Statistical Determination of Mechanical Properties of AL-Filled Glass/Polyester Sandwich Panel under Impact Loading

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Abstract. Taguchi method and a regression model have been developed to study the effect of AL\% filler contents on the glass/polyester honeycomb sandwich panel behavior subjected to impact load. Using the standard Taguchi’s array L9, analysis of means (ANOM) including main effects of S/N ratio and experimental response, ANOVA was used to determine the optimum process parameters with its significant factor. Three parameters as controlled variables have considered: AL\%, mass, and height with three levels for each of them in destructive and non-destructive tests. The results show that for deflection: the mass has the highest contribution at (58.2439\%) followed by the AL\% filler (21.3718\%). The AL\% has the highest contribution for the deformation, with a percentage of (89.1144\%) followed by the height and mass with a relative contribution to each other. The regression model has a good prediction, with a perfect correlation between the output and input variables. The coefficient of determination and the correlation coefficient are 89.88\% and 0.94, respectively, for deflection, while for deformation are 81.45\% and 0.9, respectively. The average error MAPE equals 6.19\% and 12.128\% for deflection and deformation, respectively. There is a strong relationship between the variables depending on the correlation coefficient, which presents as 0.94 for deflection and 0.9 for deformation. Confirmation results show that the experimental and predicted values were close to each other.

Keywords. Mechanical properties, Glass, Polyester, Sandwich panel.

1. Introduction
With high specific strength, high specific stiffness, and the ability of variable fiber orientation to have required mechanical properties, composite materials become a competitive substitute for use in various structures. Sandwich panel structures constructed from light, stiff, strong face sheets separated by low-density cores are highly efficient at supporting bending loads and widely used in weight-sensitive applications [1]. Many researchers are predicting the sandwich structures strength using mathematical models. The desired sandwich process parameters were determined based on the experience. The statistical design of experimental techniques and other optimization tools can impart a scientific approach in sandwich structures [2]. Low-velocity impacts are common phenomena observed in normal situations such as items falling on composites casing of a body, automobiles bumping into each other at low speeds, and ballistic impacts on military aircraft all create such type of impact scenarios. The low-velocity impact of composite sandwich panels constructed from glass fiber reinforced face sheets surrounding the honeycomb core was studied by Eriction et al. [3]. Alpaydin
and Turkmen [4] presented the dynamic behavior of sandwich panels subjected to the impact load experimentally and numerically. They investigated the dynamic response of the panel by measuring strain on particular locations on the panel. Nusrathulla and Shantharaja [5] reported the fiber-reinforced plastic corrugated sandwich structure’s behavior under the low-velocity impact parameters using the drop test method. Farag et al. [6] experimentally demonstrate the effect of aluminum filler contents on the glass-polyester sandwich panel’s dynamic behavior under the low-velocity impact.

In order to achieve the parameters that influence the process has to be controlled accordingly. Such parameters are too large, and the parameter correlations property is not always known, statistical methods can be employed to identify significant control parameters.

Taguchi technique is a powerful tool for the design of high-quality systems [7,8]. Nowadays, the Taguchi method has become an accepted method for improving productivity. This method consists of a minimum number of experiments with the objective data in a controlled way, executing and analyzing experiment data to obtain a given process’s behavior. Precisely, Taguchi’s design is simple, efficient, and systematic to optimize designs [9, 10, 11, 12]. Using the analysis of means and variance of the influence factors to analyzed experimental results [13]. This research aim is to determine the effect of AL% filler weight fraction on the deformation and deflection of sandwich panel composite material under low-velocity impact by using a multiple regression model and Taguchi method.

2. Sandwich preparation
The corrugated core sandwiches panel shown in Figure 1 was fabricated using polyester resin and E-woven fabric glass fiber with various (0.25%, 0.5%, and 0.75%) AL- filler content by hand layup technique at 30% weight fraction. The materials used to prepare composite laminates are unsaturated polyester resin known commercial by TOPAZ -1110 TP, E-glass woven roving fiber, and aluminum powders with a suitable size of 75µm.

3. Impact test
The drop weight testing is used in this investigation. In the non-destructive testing (deflection), the used equipment consists of stainless steel balls weighing (45, 65, and 85) g. A guide metal pipe used to drop the steel ball on the panel center, and TVC 200 vibration data collector device. The honeycomb sandwich panel of (80×40×40) mm has been fixed from three sides and free from the other. The spherical ball’s height of fall is varied (90, 105, and 120) cm. The accelerometer has been glued at the center of the lower sheet to measure the strain. While, in the destructive testing (deformation), the low-velocity impact tests done by drop a steel impactor of (12, 15, and 18) kg weight from a tower of (1.5, 2, and 2.5) m height on the honeycomb sandwich panel supported on a rigid foundation. The shortness in the length of the panel was measured using a vernier caliper.

4. Design of experiments
Three parameters (AL % filler content, impact mass, and height) with three levels for each were considered to optimize the deflection and deformation in destructive and non-destructive tests, respectively. The parameters with their levels are shown in Table 1. The Taguchi approach to experimentation was used to collect, analyze, and interpret the data, which can obtain the maximum amount of information. Taguchi design of experiment is a powerful analysis tool for modeling and analyzing the influence of control factors.

The most important stage in the design of experiment lies in the selection of the control factors. Choosing the proper Taguchi orthogonal array with control parameters and levels to obtain the optimum level combination [14, 15]. The impact of three such parameters are studied using L9 (3^3) orthogonal design as presented in Table 2.
Figure 1. The honeycomb sandwich panel.

Table 1. Factors and their levels for:

| Factor and Unit | Symbol | Factor levels |
|-----------------|--------|---------------|
|                 |        | Level-1 | Level-2 | Level-3 |
| AL (%)          | AA     | 2.5 %   | 5 %     | 7.5 %   |
| Mass (g)        | BB     | 45      | 65      | 85      |
| Height (cm)     | CC     | 90      | 105     | 120     |

b. Destructive test.

| Factor and Unit | Symbol | Factor levels |
|-----------------|--------|---------------|
|                 |        | Level-1 | Level-2 | Level-3 |
| AL (%)          | AA     | 2.5 %   | 5 %     | 7.5 %   |
| Mass (kg)       | BB     | 12      | 15      | 18      |
| Height (m)      | CC     | 1.5     | 2       | 2.5     |

Table 2. Standard taguchi’s orthogonal.

| No. | A | B | C |
|-----|---|---|---|
| 1   | 1 | 1 | 1 |
| 2   | 1 | 2 | 2 |
| 3   | 1 | 3 | 3 |
| 4   | 2 | 1 | 2 |
| 5   | 2 | 2 | 3 |
| 6   | 2 | 3 | 1 |
| 7   | 3 | 1 | 3 |
| 8   | 3 | 2 | 1 |
| 9   | 3 | 3 | 2 |

5. Results and discussion

5.1. Analysis of experimental results

The other essential element of the Taguchi method is the signal-to-noise ratio. The experimental observations are transformed into a signal-to-noise (S/N) ratio. There are several (S/N) ratios available, depending on the type of characteristics. Based on the type of performance characteristics, one has to select a suitable S/N ratio [16, 17]. In this study, the characteristic “smaller is better” is considered to minimize deflection and deformation. The S/N ratio is calculated as a logarithmic transformation of loss function [15, 17].

\[
S/N = -10 \log_{10} \left[ \frac{1}{n} \sum_{i=1}^{n} y_i^2 \right]
\]

S/N is the signal to noise ratio; n the number of observations; and \( y_i \) the observed data. After conducting the nine experiments, the S/N calculated values with the experimental results of both destructive and non-destructive tests are listed in Table 3.
5.2. Analysis of means (ANOM)

S/N ratio, deflection, and deformation analysis have been used to find the optimal parameter levels. Depending on the experimental results for deflection, deformation, and the calculated values of S/N ratios, the optimum levels can be determined using the main effects. In terms of this concept, the average value of the S/N ratio for each parameter at each level were found and summarized in Table 4. For example, the mean of level-1 for AL % is found by averaging the first three values located in deformation, deflection, and S/N ratio columns. For mass parameter, level-1 is found by averaging the values corresponding to level-1 in column B of Table 3. The other levels are found in the same way. The means of experimental results are summarized in Table 5. Analysis of the results concludes that optimum levels of the parameters for deflection and deformation are A2, B1, and C1. These levels are compatible with the quality characteristic, “smaller is better.” They are equivalent to 5 % AL, a mass of 45 g, and a height of 90 cm for deflection response. While the deformation is equivalent to 5 % AL, a mass of 12 Kg, and a height of 1.5 m. Tables 4 and 5 summarize the results and show the ranking of parameters according to significance. For the non-destructive test, the mass parameter is more significant than others, but the (AL%) parameter is more significant for the destructive test.

### Table 3. Experimental results and S/N calculated values of:

| Exp. No. | Combinations | Deflection (µm) | S/N ratio (dB) |
|----------|--------------|----------------|----------------|
| A (%)    | B (g)        | C (cm)         |                |
| 1        | 2.5%         | 45             | 90             | 3.718 | -11.40619 |
| 2        | 2.5%         | 65             | 105            | 5.945 | -15.48304 |
| 3        | 2.5%         | 85             | 120            | 9     | -19.08485 |
| 4        | 5%           | 45             | 105            | 4.51668 | -13.09639 |
| 5        | 5%           | 65             | 120            | 6.215 | -15.86882 |
| 6        | 5%           | 85             | 90             | 5.931 | -15.46256 |
| 7        | 7.5%         | 45             | 120            | 9.32  | -19.38832 |
| 8        | 7.5%         | 65             | 90             | 6.7831 | -16.62856 |
| 9        | 7.5%         | 85             | 105            | 9.32  | -19.38832 |

### Table 4. Experimental results and S/N calculated values of:

| Exp. No. | Combinations | Deformation (mm) | S/N ratio (dB) |
|----------|--------------|-----------------|----------------|
| A (%)    | B (kg)       | C (m)           |                |
| 1        | 2.5%         | 12              | 1.5            | 12.0  | -21.58362 |
| 2        | 2.5%         | 15              | 2.0            | 14.0  | -22.92256 |
| 3        | 2.5%         | 18              | 2.5            | 17.2  | -24.71057 |
| 4        | 5%           | 12              | 2.0            | 7.14  | -17.07396 |
| 5        | 5%           | 15              | 2.5            | 8.0   | -18.06180 |
| 6        | 5%           | 18              | 1.5            | 7.4   | -17.38463 |
| 7        | 7.5%         | 12              | 2.5            | 9.0   | -19.08485 |
| 8        | 7.5%         | 15              | 1.5            | 8.35  | -18.43373 |
| 9        | 7.5%         | 18              | 2.0            | 9.5   | -19.55447 |
Table 4. Mean of S/N ratio for each factor level of:

| Factor | Symbol | Average of levels for S/N ratio | Max-Min | Rank |
|--------|--------|---------------------------------|--------|------|
|        |        | Level-1 | Level-2 | Level-3 |       |      |
| a. Non-destructive test | | | | | |
| AL (%) | A | -15.32469 | -14.80926 | -17.36428 | 2.55503 | 2 |
| Mass (g) | B | -13.52618 | -15.99347 | -17.97858 | 4.45239 | 1 |
| Height (cm) | C | -14.49910 | -15.98925 | -17.00988 | 2.51078 | 3 |
| b. Destructive test | | | | | |
| AL (%) | A | -23.07225 | -17.50680 | -19.02435 | 5.56545 | 1 |
| Mass (kg) | B | -19.24748 | -19.80603 | -20.54989 | 1.30241 | 3 |
| Height (m) | C | -19.13400 | -19.85033 | -20.61907 | 1.48508 | 2 |

Optimum level (A<sub>2</sub>B<sub>1</sub>C<sub>1</sub>).

Table 5. Mean of experimental results for each factor level of:

| Factor | Symbol | Average of levels for deflection (δ) | Max-Min | Rank |
|--------|--------|-------------------------------------|--------|------|
|        |        | Level-1 | Level-2 | Level-3 |       |      |
| a. Non-destructive test | | | | | |
| AL (%) | A | 6.22100 | 5.55423 | 7.48937 | 1.93514 | 2 |
| Mass (g) | B | 4.86656 | 6.31437 | 8.08367 | 3.21711 | 1 |
| Height (cm) | C | 5.47737 | 6.59389 | 7.19333 | 1.71597 | 3 |
| b. Destructive test | | | | | |
| AL (%) | A | 14.40000 | 7.51333 | 8.95000 | 6.88667 | 1 |
| Mass (kg) | B | 9.38000 | 10.11667 | 11.36667 | 1.98667 | 3 |
| Height (m) | C | 9.25000 | 10.21333 | 11.40000 | 2.15000 | 2 |

Optimum level (A<sub>2</sub>B<sub>1</sub>C<sub>1</sub>).

Figure 2 shows a graphical representation of the influence of process parameters on deflection and deformation depending on the experimental results and the S/N ratio. The data in Tables 4 and 5 have been used to create Figure 2. From this figure, it can be noticed clearly the relationship between the means and levels of each parameter for both destructive and non-destructive tests. For the deflection, it can be seen that at level-2 of the AL% parameter, the mean of S/N ratio has a maximum value while the mean of deflection has a minimum, i.e., level-2 is optimum. However, for each mass and height, level-1 is optimum. The graph also shows that for deformation, the level-2 of AL% corresponds to the highest S/N mean value, while level-1 gives the highest S/N mean for mass and height parameters. The mass and height parameters in all cases, as shown in the figures, give a positive relationship, i.e., increase the values of them increases deflection and deformation.
5.3. Analysis of variance (ANOVA)

The variance method ANOVA objective is to analyze the influence of the design parameters on the total variance of results [18]. The parameter that is statistically more significant than others can be identified in ANOVA analysis. Table 6 shows the results of ANOVA analysis for the deflection and deformation. It is noticed in Table 6a that the mass has the highest percentage contribution through the process by 58.2439%. Thus, it is considered the most significant parameter in comparison with others. The mass has the most significant influence on the deflection, followed by the AL% filler with 21.3718% contribution. Finally, the height parameter comes after them, with a contribution of 18.6645%. Hence, the mass parameter is the dominant parameter. For the deformation, Table 6b
shows that the AL % filler parameter is dominant; it has a high contribution of 89.1144 %, followed by the height parameter and the mass with a close contribution.

### Table 6. ANOVA table for:

#### a. Deflection (non-destructive test).

| Source    | Sum of Square | Degree of Freedom | Mean Squares | F value (MS/error) | Contribution (%) |
|-----------|---------------|-------------------|--------------|--------------------|------------------|
| AL (%)    | 10.9538       | 2                 | 5.4769       | 12.43              | 21.3718          |
| Mass (g)  | 29.852        | 2                 | 14.926       | 33.87              | 58.2439          |
| Height (cm)| 9.5662       | 2                 | 4.7831       | 10.85              | 18.6645          |
| Error     | 0.8815        | 2                 | 0.4407       |                    | 1.7198           |
| Total     | 51.2534       | 8                 |              |                    | 100              |

#### b. Deformation (destructive test).

| Source    | Sum of Squares | Degree of Freedom. | Mean Squares | F value (MS/error) | Contribution (%) |
|-----------|----------------|--------------------|--------------|--------------------|------------------|
| AL (%)    | 49.6627        | 2                  | 24.8314      | 254.44             | 89.1144          |
| Mass (kg) | 2.5616         | 2                  | 1.2808       | 13.12              | 4.5965           |
| Height (m) | 3.3096       | 2                  | 1.6548       | 16.96              | 5.9387           |
| Error     | 0.1952         | 2                  | 0.0976       |                    | 0.35             |
| Total     | 55.7291        | 8                  |              |                    | 100              |

### 5.4. Development regression model

A regression model was built using MATLAB software. The model expresses the relationship between the output response, dependent variables such as deflection (\(\delta\)) and deformation (\(\Delta\)), and inputs, independent variables such as AL%, mass, and height. So, \(\delta\) or \(\Delta\) is a function for inputs. The developed regression model, in terms of notations used in this study, for the experimental results of \(\delta\) and \(\Delta\) can be expressed as follows [19, 20]

\[
\delta_{\text{pre or } \Delta_{\text{pre}}} = \beta_0 + \beta_1 \text{AL} + \beta_2 M + \beta_3 H + \beta_4 \text{AL} \times M + \beta_5 \text{AL} \times H + \beta_6 M \times H + \beta_7 \text{AL} \times M \times H
\]  

(2)

Where;

- \(\delta_{\text{pre}}, \Delta_{\text{pre}}\): The value of the predicted output response (expected deflection or deformation).
- \(\text{AL, M, and H}\): The process parameters (inputs).
- \(\beta_0\): The regression constant.
- \(\beta_1, \ldots \beta_7\): Regression coefficients model

By using the software, the unknown regression model coefficients are estimated, and the equations can be written as:

\[
\delta_{\text{pre}} = 27.0701 + 0.0 \text{AL} - 0.3261 M - 0.3154 H - 1.0258 \text{AL} \times M + 1.2452 \text{AL} \times H + 0.0045 M \times H - 0.0017 \text{AL} \times M \times H
\]

(3)

\[
\Delta_{\text{pre}} = 74.5286 + 0.0 \text{AL} - 3.0849 M - 49.95 H - 22.583 \text{AL} \times M + 257 \text{AL} \times H + 2.7854 M \times H - 7.15 \text{AL} \times M \times H
\]

(4)

To show the regression model’s capability described in Equations 3 and 4, the coefficient of determination, \(R^2\), has been determined. It is widely used as a measure of fit for the regression model [21]. The equations used for computing \(R^2\) can be described as [21]:

\[
R^2 = 1 - \frac{SS_E}{SS_{yy}}
\]

(5)

Where;

- \(SS_E\) is the sum of squares of error which is calculated in terms of notations used in this work as

\[
SS_E = \sum (\delta_{\text{exp}} - \delta_{\text{pre}})^2
\]

(6)
SS_yy is the sum of squares of the dependent variable. It is calculated and can be written as
\[ SS_y = \sum (\bar{y}_{i} - \bar{y})^2 = \sum \delta_{exp}^2 - \frac{(\sum \delta_{exp})^2}{n} \] (7)

Where;
\( \bar{y} \) is the mean of deflection for the nine experiments (n).
The coefficient of determination, \( R^2 \), was found to be 0.8988 or 89.88 %. Thus, the correlation coefficient, \( R \), was 0.94.

Also, the mean absolute percentage error MAPE of prediction for deflection has been calculated from the equation shown below:
\[ MAPE = \frac{1}{n} \sum_{i=1}^{n} \left| \frac{\delta_{exp} - \delta_{pre}}{\delta_{exp}} \right| \times 100 \] (8)

Where;
i = 1, 2, ..., n (number of experiments).
\( \delta_{exp} \) is the experimental value of deflection.
\( \delta_{pre} \) is the predicted value of deflection.
The results of applying the developed regression model and the errors and the total absolute average error are listed in Table 7.

| No. | \( \delta_{exp} \) | \( \delta_{pre} \) | Residuals | Error % |
|-----|-------------------|-------------------|-----------|--------|
| 1   | 3.718             | 3.7101            | 0.0079    | 0.2125 |
| 2   | 5.945             | 4.7808            | 1.1642    | 19.5828|
| 3   | 9.0               | 8.5259            | 0.4741    | 5.2678 |
| 4   | 4.51668           | 4.3689            | 0.14777   | 3.2719 |
| 5   | 6.215             | 6.5999            | 0.3849    | 6.1931 |
| 6   | 5.931             | 5.9841            | 0.0531    | 0.8953 |
| 7   | 6.365             | 5.9038            | 0.4612    | 7.2459 |
| 8   | 6.7831            | 6.471             | 0.3121    | 4.6011 |
| 9   | 9.32              | 8.5256            | 0.7944    | 8.5236 |
| **Average** | **6.19 %** | **6.19 %** | **6.19 %** | **6.19 %** |

The same thing has been done for the deformation, so the coefficient of determination, \( R^2 \), was 0.8145 or 81.45 %. The correlation coefficient, therefore, will be of 0.9. The experimental and expected results of deformation are shown in Table 8.

| No. | \( \Delta_{exp} \) | \( \Delta_{pre} \) | Residuals | Error % |
|-----|-------------------|-------------------|-----------|--------|
| 1   | 12                | 12.4645           | 0.4645    | 3.87   |
| 2   | 14                | 11.0577           | 2.9423    | 21.01  |
| 3   | 17.2              | 17.4709           | 0.2709    | 1.57   |
| 4   | 7.14              | 8.2244            | 1.0844    | 15.18  |
| 5   | 8.0               | 9.8576            | 1.8576    | 23.22  |
| 6   | 7.4               | 8.8712            | 1.4712    | 19.88  |
| 7   | 9.0               | 8.2643            | 0.7357    | 8.17   |
| 8   | 8.35              | 7.8079            | 0.5421    | 6.49   |
| 9   | 9.5               | 8.5711            | 0.9289    | 9.77   |
| **Average** | **12.128 %** | **12.128 %** | **12.128 %** | **12.128 %** |
5.5. Confirmation test

To examine the quality characteristic and validate the optimized condition, the Taguchi method confirms the analysis results, which is the final step in the method [22]. The optimum levels of the process parameters that have been obtained by analysis of the S/N ratio and experimental results of deflection and deformation were used to develop the confirmation test. The values of optimum levels and the total mean value for each S/N and experimental results shown in Tables 4 and 5, respectively, have been used in Equation 9 [15, 22]. This model that is expressed by this equation can be called as predicted optimum deflection or deformation.

\[ \eta_{opt} = \eta_m + \sum_{i=1}^{k}(\eta_i - \eta_m) \]  

Where:

- \( \eta_{opt} \): Predicted optimum value.
- \( \eta_m \): Total mean value.
- \( \eta_i \): Mean value at optimum levels from tables (4 and 5).
- \( k \): Number of main design parameters that affect the quality characteristics.

The optimum combination, as mentioned previously, at the levels designated \( A_2B_1C_1 \). The total means’ values can be calculated by averaging the nine readings in Table 3 for each S/N and the experimental results for deflection and deformation. Table 9 summarizes the results of the confirmation test.

Table 9. Confirmation results of:

| Process Characteristic | Best Initial Conditions | Optimum Parameters |
|------------------------|-------------------------|--------------------|
|                        | AL (2.5%), Mass (45g), Height (90cm) | AL (5%), Mass (45g), Height (90cm) |
|                        | Experiment | Predication using Table-5 | Table-4 |
| Levels                 |   A1B1C1   | A2B1C1 | A1B1C1 | A2B1C1 |
| Deflection (µm)        |   3.718    | 3.451  | 3.055  | 3.2216 |
| S/N (dB)               |  -11.40619 | -10.758 | -9.7   | -10.16906 |

| Process Characteristic | Best Initial Conditions | Optimum Parameters |
|------------------------|-------------------------|--------------------|
|                        | AL (5%), Mass (12kg), Height (2m) | AL (5%), Mass (12kg), Height (1.5m) |
|                        | Experiment | Predication using Table-5 | Table-4 |
| Levels                 |   A1B1C2   | A2B1C1 | A1B1C1 | A2B1C1 |
| Deformation (mm)       |   7.14     | 6.34   | 5.568  | 6.42  |
| S/N (dB)               |   -17.07396 | -16.041 | -14.914 | -16.153 |

6. Conclusions

The following conclusions can be drawn based on the obtained results:

1. The mass has the primary influence on the deflection, while the AL% has the dominant parameter for deformation. They have the most considerable contribution among the other parameters.
2. The optimum combination levels for the deflection and deformation are level-2 for AL%, level-1 for mass, and level-1 for height. They have the designation of \( A_2B_1C_1 \).
3. Analysis of variance (ANOVA) indicated that for deflection: the mass has the highest contribution at (58.2439%) followed by the AL% filler with a contribution of (21.3718%). While for the deformation, the AL% has the highest contribution with a percentage of (89.1144%) followed by the height and mass with a close contribution to each other.
4. The regression model has a correct prediction, with a perfect correlation between the output and input variables. The coefficient of determination and the correlation coefficient are 89.88 % and 0.94, respectively, for deflection, while for deformation are 81.45 % and 0.9,
respectively. This indicates that the predicted and actual values are close. The average error MAPE equals to 6.19 % and 12.128 % for deflection and deformation, respectively.

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