ağırlığına maruz bırakılmış ankastre tabakalı kompozit plakaların yer değişimi yanıtı sonlu elemanlar ve Taguchi metotları kullanılarak analiz edilmiştir. Plakalar 12 tabakalı cam fiberle güçlendirilmiş polimer kompozitlerden yapılmıştır. Tabakaların fiber oryantasyon açılarının sıralanması Taguchi L9 (33) ortogonal dizi kullanılarak yapıldı. Her dört tabaka kontrol faktörü olarak kabul edildi. Fiber oryantasyon açıları 10 derecenden 90 dereceye değiştirildi. Plakalar sonlu elemanlar yazılımı ANSYS kullanılarak modellendi. Sinyal gürültü oran analizi minimum yer değişim yanıtı için optimum seviyeli kontrol faktörlerini değerlendirmek için kullanıldı. Varyans analizi yanıtlar üzerinde güçlü etkili kontrol faktörleri ve onların yüzde katkılarını analizi için gerçekleştirildi.

Anahtar Kelimeler: Fiber takviyeli kompozit tabakalar, sonlu elemanlar analizi, Taguchi metodu, plaka.

1. INTRODUCTION

Fiber reinforced composite laminates can be manufactured as laminated composite plates or beams. The composite laminates have higher stiffness, strength and less weight according to the conventional metallic structures [1]. The laminated composite plates are generally used in the different areas. Thus many studies using these materials were presented for different analyses bending, vibration, buckling etc. In literature, there are many studies with deflection and bending analyses of laminated composite plates and beams. Rakočević and Vatin [2] studied bending behavior of plates made of laminated composite. Rakočević and Popović [3] evaluated the bending behavior of rectangular plates made of laminated composites under simply supported boundary conditions. Iyengar and Umaretiya [4] investigated the deflection behavior of laminated plates made of hybrid composite. Reddy et al. [5] studied the bending behavior of plates made of laminated composite according to finite element approach. Ćetković and Vuksanović [6] evaluated the bending, natural vibrations, and buckling characteristics of the laminated composite and sandwich plates and they also used a layerwise displacement model. Maiti and Sinha [7] investigated the bending, natural vibration, and impact behaviors of thick plates made of laminated composite. Karama et al. [8] investigated the bending, buckling, and natural vibration characteristics of the laminated composite and they also used a transverse shear stress continuity model for analyses. Khdeir and Reddy [9] presented a study containing an exact solution about the bending behavior of thin and thick cross-ply laminated beams. Lee et al. [10] analyzed the bidirectional bending behavior of plates made of

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laminated composites and they also used an improved zig-zag model in analysis. In this study, the effects of fiber orientation angles of plies on the deflection behavior of the laminated composite plates were investigated using finite element and Taguchi methods. In literature, the finite element method in many studies [11] were used for various analyses. The numerical analyses and arrangements of the fiber orientation angles was conducted using L9 orthogonal array based on Taguchi method. The finite element analysis were performed using ANSYS finite element software.

2. MATERIAL and METHOD

In the analyses, the rectangular square laminated composite plates were used. The laminated plates were made of glass fiber reinforced polymer composite (GFRP) [12]. The sum of plies for plates were assumed to be 12. Fibers with 0^0 angle were considered in the axial direction (x-axis). The stacking sequences of the plies were determined in the thickness direction. The material constant were listed in Table 1.

Table 1. The material constants [12]

E_1	E_2=E_3	G_{12} = G_{13} = G_{23}	ν_{12} = ν_{13}	ν_{23}	ρ
37.78 (GPa)	10.9 (GPa)	4.91 (GPa)	0.3 (-)	0.11 (-)	2003.5 (kg m^{-3})

Fiber orientation angles were assumed to vary from 10^0 to 90^0. The arrangements of the fiber angles were conducted using Taguchi's L9 orthogonal array. The array consists of three control factors and each control factor contains three levels. The levels were considered to be fiber orientation angles. For laminated composite rectangular square plates, four plies were determined to be a control factor and it was symbolized to be A, B, and C. The control factors and levels were tabulated in Table 2.

Table 2. Control factors and levels

Control Factor	Unit	Symbol	Levels		
			Level 1	Level 2	Level 3
First Four Laminates	Degree	A	10	20	30
Second Four Laminates	Degree	B	40	50	60
Third Four Laminates	Degree	C	70	80	90

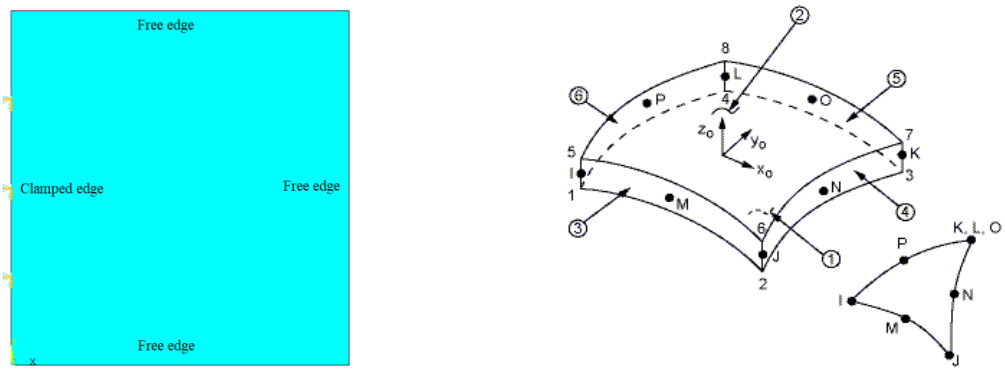
As can be seen from Table 2, fiber orientation angles for the first four laminates as called A were considered to vary from 10^0 to 30^0. Fiber orientation angles for the second four laminates as encoded B were assumed to vary from 40^0 to 60^0. Fiber orientation angles for the third four laminates as named C were designed to vary from 70^0 to 90^0. The numerical deflection results of the laminated square composite plates were determined using statistical software Minitab 15 [13]. The finite element results were converted to S/N ratio data according to "Smaller is Better" quality characteristic as shown in Equation 1 [14].

$$(\mathrm{S/N})_{\mathrm{SB}} \text{ for } \mathrm{y} = -10.\log\left(\mathrm{n}^{-1}\sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{y_i})^2\right) \qquad (1)$$

where, n represents the number of analyses for deflection in a trial and y_i shows ith data observed. In order to determine the minimum deflection result of the laminated composite plates subjected to the weight of itself, the quality characteristic was used.

3. FINITE ELEMENT MODELLING

The numerical analysis and modelling of the laminated composite plates were achieved using the finite element software ANSYS V13 Mechanical APDL called as ANSYS Parametric Design Language [15]. The numerical analyses for deflections were conducted based on L9 orthogonal array. Each laminated composite square plate was considered as length with 204.6 mm [12] and thickness with 2.11 mm [12]. The ply orientation distributions of the plates were assumed in thickness directions. Acceleration was defined to be 9.81m/s^2 along the z-direction. The cantilever laminated composite plate was caused by the weight of itself. Mesh operation was done using 80x80 mesh sizes according to Mapped mesh. In the software, SHELL281 element type was used and it consists of eight nodes containing six degrees of freedom according to each node: translations based on the x, y, and z axes, and rotations for the x, y, and z axes [16]. The laminated composite plates were determined to be the left edge clamped and remaining edges free (C-F-F-F) boundary conditions. In addition, the plate with C-F-F-F boundary conditions and element geometry were demonstrated in Figure 1.



(a) (b)

Figure 1. (a) Plate with C-F-F-F and (b) SHELL281 [16] element geometry

4. RESULTS and DISCUSSIONS

Finite element analyses of the cantilever laminated composite plates were conducted to investigate the influences of the fiber orientation angles on the response characteristic. The stacking sequences were designed using Taguchi's L9 orthogonal array. The finite element data and their S/N ratio values (η) for "Smaller is Better" quality characteristic were presented in Table 3.

Table 3. Numerical and S/N ratio results

Run	Designation	Control Factors			Results	
		Stacking Sequence			y (mm)	η (dB)
1	$A_1B_1C_1$	$(10)_4$	$(40)_4$	$(70)_4$	0.620	4.15217
2	$A_1B_2C_2$	$(10)_4$	$(50)_4$	$(80)_4$	0.638	3.90359
3	$A_1B_3C_3$	$(10)_4$	$(60)_4$	$(90)_4$	0.650	3.74173
4	$A_2B_1C_2$	$(20)_4$	$(40)_4$	$(80)_4$	0.688	3.24823
5	$A_2B_2C_3$	$(20)_4$	$(50)_4$	$(90)_4$	0.704	3.04855
6	$A_2B_3C_1$	$(20)_4$	$(60)_4$	$(70)_4$	0.704	3.04855
7	$A_3B_1C_3$	$(30)_4$	$(40)_4$	$(90)_4$	0.775	2.21397
8	$A_3B_2C_1$	$(30)_4$	$(50)_4$	$(70)_4$	0.775	2.21397
9	$A_3B_3C_2$	$(30)_4$	$(60)_4$	$(80)_4$	0.794	2.00359
Overall Means ($\bar{T}_y$)					0.705	

4.1 Effects of Fiber Angles

The laminated composite plates were made from different fiber orientation angles. The fiber angles were conducted using L9 orthogonal array. In order to see the influences of fiber orientation angles of the plies on the deflection analysis, the average values of the deflection results for each control factor at level 1, level 2, and level 3 according to finite element and S/N ratio results were calculated using Minitab 15 statistical software. The numerical and statistical data calculated were tabled in Table 4.

Table 4. Response table for S/N ratio and mean

Level	S/N ratios in dB			Means in mm		
	A	B	C	A	B	C
1	3.932	3.205	3.138	0.6360	0.6943	0.6997
2	3.115	3.055	3.052	0.6987	0.7057	0.7067
3	2.144	2.931	3.001	0.7813	0.7160	0.7097
Delta	1.789	0.273	0.137	0.1453	0.0217	0.0100
Rank	1	2	3	1	2	3

It can be seen from Table 4 that the optimum result for the minimum deflection value was obtained using laminate with the first levels. In addition, the delta and rank values show that the first four plies encoded as A have the maximum effect on the deflection analysis and it is followed by B and C respectively. The average results of the deflection values for each level of each control factor according to S/N ratio were plotted in Figure 2.

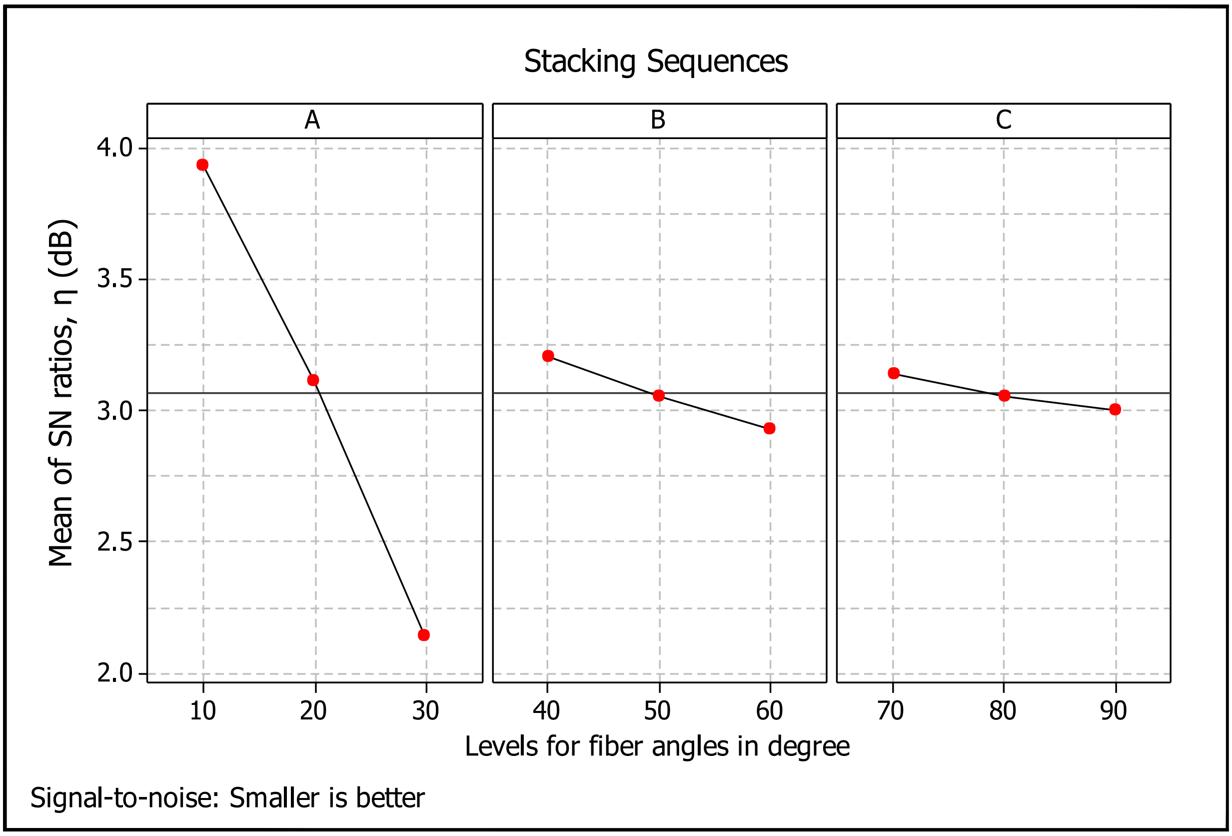


Figure 2. Main effects plot of S/N ratios

As can be seen from Figure 2, the increase of the levels of fiber angles causes the increase of the deflection values. In other words, the decrease of the fiber orientation angles of plies from 90 to 10 leads to the decrease of the displacement of the laminated composite plates along z-axes.

4.2 Analysis of Variance

In the deflection analysis of the laminated composite plates, analysis of variance (ANOVA) was employed in order to analyze the powerful influential plies and their % contributions on the deflection behavior. The analysis was carried out using the numerical results according to the 95 % confidence level. The ANOVA result performed for R-Sq = 99.99 % and R-Sq(adj) = 99.94 % was listed in Table 5.

Table 5. ANOVA result

Source	DF	Seq SS	Adj MS	F	P	% Effect
A	2	0.0318830	0.0159410	6832	0.000	97.352
B	2	0.0007050	0.0003520	151	0.007	2.152
C	2	0.0001580	0.0000790	33.86	0.029	0.482
Error	2	0.0000047	0.0000023			0.014
Total	8	0.0327500				100

According to Table 5, the laminates called as A, B, and C were determined to be significant control factors on the deflection analysis because of P-value < 0.05 depending on 95 % confidence level. The percent contributions of the laminates such as A, B, and C were found to be 97.352 %, 2.152 %, and 0.482 % respectively. The error data was calculated to be 0.014 %.

4.3 Estimation of Optimum Deflection Characteristic

The optimum result of deflection behavior was predicted for the optimal levels of significant control factors. The significant control factors were determined to be A, B, and C in ANOVA. The estimated mean of response characteristic as called deflection behavior can be calculated in Equation 2 [14].

$$\mu_y = \overline{A_1} + \overline{B_1} + \overline{C_1} - 2\overline{T}_y \qquad (2)$$

where, $\overline{T}_y$ is used to be overall mean of deflection results based on L9 orthogonal array in Taguchi method and it was taken to be 0.705 mm from Table 3. $\overline{A_1}$= 0.6360, $\overline{B_1}$= 0.6943, and $\overline{C_1}$ = 0.6997 were taken to be average values of numerical deflection results at first level of the control factors such as A, B, and C in Table 4. Substituting the values of different terms in Equation 2, μ_y was calculated to be 0.620 mm. The 95 % confidence intervals for confirmation analyses (CI_{CE}) and population (CI_{POP}) were analyzed using Equation 4 and Equation 5 [14].

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

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

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

in which, $\alpha = 0.05$ represents the risk and n_2 is used to be the error value based on the degree of freedom and it is determined to be 2 in ANOVA. Thus $F_{0.05;1;2}$ is employed to be 18.5 [14] according to F ratio results for the 95 % CI (α=0.05). Error value for variance in Table 5 was symbolized to be V_{error} and it is used 0.0000023 value. In addition, R is determined to be the sample size of confirmation analyses and it is used to be 1. Sum of the number of the data is encoded to be N and is used to be 9 in Table 3. Sum of the degrees of freedom for significant control parameters is shown to be T_{DOF} and is solved to be 6. n_{eff} is determined to be 1.286 so CI_{CA} and CI_{POP} are found to be ± 0.009 and ± 0.006 respectively. Thus, the predicted confidence interval according to confirmation analyses [14] is as follows:

$$\text{Mean } \mu_y - CI_{CA} < \mu_y < CI_{CA} + \text{Mean } \mu_y$$

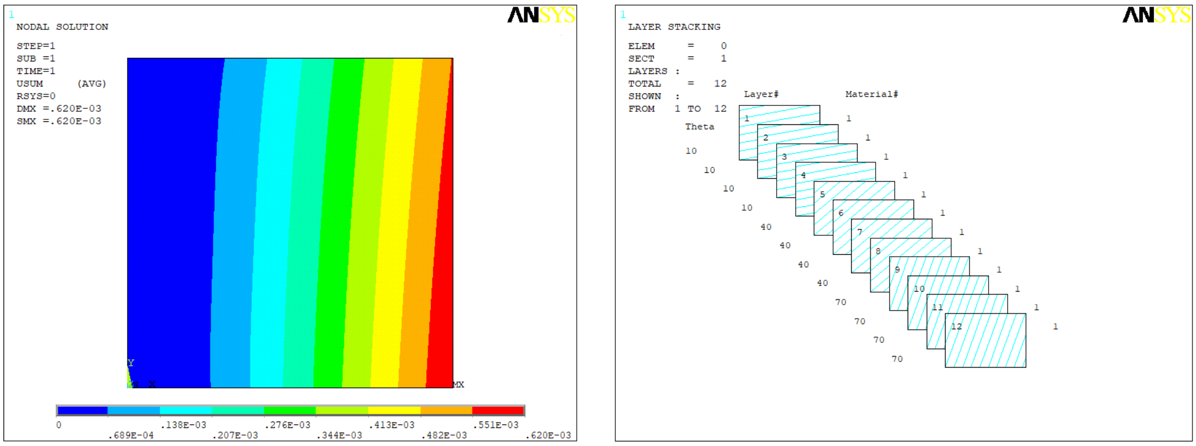
The population according to the 95 % confidence interval [14] is as follows:

$$\text{Mean } \mu_y - CI_{POP} < \mu_y < CI_{POP} + \text{Mean } \mu_y$$

The numerical and predicted results for the optimal plies were calculated for CI_{CA} and CI_{POP} and these results were tabulated in Table 6. The finite element result and the stacking sequence for laminated composite plates made of the plies with optimum fiber orientation angles were demonstrated in Figure 3 visually.

Table 6. Numerical and predicted results

Optimal Plies	Numerical Result	Predicted Result	Estimated Confidence Intervals for 95% Confidence Level
$A_1B_1C_1$	0.620 mm	0.620 mm	$0.611 < \mu_y < 0.629$ for CI_{CA}
			$0.614 < \mu_y < 0.626$ for CI_{POP}



(a) (b)

Figure 3. Optimal data: (a) ANSYS result and (b) stacking sequence

According to Figure 3a, the minimum deflection data was obtained on the clamped edge whereas the maximum deflection value was determined for opposite edge of this clamped edge.

4.4 Effects of Stacking Sequences

In order to see the effects of stacking sequences on the deflection analysis, the laminated composite plate with optimum fiber angles was used. The plies with the optimum levels were determined using Taguchi method. Thus the different combinations of the plies with optimum fiber orientation angles were modelled using finite element software ANSYS and the numerical results obtained were tabulated in Table 7.

Table 7. Deflection results of different plates with optimum plies

Plate Combination	Designation	Stacking Sequence	y (mm)
Plate 1	$A_1B_1C_1$	$[(10)_4/(40)_4/(70)_4]$	0.620
Plate 2	$C_1B_1A_1$	$[(70)_4/(40)_4/(10)_4]$	0.620
Plate 3	$A_1C_1B_1$	$[(10)_4/(70)_4/(40)_4]$	0.531
Plate 4	$B_1C_1A_1$	$[(40)_4/(70)_4/(10)_4]$	0.531
Plate 5	$B_1A_1C_1$	$[(40)_4/(10)_4/(70)_4]$	0.815
Plate 6	$C_1A_1B_1$	$[(70)_4/(10)_4/(40)_4]$	0.815

It is noticed from Table 7 that the laminated composite plates with optimum levels for minimum deflection were determined as Plate 1 with $[(10)_4/(40)_4/(70)_4]$ and Plate 2 with $[(70)_4/(40)_4/(10)_4]$. But, deflection values in the analysis performed using Plate 3 containing $[(10)_4/(70)_4/(40)_4]$ and Plate 4 containing $[(40)_4/(70)_4/(10)_4]$ smaller than displacements of the plates determined according to Taguchi method. It is clear that fiber orientation angle of the outermost layer has more significant effect on the deflection analysis of the laminated composite plates.

5. CONCLUSIONS

In this study, the effects of fiber orientation angles on the deflection analysis of the laminated composite plates were investigated using finite element and Taguchi methods. The laminated composite plates were determined to be the left edge clamped and remaining edges free (C-F-F-F) boundary conditions. Numerical deflection analysis was studied using finite element software ANSYS Parametric Design Language. The arrangements of the plies and numerical analyses were conducted using Taguchi's L9 (3^3) orthogonal array. The optimum levels of the plies were carried out using analysis of S/N ratio. Significant control parameters on the deflection analysis were observed using ANOVA. The important conclusions from this study are explained as follows:

- ❖ The increase of the fiber orientation angles of plates from 0^0 to 90^0 leads to the increase of deflection values.
- ❖ According to analysis of signal-to-noise ratio, the minimum deflection result was obtained using the laminated composite plate with fist levels.
- ❖ The fiber orientation angle of the outermost layer has more significant effect on the deflection analysis of the laminated composite plates.
- ❖ It is clear from ANOVA that each four plies is significant control parameters due to P-value < 0.05 for 95 confidence level.
- ❖ The most effective plies called as A, B, and C were found to be 97.352 % contribution, 2.152 % contribution, and 0.482 % contribution respectively.
- ❖ Estimated minimum deflection results at 95 % confidence intervals of confirmation analyses (CI_{CA}) and population (CI_{POP}) are determined to be $0.611 < \mu_y < 0.629$ for CI_{CA} and $0.614 < \mu_y < 0.626$ for CI_{POP} respectively.
- ❖ The overall mean of deflection results was found to be 0.705 mm according to L9 orthogonal array.
- ❖ The minimum deflection result was observed on the clamped edge whereas the maximum deflection value was detected the opposite edge of this edge.
- ❖ The stacking sequence of the plies has important effects on deflection analysis of the cantilever laminated composite plates

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