

The Application of Statistical Design of Experiments to Study the In-Plane Shear Behaviour of Hybrid Composite Sandwich Panel

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The Application of Statistical Design of Experiments to Study the In-Plane Shear Behaviour of Hybrid Composite Sandwich Panel

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Abstract: This paper presents a statistical aspect of experimental study on the in-plane shear behaviour of hybrid composite sandwich panel with intermediate layer. The study was aimed at providing information of how significant the contribution of intermediate layer to the in-plane shear behaviour of new developed sandwich panel. The investigation was designed as a single factor experimental design and the results were thoroughly analysed with statistics software; Minitab 15. The panels were tested by applying a tensile force along the diagonal of the test frame simulating pure shear using a 100 kN MTS servo-hydraulic UTM. The result shows that the incorporation of intermediate layer has significantly enhanced the in-plane shear behaviour of hybrid composite sandwich panel. The statistical analysis shows that the value of F_0 is much higher than the value of F_{table} , which has a meaning that the improvement provided by the incorporation of intermediate layer is statistically significant.

Keywords: Design of experiment; hybrid composite; in-plane shear; sandwich panel; statistical analysis.

Introduction

A hybrid sandwich panel that is formed by inserting intermediate layer between skins and core has shown excellent performance under flexural loading as reported by Fajrin et al. [1,2]. The concept of hybrid sandwich panel with intermediate layer itself was first developed by Mamalis et al. [3]. However, flexural behaviour is not of considerable importance when applying sandwich panel as a wall of building structure. In-plane shear behaviour is the most critical behaviour that needs to be carefully understood when using sandwich panel for a wall especially when the wall is considered as a structural component. It was expected that employing intermediate layer could enhance the in-plane shear behaviour of sandwich panels. The stress discontinuity along the cross section of the panel is believed as a prime contributor for failure in sandwich panel. The idea of adding intermediate layer, which has intermediate properties between the skins and core, is to reduce the problem. The abrupt step between the high and low stresses within the skins and core might be reduced when the intermediate layers are incorporated.

Theoretically, as stated in reference [3], the existence of intermediate layers generates sandwich panel with higher load carrying capacity due to its ability to prevent early failure modes such as face wrinkling or indentation. Further theoretical analysis reported by Fajrin [4] also shows a significant contribution of intermediate layer to increase the flexural rigidity of a sandwich panel.

The term of "statistical experimental design" was introduced by Montgomery [5]. Other terms are used by statisticians such as "designed experiments" or "design of experiments" to describe the same process. In a designed experiment, the researchers make deliberate or purposeful changes in the controllable variables of the system or process, observe the resulting system output data, and then make an inference or decision about which variables are responsible for the observed changes in output performance. While all experiments may be considered to be designed experiments, some are poorly designed that may result in ineffectively uses of valuable resources. Statistically designed experiments allow efficiency and economy in the experimental process and also obtain scientific objectivity conclusions [6].

Although the experimental results can be simply analysed with descriptive statistics, involving inferential statistics may enrich the value of findings. In this study, a specific hypothesis was tested using significance analysis which is a mathematical tool that is commonly used to determine whether the outcome of an experiment is the result of a relation-

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ship between specific factors or solely the result of chance [7]. Commonly, experimental researches in civil engineering field are conducted according to a standardized procedure which only involving descriptive statistics in the analysis. It rarely found a report that uses inferential statistics analysis for making conclusions [8]. The descriptive statistics only presents an immediate result without proper analysis how significant the differences between the conditions under investigation and those are kept constant. The significance analysis, which is a part of inferential statistics, is commonly performed by examining the variation in a set of responses and assign portions of this variation to each variable in a set of independent variables. This analysis is also known as the analysis of variance (ANOVA) with the aims to identify important independent variables and determine how they affect the response [5]. As in the experiment only one variable was investigated, the analysis employed was called as the one-way or single factor ANOVA. This paper presents a statistical aspect of the experimental study on the in-plane shear behaviour of hybrid composite sandwich panel with intermediate layer.

The Application of Statistical Analysis in Composite Research

Statistical aspects, especially inferential statistics, often ignored in structural researches due to time and cost constraint. However, it has been extensively used in the broad field of composite material research. Some case studies are provided as follow. Phoenix et al. [9] used Weibull statistics to establish theoretical model for predicting the strength and lifetime in creep rupture of carbon-epoxy composites. Also, Phoenix [10] presented statistics aspects of the failure of composites consisting of brittle fibers aligned in a brittle matrix. In other study Bayerlein and Phoenix [11] used statistics analysis to study the effect of size to the strength of composites prepared with carbon fibers and epoxy resin. Toutanji et al. [12] employed Weibull statistics analysis to investigate the effect of adding carbon fibers on the mechanical properties of cement paste composites. Alhozaimy et al. [13] performed statistical significance analysis to study the effect of adding polypropylene fibers on the compressive, flexural and impact properties of concrete materials with different binder compositions.

More recent studies in this research area also involve statistics analysis. Balzer and McNabb [14] employed a two-way ANOVA to study the effect of microwave curing on tensile strength of carbon fibre composite. Jun et al. [15] used response surface method to determine the significant factors that affected the properties of the wood-rubber composite.

The similar method was employed by Mathivanan et al. [16] in observing the factors influencing deflection in sandwich panels subjected to low-velocity impact. A full factorial design, which is a branch of design of experiments, was employed by Shahdin et al. [17] to study the significance of low energy impact on modal parameters for composite beams. Also, Dwivedi et al. [18] used a two-level full factorial design of experiment to study the abrasive wear behaviour of bamboo powder filled polyester composites. Sathapathy and Patnaik [19] used Taguchi method in designing their experiment to investigate the dry sliding wear behaviour of red mud filled polyester composites. Furthermore, Davim and Reis [20] used the same method in designing experiment for establishing the correlation between cutting velocity and feed rate with the delamination in carbon fiber reinforced epoxy composites.

Although statistical analysis is hardly found as a primary approach in earlier green composite research, few studies dealing with natural fibers composites have recently been designed and analysed using statistical frameworks. Prasad et al. [21] conducted optimization of design parameters using ANOVA to study the performance of jute and banana fibers reinforced polymer matrix. The same method also employed by Venkateshwaran et al. [22] to study the effect of layering pattern to the mechanical properties of woven jute/banana hybrid composites. More recently, El-Shekeil et al. [23] designed their experiment to study the significance of different parameter to the tensile strength of kenaf fibers reinforced polyurethane composites using Taguchi model and analysed the results using ANOVA. Clearly, a few different statistic methods have been extensively used in fiber composite researches.

Experimental Design and Testing Program

The experiment was designed as a single factor experiment in which 3 levels of a factor had been examined. The factor refers to the type of intermediate layer used in the sandwich panel. Level 1 and 2 refer to as jute fibre composite (JFC) and medium density fibre (MDF) while level 0 was a reference or control level (CTR) which was sandwich panels without intermediate layer. The specimens had overall dimensions of 380 x 380 mm providing a clear internal dimension of 300 x 300 mm between frame boundaries. The overall thickness was maintained at 26 mm for all specimens. The aluminium sheet with the thickness of 0.5 mm was used as the skins and expanded polystyrene (EPS) for the core. The thickness of EPS core for the control specimens was 25 mm and 19 mm for the specimens with intermediate layer. Each specimen group was

replicated 5 times with a total of 15 samples tested. The sample arrangement for the in-plane shear specimens and the schematic testing program are presented in Table 1 and Figure 1, respectively.

Table 1. Sample Arrangements for in-plane Shear Testing

Samples Code	Skin		Intermediate layer		Core Thickness	Total Thickness
	Material	Thick-ness	Mate-rial	Thick-ness		
CTR	Aluminium	0.5 mm	None	-	EPS 25 mm	26 mm
JFC	Aluminium	0.5 mm	Jute	3 mm	EPS 19 mm	26 mm
MDF	Aluminium	0.5 mm	Hemp	3 mm	EPS 19 mm	26 mm

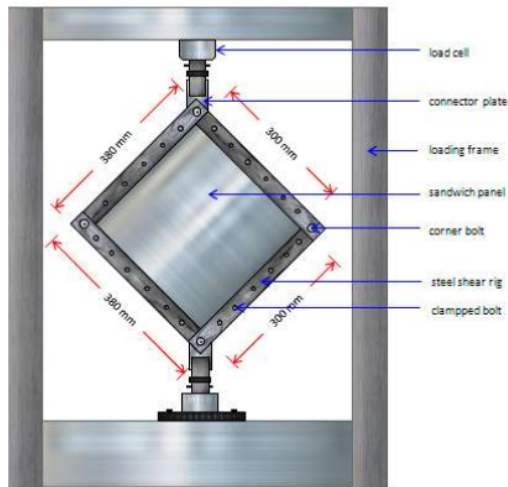


Figure 1. Schematic Illustration of Diagonal Tension Shear Test

A tensile force was applied along the diagonal of the test frame simulating pure shear and the testing rig was enabled to freely rotate by placing a pin bolt at each corner. This ensured that the frame did not contribute to the load carrying capacity of the whole system. The corners of the panel were cut to enable the connector plate to go through to the frame while minimizing stress concentration at the corners.

Results and Discussions

The failure loads of specimens tested under in-plane shear testing are listed in Table 2. The average ultimate diagonal load for hybrid sandwich panels with JFC and MDF intermediate layer was 49816 N and 22370 N, respectively. These values were significantly higher than the load carrying capacity of the sandwich panel without intermediate layer, which was only 10253 N. In more general terms, it can be said that the introduction of JFC and MDF intermediate layer has increased the diagonal load carrying capacity of sandwich panels by 386% and 118%, respectively. These values were obtained by

comparing the load carrying capacity of hybrid sandwich panels (JFC and MDF) to the control specimen group (CTR). The comparison between the two hybrid sandwich panels shows that the panels with JFC intermediate layer were stronger than the panels with the MDF intermediate layer by 123%. This indicates that the material employed for the intermediate layer can provide significant contribution to the overall performance of the hybrid sandwich panels. It can also be observed from the table that the coefficient of variation (CV) of the in-plane shear load test results was 18.48 for CTR, 5.40 for JFC and 1.75 for MDF. These CV values are considered as highly acceptable especially for JFC and MDF panels.

Table 2. Failure Loads of Specimens Tested under in-plane Shear Loading Scheme

Samples number	Failure Loads (N)		
	CTR	JFC	MDF
1	9228	49006	21809
2	10043	47921	22324
3	13575	53834	22442
4	9051	51127	22366
5	9367	47192	22908
Average	10253	49816	22370
Stdev	1895	2692	391
CV	18	5	2

As previously mentioned, the experiment was designed as a single factor experiment in which 3 levels of a factor had been observed. The factor refers to the type of intermediate layer incorporated within the hybrid sandwich panel. For the analysis purpose, the data for ANOVA are tabulated as shown in Table 3.

Table 3. Tabulated Data for Analysis of Variance (ANOVA)

Factor levels	Observations					Totals	Averages
	1	2	3	4	5		
Level 0 (CTR)	9228	10043	13575	9051	9367	51264	10253
Level 1 (JFC)	49006	47921	53834	51127	47192	249080	49816
Level 2 (MDF)	21809	22324	22442	22366	22908	111849	22370

Table 4. The Theoretical Results of ANOVA

Source of variations	Sum of square	Degrees of freedom	Mean square	F ₀
Intermediate layer	4108937296.00	2	2054468648.00	560.73
Error	43967235.60	12	3663936.40	
Total	4152904532.00	14		

As it can be seen in Table 3, some important parameters for theoretical calculations can be determined such as replications (n = 5), total number of samples (N = 15), and number of levels or treatments (a = 3). The theoretical results of the ANOVA are summarized in Table 4 while such analysis obtained by statistical software Minitab 15 is presented in Table 5.

Table 5. ANOVA Results Obtained by Statistical Software Minitab 15

One-way ANOVA: Flexural Load versus Intermediate Layer					
Source	DF	SS	MS	F	P
Intermediate Layer	2	4108937296	2054468648	560.73	0.000
Error	12	43967236	3663936		
Total	14	4152904532			
S = 1914 R-Sq = 98.94% R-Sq(adj) = 98.76%					
Individual 95% CIs For Mean Based on Pooled StDev					
Level	N	Mean	StDev		
0	5	10253	1895	(-*)	
1	5	49816	2692	(-*)	
2	5	22370	391	(-*)	
		12000	24000	36000	48000

Both tables showed that the mean square between treatments was many times larger than the error mean square, meaning that the average values of in-plane shear load of each treatment are significantly different. It is also noticeable that the theoretical calculations were comparable to the analysis results obtained by statistical software Minitab 15. The value of F_0 for the in-plane shear test was 560.73, which is much larger than the value obtained from F-distribution table. The F value, obtained by using the significance level of 95% ($\alpha = 0.05$), 3 levels of treatment replications ($a = 3$) and 15 samples ($N = 12$), was 3.89 or can be written as $F_{(0.05,2,12)} = 3.89$. As the value of F_0 was much higher than the value of F table, it can be concluded that the null hypothesis (H_0) should be rejected, and accept the alternative hypothesis (H_1) which stated that there has a significant difference in the treatments means.

The inference statement suggests that the in-plane shear load carrying capacity of hybrid sandwich panels with JFC and MDF intermediate layer was significantly higher than the conventional sandwich panels. This statement has a 95% chance of being true, or 5% of not being true, as the significance level used for the analysis was 95%. Based upon the P value, which was much less than 0.005, it can also be concluded that there has factor levels or treatments that have different means. The P-value for this experiment, as presented in the Table 5, was approximately 0.000. A pairwise comparisons were also conducted in this in-plane shear test results to confirm the decisions drawn from the analysis of variance. The results of Tukey's, Dunnett's, and Fisher's test are presented in Table 6, 7, and 8, respectively.

Table 6 shows the result of Tukey's test conducted for the data of in-plane shear test. The comparison of level 0 to level 1 has the confident interval of 36336 for the lower value and 42790 for the upper value, and the critical value of 39563. For level 0 to level 2, the lower and the upper value was 8890 and 15344, respectively. In contrast, the analysis showed negative confident values when the level 2 was compared

to the level 0. The lower and upper value was -30673 and -24219, respectively with the centre or critical value of -27446. Although all the confident values were negative, it has a similar meaning with the previous all positive values because they are not containing zero number. The rule for concluding that all levels are different was that whenever the Tukey's confidence intervals contain zero number, it indicates that the means are not different. In short, it can be concluded that all the treatment means differ as none of confident levels contains zero. The Tukey's test also suggests that there is a significant different between level 1 and level 2, as they contain only negative numbers or none of confident levels contains zero.

Table 7 presents the results of Dunnett's test for the data of in-plane shear test. It is clearly shown in the table that all confidence intervals include only positive numbers. The lower and upper values of confident intervals for level 1 was 36534 and 42593, respectively. The corresponding values for level 2 was 9088 and 15146. The critical value of control level was 2.50, which is much lower than the critical values of level 1 and level 2. The critical value for level 1 was 39563, and 12117 for level 2. In short, it can be concluded that the load carrying capacity of level 1 and level 2 are much higher than control level.

Table 6. The Results of Tukey's Test Obtained by Statistical Software Minitab 15

Tukey 95% Simultaneous Confidence Intervals					
All Pairwise Comparisons among Levels of Intermediate Layer					
Individual confidence level = 97.94%					
Intermediate Layer = 0 subtracted from:					
Intermediate Layer	Lower	Centre	Upper		
1	36336	39563	42790	(-*)	
2	8890	12117	15344	(-*)	
		-20000	0	20000	40000
Intermediate Layer = 1 subtracted from:					
Intermediate Layer	Lower	Centre	Upper		
2	-30673	-27446	-24219	(*)	
		-20000	0	20000	40000

Table 7. The Results of Dunnett's Test for in-plane Shear Test Obtained by Statistical Software Minitab 15

Dunnett's comparisons with a control					
Family error rate = 0.05					
Individual error rate = 0.0278					
Critical value = 2.50					
Control = level (0) of Intermediate Layer					
Intervals for treatment mean minus control mean					
Level	Lower	Centre	Upper		
1	36534	39563	42593	(--*)	
2	9088	12117	15146	(--*)	
		10000	20000	30000	40000

The result of Fisher's test is given in Table 8 which shows a similar configuration with the Tukey's test. The comparison of level 0 to level 1 and level 2 has all positive confident intervals while the comparison of level 1 to level 2 has all negative numbers. The configuration of the confident values, that only contain positive or negative numbers, indicate that the means are different as they are not including zero number.

Table 8. The Results of Fisher's Test for in-plane Shear Test Obtained by Statistical Software Minitab 15

Fisher 95% Individual Confidence Intervals				
All Pairwise Comparisons among Levels of Intermediate Layer				
Simultaneous confidence level = 88.44%				
Intermediate Layer = 0 subtracted from:				
Intermediate Layer	Lower	Centre	Upper	
1	36926	39563	42201	(-*)
2	9479	12117	14755	(*)
-20000 0 20000 40000				
Intermediate Layer = 1 subtracted from:				
Intermediate Layer	Lower	Centre	Upper	
2	-30084	-27446	-24809	(*-)
-20000 0 20000 40000				

Conclusions

A comprehensive statistical analysis has been conducted to the data of in-plane shear load of hybrid and conventional composite sandwich panel. The experiment was designed based upon the principle of statistical design of experiment. The primary conclusion drawn was that the incorporation of intermediate layer to form a hybrid composite sandwich panel has significantly improved the capability of composite sandwich panel to carry in-plane shear load. The average in-plane shear load for hybrid sandwich panel with JFC intermediate layer was 49816 N which is 386% higher than the load carried by the conventional composite sandwich panel without intermediate layer (CTR) which was only 10253 N. While the average load for hybrid sandwich panels with MDF intermediate layer was 22370 N. This value is approximately 118% higher than in-plane shear load carried by the composite sandwich panel without intermediate layer. The statistical analysis shows that the value of F_0 is much higher than the value of F_{table} , which has a meaning that the improvement provided by the incorporation of intermediate layer is statistically significant.

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