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# Statistical Analysis of Parameters Effects on Maximum Strain and Torsion Angle of FRP Honeycomb Sandwich Panels Subjected to Torsion

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***Abstract*****—**In recent years, honeycomb fiber reinforced plastic (FRP) sandwich panels have been increasingly used in various industries. Low weight, low price and high mechanical strength are the benefits of these structures. However, their mechanical properties and behavior have not been fully explored. The objective of this study is to conduct a combined numerical-statistical investigation of honeycomb FRP sandwich beams subject to torsion load. In this paper, the effect of geometric parameters of sandwich panel on maximum shear strain in both face and core and angle of torsion in a honeycomb FRP sandwich structures in torsion is investigated. The effect of Parameters including core thickness, face skin thickness, cell shape, cell size, and cell thickness on mechanical behavior of the structure were numerically investigated. Main effects of factors were considered in this paper and regression equations were derived. Taguchi method was employed as experimental design and an optimum parameter combination for the maximum structure stiffness has been obtained. The results showed that cell size and face skin thickness have the most significant impacts on torsion angle, maximum shear strain in face and core.

***Keywords***—Finite element, honeycomb FRP sandwich panel, torsion, civil engineering.

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## I. Introduction

IN recent years, the honeycomb sandwich panels are widely used in the automotive and aerospace industries due to advantage of lightweight. In some applications, these structures are used for energy absorbing. High strength-to-weight ratio is the prominent characteristics of this structure. By improving fiber-reinforced plastic (FRP) material, the use of these materials in honeycomb sandwich structures, especially in the bridge deck and aerospace industries, was begun. Because of low stiffness of FRP structures, they exhibit large deformation and predicting their behavior and response under various loading is important.

Sandwich structures are increasingly used to provide torsional rigidity. Examples include body and floor pan of automotive vehicles, airplane wings and highway bridge decks. The Computational models of sandwich panels were reviewed by [1]. Tahir et al. analyzed shear stress distribution of the torsional torque on the aircraft wing honeycomb structure [2]. Qiao et al. [3] calculated the shear stiffness of honeycomb sandwich structures using the analytical method. The idea of using FRP sandwich beam in highway bridge deck was introduced by [4]. Robinson et al. [5] investigated the torsional and bending strength of FRP honeycomb sandwich beams with sinusoidal core geometry in the plane and extending vertically between face laminates. The results of the finite element modeling and experimental testing indicate that equivalent panel properties can be utilized to correctly predict responses of the FRP honeycomb sandwich structure.

Xiang Li et al. [6], [7] presented a minimum weight optimization method for sandwich structures to meet both torsion and bending rigidity requirement.

Despite the above-mentioned studies, the effect of geometric parameters of FRP honeycomb sandwich panels on mechanical behavior of the structure has not fully explored due to the complexity of the issue. In this paper, focus is made to investigate angle of rotation and maximum shear strain in both face and core of a FRP honeycomb sandwich panel subjected to torsional loading. The aim of this research is to analyze the influence of geometric parameters including core thickness, cell thickness, cell shape, face skin thickness and cell size on mechanical behavior of the composite honeycomb sandwich panel using numerical-statistical method. This is done by means of analysis of variance (ANOVA). Further regression analysis is used to establish the correlation between factors and responses (angle of rotation, maximum shear strain in face and core). The appropriate degrees of the polynomial regression equations found are considered to be useful evaluation of the predictive equations. Finally, the optimal factor levels are obtained and evaluated.

## II. The Structure of Honeycomb Sandwich Panels

Rigid and strong structural members made of two faces which are separated by a lightweight core are known as sandwich structures. The separation of the faces, which carry the majority of the applied load, by a low density core, increases the moment of inertia of the structure with little increase in weight producing an efficient structure. Sandwich panels in various shapes and sizes are used in industry. One of them is honeycomb sandwich panels. The core cell in honeycomb sandwich panels can be in various forms such as square, hexagonal, triangular and sinus. Fig. 1 shows the basic structure of honeycomb sandwich panels. FRP sandwich panels are increasingly been used as alternative to traditional metallic due to its superior properties like high strength to

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weight ratio, high stiffness and high energy absorption. The composite sandwich structures are widely used in boats, aircraft and bridge decks. Most of sandwich structures are subjected to torsional loading. The geometric characteristics of the honeycomb sandwich panels including core thickness, cell thickness, cell shape, face skin thickness and cell size are effective on mechanical behavior of the panels. In this paper, the influence of these parameters of sandwich panels on the shear strain and angle of rotation during torsional loading is investigated.

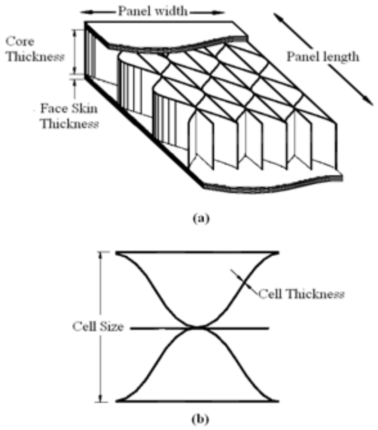


Fig. 1 (a) The basic structure (b) Section of honeycomb sandwich panels

## III. Finite Element Simulation of Honeycomb Sandwich Structures under Torsion

In order to simulate the responses of the FRP honeycomb sandwich beam under torsion, finite element analysis was performed. In the modeling, the model was created using shell elements. The constituent materials used for the FRP honeycomb sandwich panel (both face laminates and core) are E-glass fibers and polyester resin, for which their material properties can be found in Table I.

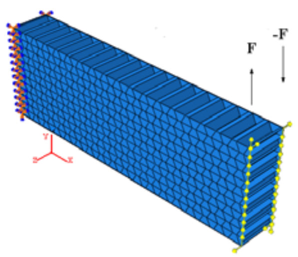


Fig. 2 The model and boundary and loading conditions

In this research, the fiber system of the face laminate includes two layers of specified bi-ply combination mat. These layers consisting of a 00/900 stitch fabrics (SF) and a continues strand mat (ContSM) layer, consisting of continuous randomly oriented fibers, six layers of unidirectional combination mat consisting of a unidirectional layer and one bonding layer chopped strand mat (ChopSM) which is made of short fibers randomly oriented resulting in nearly isotropic in-plane properties. Core consists of one layer ContSM. After determining the mechanical properties of the sandwich panel, it was meshed and boundary and loading conditions were applied. A fixed-free boundary condition was assumed in the model with all of the nodes at one end completely constrained. The torque was applied using a coupled traction loading on the edge nodes of the free end of the model. The amount of applied torque was 1000 pounds-inch. The angle of rotation and shear strains of interest can be directly obtained from the model. Fig. 2 shows the model and boundary and loading conditions.

TABLE I
Properties of the Constituent Materials

| Material | E (GPa) | G (GPa) | ν | ρ, g/cm$^3$ |
|---|---|---|---|---|
| E-glass fiber | 72.4 | 28.8 | 0.255 | 2.55 |
| Polyester resin | 5.06 | 1.63 | 0.3 | 1.14 |

In order to study the mechanical behavior of the structure subjected to torsional loading, angle of rotation and shear strain were considered as the criterion for determining torsional stiffness. The maximum shear strain in the core and face and angle of rotation can indicate stress concentration and strain in the structure. The lateral displacement of the center nodes on the top and bottom plates can be used to define a right triangle, and because of the small angle theory, the sum of their displacements can be divided by their vertical distance to give the angle of twist. Fig. 3 shows a sketch of the rotation of the cross-section, which is used to calculate the angle of twist as,

$$\theta = (|\delta_1| + |\delta_2|) / h \qquad (1)$$

Since the cell and face have two different thicknesses, strain and deformation of the structures under torsion was investigated in both cell and face. In structures with rectangular cross-section, the maximum stress occurs on the external face (in the middle of the larger side). Here, the simulation results confirm that the maximum strain in the core and face occurs in the middle of the sides. To determine the effect of geometric parameters on the mechanical behavior of the structure under torsional loading, numerous simulations are needed. In this paper, effects of geometric parameters were analyzed using statistical method. Due to the long duration of the simulations, the method of Taguchi was selected for design of experiments.

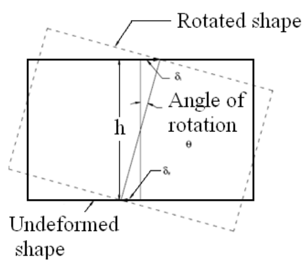


Fig. 3 Rotated cross-section of FRP beam sample in torsion

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## IV. DESIGN OF EXPERIMENTS FOR SIMULATIONS

Selection of parameters and their levels was based on a commercial FRP honeycomb sandwich beam (KSCI, Russell, Kansas). Sandwich structure with a length of 36 inches and a width of 12 inches was chosen. Input parameters (factors) are five important parameters influencing torsional stiffness and stress distribution in the structures. Table II shows the factors and factors levels determined in this study. As mentioned before, the design of experiments was performed through Taguchi method of the experimental design [8]. In this study, experiments are simulation of the loading condition with desired parameters using finite element method. Accordingly, based on the number of factors and their levels, 16 simulations have been required (L-16). The effect of changing parameters in simulation on angle of rotation and the maximum shear strain in both face and core of FRP honeycomb sandwich beam (responses) was investigated. These responses indicate the torsional stiffness of the structure under applied torque.

TABLE II
FACTORS AND FACTORS LEVEL

| Factor | Level 1 | Level 2 | Level 3 | Level 4 |
|---|---|---|---|---|
| A- Face skin thickness (in) | 0.2 | 0.3 | 0.4 | 0.5 |
| B- Cell thickness(in) | 0.08 | 0.09 | 0.1 | 0.11 |
| C- Core thickness(in) | 3.5 | 4 | 4.5 | 5 |
| D- Cell size(in) | 2 | 3 | 4 | 5 |
| E- Cell shape | Square (1) | Hexagonal (2) | Triangle (3) | Sinusoidal (4) |

## V. STATISTICAL ANALYSIS OF SIMULATION RESULTS

### *A. Effects of Factors on Angle of Rotation and Max Shear Strain*

Main effects plot of factors can be used to draw a preliminary conclusion about effects of factors. These plots are shown in Figs. 4 and 6. Figs. 4 (a), 5 (a) and 6 (a) show face skin thickness has a significant effect on the torsional stiffness. It can also be seen from these figure that angle of rotation and max shear strain decrease when face skin thickness increases. Figs. 4 (b), 5 (b) and 6 (b) illustrate the effect of cell thickness on torsional stiffness. These figure explain that angle of rotation and max shear strain decrease when cell thickness increase. Figs. 4 (c), 5 (c) and 6 (c) indicate the effect of core thickness on torsional stiffness. Figs. 4 (c), 5 (c) and 6 (c) show that angle of rotation and max shear strain decrease when core thickness increases. By Increasing core thickness the moment of inertia of the structure increases and thus the torsional resistance increases. Figs. 4 (d), 5 (d) and 6 (d) shows the effect of cell size on torsional stiffness. Figs. 4 (d), 5 (d) and 6 (d) show that torsional stiffness is decreased increasing in cell size, although by increasing cell size, weight of structure decreases. Eventually, Figs. 4 (e), 5 (e) and 6 (e) illustrate the effect of cell shape on torsional stiffness. Figs. 4 (e), 5 (e) and 6 (e) show that the triangle shape causes the lowest angle of rotation and shear strain in face, while the lowest shear strain in core is in square shape.

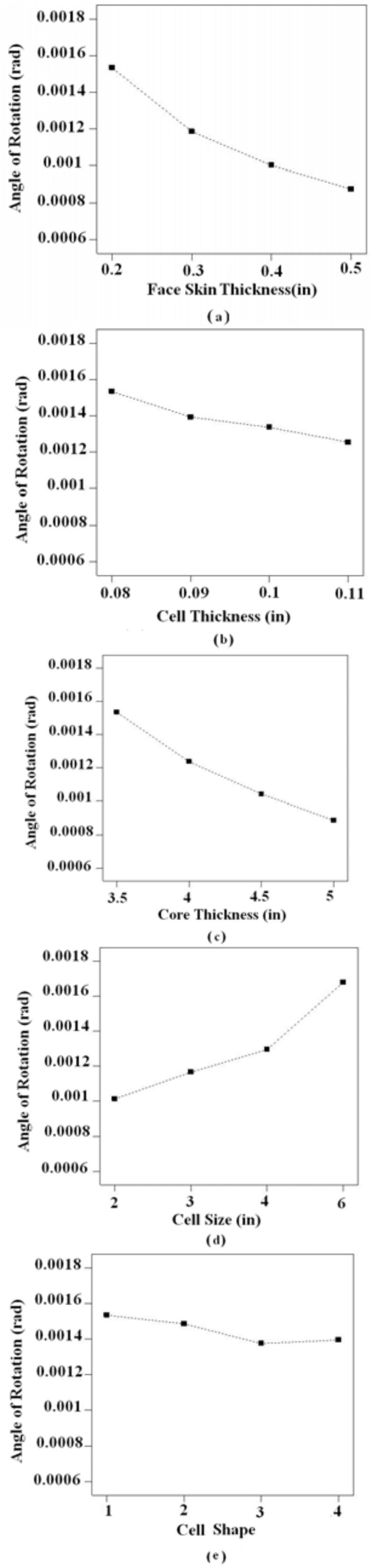


Fig. 4 (a)–(e) Plot of main effects on angle of rotation

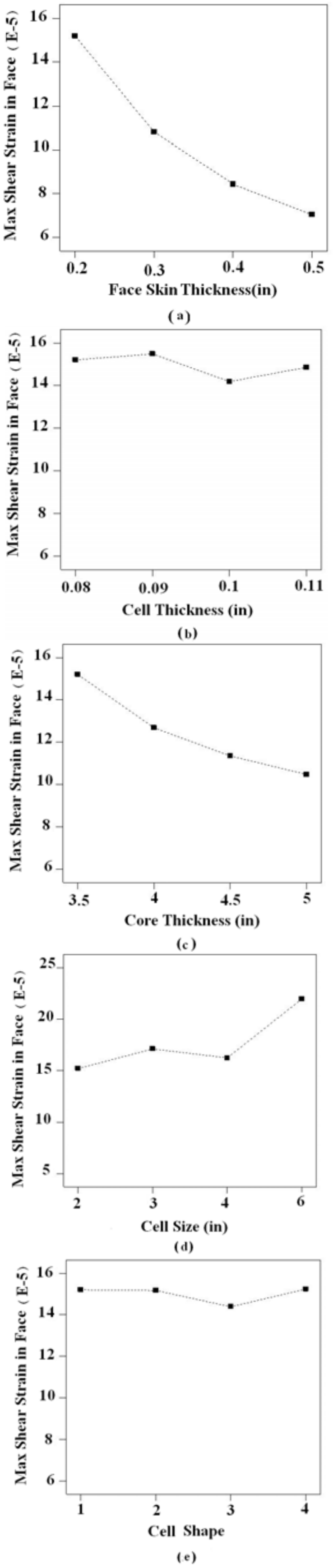


Fig. 5 (a)–(e) Plot of main effects on Max shear strain in face

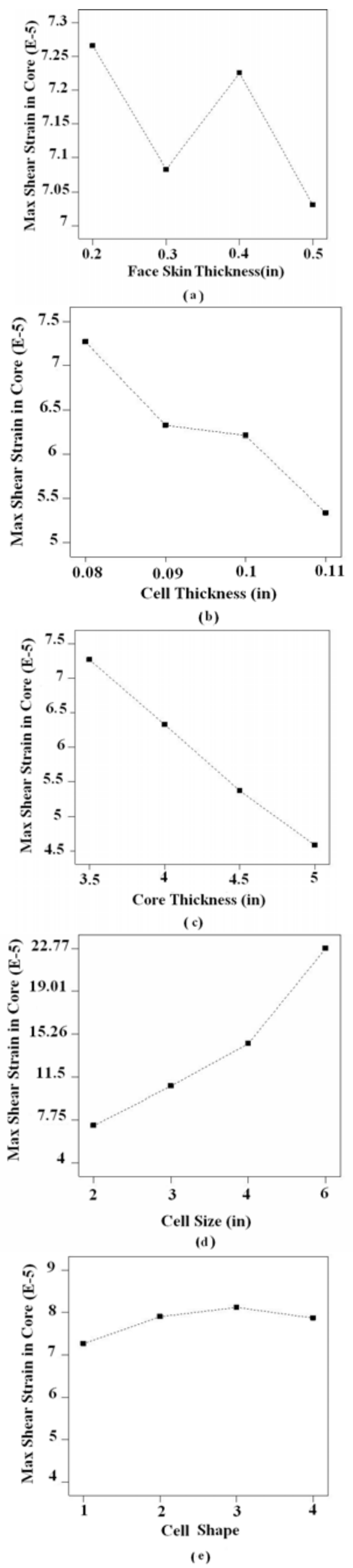


Fig. 6 (a)–(e) Plot of main effects on Max shear strain in core

Fig. 7 shows the pie chart of influence of parameters on the angle of torsion and shear strain in face and core. It shows that cell size has the greatest effect on the angle of rotation and shear strain in core, while the face skin thickness has the greatest impact on the shear strain in face.

Note that plots depicted in Figs. 4 and 6 are not used to make any inferences since they are not accurate. Only in the case of comparison, these plots are allowed to be used. To cope with the problem, analysis of variance (ANOVA) is widely used by previous researchers. Analysis of variance (ANOVA) is used for evaluating parameter effects on processes. ANOVA finds the significant factor effects based on the desired confidence interval.

One of the most important factors in ANOVA is P-value. The P-value is used to examine the conformity of experimental data to the normal distribution. The P-value is used in hypothesis tests to help decide whether to reject or fail to reject a null hypothesis. The p-value is the probability of obtaining a test statistic that is at least as extreme as the actual calculated value, if the null hypothesis is true [9], [10]. ANOVA results are listed in Table III. Confidence level is chosen to be 95% in this study. So the p-values which are less than 0.05 indicate that the effect of the respective factor is significant.

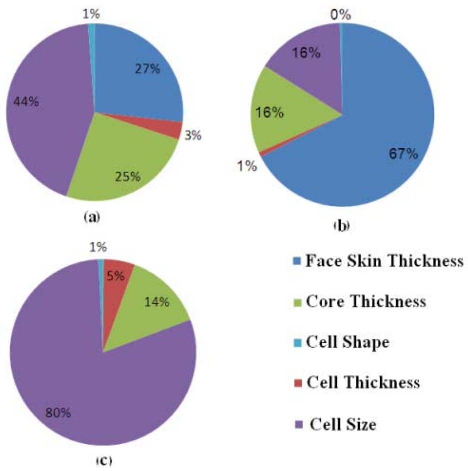


Fig. 7 The pie chart of influence of parameters on the (a) angle of torsion and (b) shear strain in face and (c) shear strain in core

TABLE III
CALCULATED P-VALUE IN ANOVA

| | Max Shear Strain in core | Max Shear Strain in face | Angle of rotation |
|---|---|---|---|
| Face skin thickness | 0.2582 | 0.0001 | 0.0155 |
| Cell thickness | 0.0751 | 0.1614 | 0.1135 |
| Core thickness | 0.001 | 0.001 | 0.0169 |
| Cell size | 0.0001 | 0.001 | 0.0077 |
| Cell shape | 0.0924 | 0.263 | 0.1154 |

It can be seen from Table III that cell size and face skin thickness have the most significant impacts on angle of rotation. Also, face skin thickness and cell size exhibit significant effect on max shear strain in face and core respectively.

## B. Regression Analysis

Using regression analysis, angle of rotation and maximum shear strain in face in core are obtained in accordance with the parameters of Table II.

$$\text{Angle of rotation (rad)} = 0.00130436 - 0.0000290759C - 0.0000224261C^2 + 0.0000460748E + 0.0000188219E^2 + 0.000437772A + 0.000407147CA - 0.000222335EA + 0.00358115A^2 + 0.000186615D - 0.000017508CED - 0.000350576AD + 0.0000272054D^2 + 0.00904436B - 0.000349844CEB - 0.0300359AB - 0.00423941CAB - 0.00107605EAB - 0.000386725CDB + 0.000227054CEDB + 0.00494774ADB - 0.00129297CADB - 0.00001353CEADB - 0.00844604B^2 \quad (2)$$

$$\text{Max shear strain in face} = 21.0357 + 3.09783C - 0.570271C^2 + 8.78042E - 1.96526E^2 + 3.89221A - 2.53965CA + 34.3704EA + 21.2517A^2 - 6.29876D - 0.314264CED - 4.76738AD + 0.479678D^2 + 107.04B - 37.6477CEB - 130.169AB - 61.9573CAB - 58.9717EAB + 2.68442CDB + 11.0345CEDB - 29.2986ADB + 26.9336CADB - 21.5639CEADB - 553.907B \quad (3)$$

$$\text{Max shear strain in core} = 1.64227 - 1.629C + 0.0446487C^2 - 0.230371E + 0.503303E^2 + 1.78369A + 5.47604CA - 13.3927EA + 0.423661A^2 + 4.36464D - 0.0147756CED + 0.18505AD + 0.180844D^2 + 34.714B + 8.25999CEB - 219.525AB - 5.00203CAB + 16.5229EAB - 5.27991CDB - 2.72065CEDB + 63.1559ADB - 20.3394CADB + 8.81298CEADB + 198.949B^2 \quad (4)$$

## C. Determination of the Optimal Condition

Optimal condition is detected by means of S/N ratio method. The rationale behind this method is to find a condition under which the effect of signals (controllable factors) is the greatest of all compared with effects of noises (uncontrollable factors). S/N ratio statistic ($\eta$) can be obtained by (5):

$$\eta = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \quad (5)$$

where $y_i$ is the $i$th observation of a treatment combination and $n$ is the number of replications. The factor level which produces the largest $\eta$ is detected as the factor level which pertains to the optimal condition. Accordingly, the optimal levels of A, B, C, D and E factors would be equal to 4, 4, 3, 1 and 1, respectively. The corresponding value of each factor level can be found out referring to Table II.

Using the obtained optimal factor levels, the structure was redesigned and torsional loading was applied and simulation was repeated. The results of the finite element simulation confirm the statistical results and show the optimum mechanical properties of this structure. Table IV compares the results of simulation of optimal condition with optimal results obtained from statistical analysis.

Table V shows the maximum strain in the face and angle of rotation in solid sample and honeycomb sample. The results are obtained from finite element analysis. It can be seen that, By changing the structure from the solid state to honeycomb sandwich panel, angle of rotation and maximum shear strain increase 1.5 time s, But the weight of the structure is reduced to 5 times.

TABLE IV
COMPARISON BETWEEN OBTAINED OPTIMAL CONDITION FROM STATISTICAL ANALYSIS AND FINITE ELEMENT SIMULATION

| | Max Shear Strain in core | Max Shear Strain in face | Angle of rotation(rad) |
|---|---|---|---|
| Statistical analysis | 0.000038154 | 0.000051204 | 0.0004867 |
| Finite element analysis | 0.000035782 | 0.000044898 | 0.0004264 |
| error | 0.07 | 0.14 | 0.14 |

TABLE V
COMPARISON BETWEEN MECHANICAL BEHAVIOR OF HONEYCOMB AND SOLID STATE STRUCTURE IN TORSION

| | Max shear strain | Angle of rotation (rad) |
|---|---|---|
| Honeycomb sandwich structure | 0.000044898 | 0.0004264 |
| Solid state | 0.0000291249 | 0.000282 |

## VI. CONCLUSION

During this study the influence of geometric parameters of a FRP honeycomb sandwich panel under torsion on its mechanical behavior was studied. ANOVA was used for this analysis. Factors which are detected to have most significant effect on angle of rotation and max shear strain in face and core:

1) Face skin thickness,
2) Cell thickness,
3) Core thickness,
4) Cell size

The correlations between factors and angle of rotation and max shear strain in face and core were derived using a regression analysis and an optimum parameter combination for the maximum torsional stiffness has been obtained by using the analysis of S/N ratios.

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