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Twisting Angle Analysis of Laminated Composite Plates Using Numerical and Statistical Methods

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Abstract: This study deals with the investigation of the effects of fiber orientation angles on the analysis of angle of twist of laminated composite plates under cantilever boundary conditions with left edge clamped and remaining edges free (C-F-F-F). Numerical twisting angle analyses were conducted based on Taguchi's L8 ortogonal array. The plates were designed using 8 plies and each two plies was determined to be a control factor. The fiber orientation angles in each control factor were assumed to vary from 100 to 800 through the axial direction. Analysis of signal-to-noise (S/N) ratio was performed to see the effects of fiber angles and to determine the optimum levels for minimum twisting angle. Analysis of Variance (ANOVA) was applied to analyze the significant control factors and percent contributions on the twisting angle results. Regression analysis was employed mathematically in order to see the effects of the fiber angles on the response. According to ANOVA result, the most effective control factors were found to be D with 87.51 %, C with 10.26 %, A with 1.22 %, and B with 0.04 % respectively.

Sayısal ve İstatiksel Metotlar Kullanılarak Tabakalı Kompozit Plakaların Burulma Açı Analizi

Anahtar Kelimeler
Tabakalı kompozit,
Burulma açısı,
ANSYS,
Plakalar

Özet: Bu çalışma sol kenarı tutulu ve kalan kenarları serbest (C-F-F-F) ankastre sınır şartlı tabakalı kompozit plakaların burulma açı analizi üzerinde fiber oryantasyon açılarının etkilerinin incelenmesi ile alakalıdır. Sayısal burulma açı analizleri Taguchi L8 ortogonal diziye bağlı gerçekleştirilmiştir. Tabakalar 8 tabaka kullanılarak tasarlanmıştır ve her iki tabaka kontrol faktörü olarak değerlendirilmiştir. Her kontrol faktöründeki fiber oryantasyon açısı eksenel yönde 100'den 800 değiştiği varsayılmıştır. Minimum burulma açısı için optimum seviyeleri karar vermek ve fiber açılarının etkisini görebilmek için sinyal gürültü oran analizi gerçekleştirilmiştir. Varyans analizi (ANOVA) burulma açı sonuçları üzerinde önemli kontrol faktörleri ve katkı oranları analiz etmek için uygulandı. Matematiksel olarak yanıtlar üzerinde fiber açılarının etkilerini görebilmek için regresyon analizi uygulanmıştır. ANOVA sonucuna göre en efektif kontrol faktörleri sırasıyla %87.51 ile D, % 10.26 ile C, % 1.22 ile A ve % 0.04 ile B olarak bulunmuştur.

1. Introduction

Composite materials are generally used in different applications of mechanical engineering due to their excellent properties. Thus laminated composite plates can be made from composite materials. Recently years, there are many studies such as vibration [1] and buckling [2] analyses of twisted plates using the laminated composite plates. The studies consisting the torsional analysis are limited. Taşdelen et al. [3] investigated the torsional behavior and numerical analysis of the shafts made of hybrid laminated composite and they used ANSYS finite element software. Badie et al. [4] presented an evaluation consisting automotive drive shaft made of hybrid carbon/glass fiber reinforced epoxy composite. Sevkat et al. [5] evaluated the torsional behavior of shafts made of hybrid composite using a combined experimental and numerical methods. Sevkat and Tumer [6] studied the residual torsional properties of shafts made of composite materials under impact loading. In this study, numerical and

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statistical twisting angle analysis of laminated composite plates subjected to torsional load under C-F-F-F boundary conditions. Finite element analyses for twisting angle were conducted using Taguchi's L8 orthogonal array.

2. Material and Method

The laminated composite plate was made from carbon fiber reinforced polymers (CFRP) and it has 8 laminates [7]. Also, the plates were determined to be rectangular square. The material constants were listed in Table 1.

Table 1. The material constants [7]

E_1	$E_2=E_3$	$G_{12} = G_{13}$	G_{23}	$\nu_{12} = \nu_{13}$	ν_{23}
172.70 (GPa)	7.20 (GPa)	3.76 (GPa)	2.71 (GPa)	0.30 (-)	0.33 (-)

The layer stacking sequences were designed according to Taguchi's L8 orthogonal array. This array has four control factors and two levels for each control factor. In addition, numerical analyses and plies arrangements were conducted for Taguchi method. The number of plies was assumed to be the control factors. The fiber orientation angles were used to be levels of the control factors. The fiber angles were considered to vary from 10 to 80 in degree. The control factors and levels were exhibited in Table 2.

Table 2. Control factors and levels

Symbol	Control Factors	Levels in Degree (α)	
A	1. and 2. Plies	10^0	20^0
B	3. and 4. Plies	30^0	40^0
C	5. and 6. Plies	50^0	60^0
D	7. and 8. Plies	70^0	80^0

The finite element analysis was assumed to obtain the minimum value of twisting angle of plates. Because of that, the smaller is better quality characteristic was used. The quality characteristic was shown in Equation 1 [8].

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

where, n is achieved to be the number of finite element analyses in a trial and yi is assumed to be ith data analyzed. The analysis of signal-to-noise ratio was performed using Minitab 15 statistical software.

3. Finite element analysis

Numerical analyses for angle of twist in X direction (Sx) were determined by finite element software ANSYS. SHELL281 element type was used and it consists of eight nodes which having six degrees of freedom depending on each node: translations for the x, y, and z axes, and rotations according to the x, y, and z-axes [9]. In the analyses, rectangular square laminated composite plates with 8 laminates were used and a side length and thickness of the plate were assumed to be 178 mm and 1.58 mm respectively [7]. The plates were modelled using cantilever boundary conditions with left edge clamped and remaining edges free (C-F-F-F). Free vertical edge (y axis) of the plate was applied a constant twisting moment with MX = 50 N/mm. The mesh operation was carried out using mapped mesh with 50x50 mesh size. The twisting moment was determined to be MX and it was divided by the node number on the free vertical edge (50/101 in N/mm).

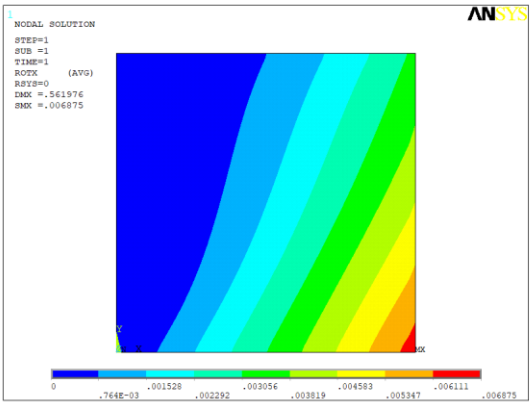
4. Results and Discussions

The study deals with the evaluation of the influences of fiber orientation angles on the twisting angle behavior of the cantilever square laminated composite plates in X direction (Sx). The finite element analyses obtained using ANSYS were conducted by using the L8 orthogonal array based on the Taguchi method. The numerical (α) and S/N (η) ratio results were tabulated in Table 3.

The finite element analyses performed for angle of twist in radian were exhibited in Figure 1. It is clear from Figure 1 that the minimum affected edge of plates is clamped edge. In addition, affected edges are distributed. That situation is explained by distribution of the fiber orientation angles of plates.

Table 3. Numerical and S/N ratio results

Analysis	Designation	Stacking Sequences				Results	
		A	B	C	D	α in Degree	η in dB
1	$A_1B_1C_1D_1$	10	30	50	70	0.393908	8.09209
2	$A_1B_1C_2D_2$	10	30	60	80	0.359359	8.88943
3	$A_1B_2C_1D_2$	10	40	50	80	0.346983	9.19383
4	$A_1B_2C_2D_1$	10	40	60	70	0.418947	7.55682
5	$A_2B_1C_1D_2$	20	30	50	80	0.354260	9.01356
6	$A_2B_1C_2D_1$	20	30	60	70	0.421812	7.49763
7	$A_2B_2C_1D_1$	20	40	50	70	0.400727	7.94303
8	$A_2B_2C_2D_2$	20	40	60	80	0.366922	8.70852
Overall mean ($\overline{T_\alpha}$)						0.382865	-



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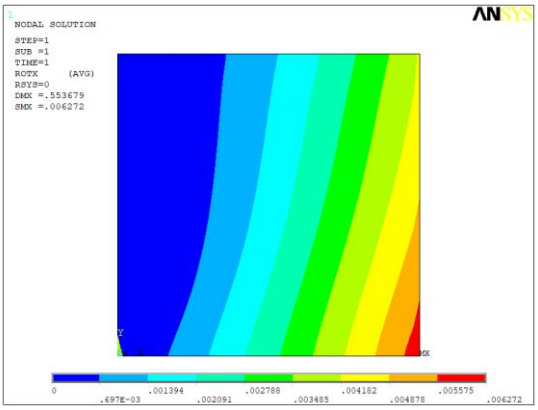

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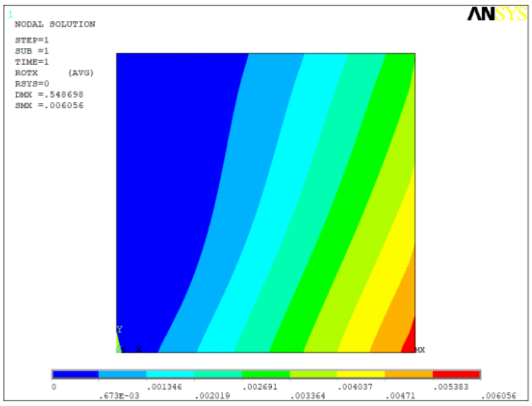

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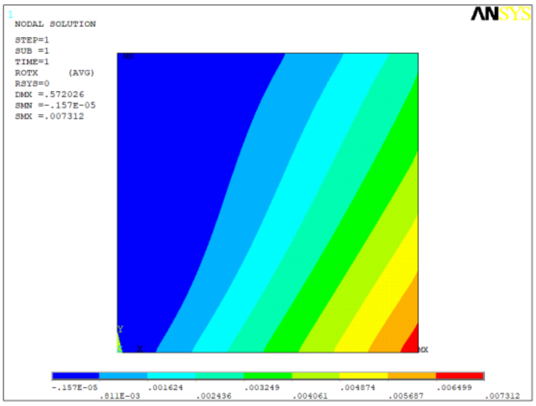

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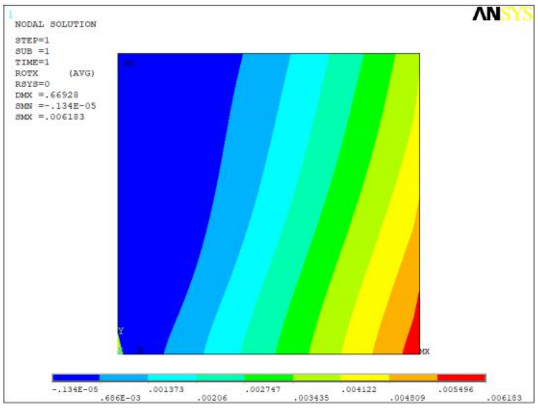

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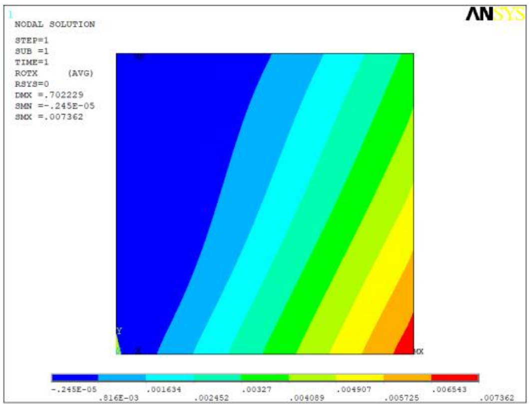

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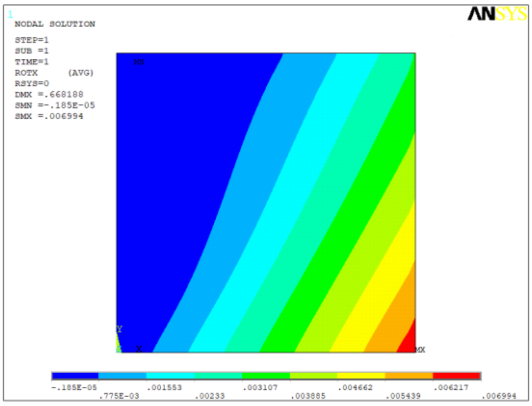

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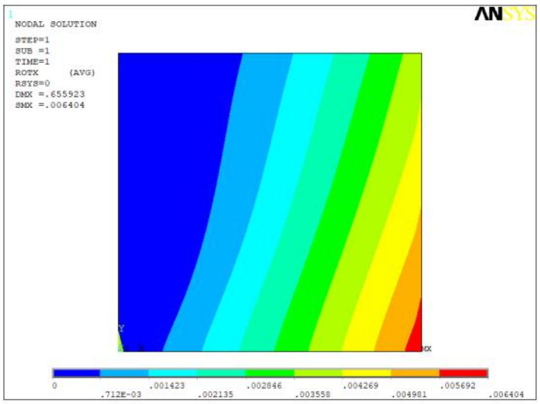


8. Test

Figure 1. Finite element results based on L8 orthogonal array

4.1 Determination of optimal levels of angles

In order to select the optimal levels of the fiber orientation angles on the angle of twist of laminated composite plates, average results of twisting angles for each control parameter at level1, and level 2 according to the numerical values and S/N ratio data were calculated using statistical software Minitab 15.

The results obtained for S/N ratios and means were presented in Table 4. According to Table 4, the optimum result for the minimum twisting angle of laminated composite plates was obtained using the first levels of the control factors named as A, B, C and the second levels of the control factor called as D.

4.2 Effect on angle of twist of plates

In order to investigate the effect on angle of twist, the numerical analyses were conducted using L8 orthogonal array. The finite element results were analyzed using Minitab 15 software in order to solve the average results of twisting angles for each level of each control factor based on S/N ratio values. The average S/N ratio results were plotted in Figure 2.

It is seen from Figure 2 that the increase of fiber angles of the first, second, third, fourth, fifth, and sixth plies increases the twisting angle of the plates whereas the increase of the fiber angles of seventh, and eighth plies decreases the twisting angle of the plates. In other words, the control factors called as A, B and C have the opposite effects on the response according to control factor named as D.

4.3 Analysis of Variance for twisting angle

In order to determine the importance levels and percent contributions of the plies towards twisting angle of laminated composite plates, analysis of variance (ANOVA) was used. The analysis was carried out using finite element data for 95 % confidence level. In addition, it is used SS adjusted for tests.

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

Level	Signal to Noise Ratios, η (dB)				Means, α (degree)			
	A	B	C	D	A	B	C	D
1	8.433	8.373	8.561	7.772	0.3798	0.3823	0.3740	0.4088
2	8.291	8.351	8.163	8.951	0.3859	0.3834	0.3918	0.3569
Delta	0.142	0.023	0.398	1.179	0.0061	0.0011	0.0178	0.0520
Rank	3	4	2	1	3	4	2	1

Table 5. Analysis of variance for twisting angle

Source	DF	Seq SS	Adj SS	Adj MS	F	P	% Effect
A	1	0.0000752	0.0000752	0.0000752	3.72	0.149	1.22
B	1	0.0000022	0.0000022	0.0000022	0.11	0.761	0.04
C	1	0.0006330	0.0006330	0.0006330	31.35	0.011	10.26
D	1	0.0054012	0.0054012	0.0054012	267.49	0.000	87.51
Error	3	0.0000606	0.0000606	0.0000202			0.97
Total	7	0.0061722					100

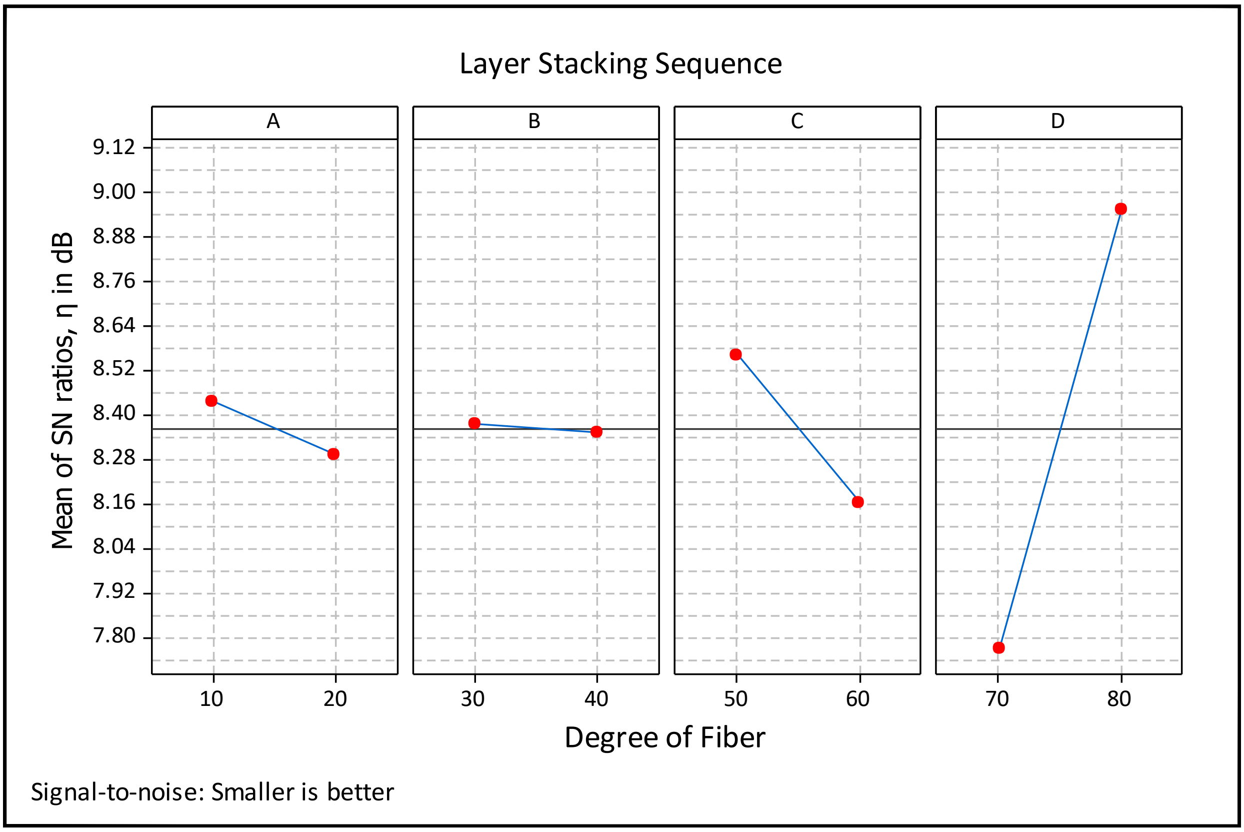


Figure 2. Main effects plot of S/N ratios

The ANOVA result for R-Sq = 99.02 %, and R-Sq (adj) = 97.71 % was presented in Table 5. According to ANOVA result, fifth, sixth, seventh, and eighth plies of plates are significant control factors for twisting angle whereas the others plies are non-significant control factors because P value is higher than 0.05 for 95 confidence level. In addition, the most effective control factors are found to be D with 87.51 %, C with 10.26 %, A with 1.22 %, and B with 0.04 % respectively.

4.4 Estimation of optimum twisting angle

The optimum twisting angle for the minimum angle was obtained using the optimum levels of the control factors. The predicted twisting angle can be calculated using Equation 2 [8].

$$\mu_\alpha = \bar{A}_1 + \bar{B}_1 + \bar{C}_1 + \bar{D}_2 - 3\bar{T}_\alpha \tag{2}$$

where, $\bar{A}_1 = 0.3798$, $\bar{B}_1 = 0.3823$, and $\bar{C}_1 = 0.3740$ represents the average data of the finite element results of twisting angle at the first levels and $\bar{D}_2 = 0.3569$ shows average data at second level for finite element results. These average data were taken from Table 4. In addition, $\bar{T}_\alpha$ = 0. 382865 is used to be the overall mean of finite element results of twisting angles based on Taguchi L8 orthogonal array and it is taken from Table 3. The optimum results for numerical and predicted data were tabulated in Table 6.

The optimum numerical result for the minimum twisting angle and the layer stacking sequence of the laminated composite plates with the optimum levels were demonstrated in Figure 3.

4.5 Regression Analysis

Regression analysis was used in order to study the effects of plies on the twisting angle of laminated composite plates mathematically. The regression equation was carried out using finite element data. The regression equation for R-Sq = 99.0 % and R-Sq (adj) = 97.7 % was demonstrated in Equation 3.

$$\propto = 0.423 + 0.00613A + 0.00106B + 0.0178C - 0.0520D \tag{3}$$

According to regression equation, A, B, and C control factors provide the positive effects on the twisting angle of laminated composite plates whereas D control factor causes the negative effects. The cantilever square laminated composite plate was plotted in Figure 4.

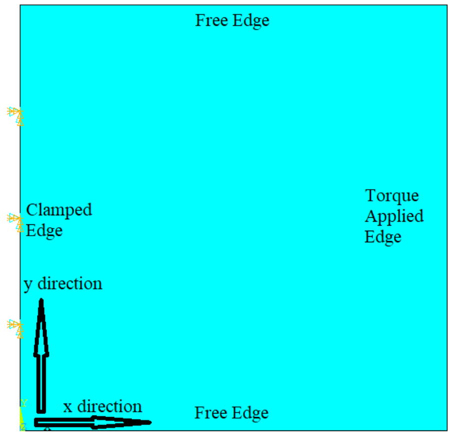


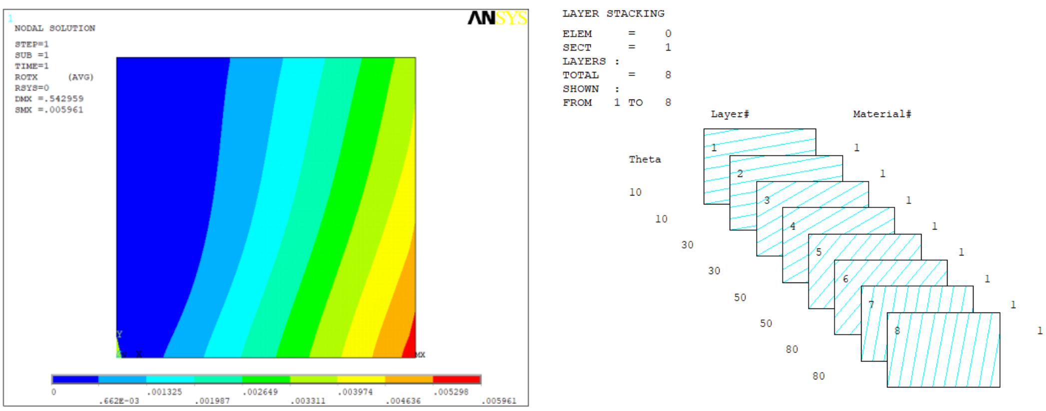
Figure 3. Laminated composite plates with C-F-F-F boundary conditions

5. Conclusions

In this study, numerical and statistical twisting angle behaviors of laminated composite plates were analyzed in clamped-free-free-free boundary conditions. Numerical analysis was performed using finite element software ANSYS and the plies arrangements and numerical analyses were conducted L8 orthogonal array based on Taguchi method.

Table 6. Comparison of numerical and predicted results

Designation	Numerical Result	Predicted Result	Residual	% Difference
$A_1B_1C_1D_2$	0.341540^{0}	0.344405^{0}	$\pm 0.002865^{0}$	0.84



a) The optimum result

b) Layer stacking

Figure 4. a) The optimum results and b) layer stacking

Analysis of signal-to-noise (S/N) ratio was used to determine the effects of fiber angles and to select the optimum levels for minimum twisting angle. Analysis of variance was carried out in order to study the significance and percent contribution of the plies towards twisting angle of laminated composite plates. In addition, Regression analysis was employed mathematically in order to investigate the effects of plies on the twisting angle of laminated composite plates. Results summarized are given below:

- The increase of fiber angles of the first, second, third, fourth, fifth, and sixth plies increases the twisting angle of the laminated composite plates whereas the increase of the fiber angles of seventh, and eighth plies decreases the twisting angle of the plates.
- The first levels of the first, second, third, fourth, fifth, and sixth plies and the second levels of seventh, eighth plies were determined to be the optimum levels for minimum twisting angle.
- According to ANOVA result, fifth, sixth, seventh, and eighth plies of plates were selected to be the significant control factors for twisting angle whereas the others plies were found to be the non-significant control factors because P value is higher than 0.05 for 95 confidence level.
- The most effective control factors were found to be D with 87.51 %, C with 10.26 %, A with 1.22 %, and B with 0.04 % respectively.
- The optimum results for finite element and predictive were calculated to be 0.341540 in degree and 0.344405 in degree respectively.
- According to regression analysis, first, second, third, fourth, fifth, and sixth plies provide the positive effects on the twisting angle of laminated composite plates whereas the seventh, and eighth plies cause the negative effects.

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