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Improving the Quality of Experimental Research in Civil Engineering by Employing Statistical Design of Experiment; A Case Study in Developing Composite Hybrid Sandwich Panel

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Abstract. This paper presents comprehensive discussions about how to use statistical design of experiment in civil engineering based experimental works. Appropriate available literatures in related area were cited and also theoretical frameworks. The paper was then enriched with a case study of implementing statistical design of experiment in civil engineering field. The discussedtopic was about the development of composite hybrid sandwich panel that incorporating intermediate layer. The experiment was designed as a single factor experimental design.A significance analysis had been conducted to the data of ultimate load provided from flexural test. It was found that the incorporation of intermediate layer has significantly enhanced the load carrying capacity of sandwich panels. Overall, the statistical design of experiment employed in this study has demonstrated its ability in drawing inferential results of an experimental work in civil engineering field.

Introduction

Experimental works in civil engineering field are commonly conducted based on standardized test procedures. In this typical experiment, all conditions are kept constant except those under investigation. The variation in the conditions under investigation are then measured and recorded in standardized form to obtain immediately readable results [1]. The weakness of this type of experiment is that the conclusion drawn is only based on descriptive statistics which only tell the reader an immediately result without proper analysis how significant the differences between the conditions under investigation and those are kept constant. There has anequivalent method in statistical based experiment to the above method that is called as single factor experiment. This approach is frequently employed to explore the difference among more than two levels of a factor. The most advantage of statistical based experiment is that it can provide more accurate results since both descriptive and inferential statistics analysis are involved. Inferential statistics analysis can be defined as a process of inferring characteristics about a population, from a sample drawn from that population [2].

There is a problem with the implementation of standardized test procedures as different countries tend to define specific procedures for their own implementation. Much research has been undertaken on composite sandwich panels. Most of the research however, has only presented test results descriptively without fully testing the research hypothesis using statistical inference. It is not surprising that the results of many published papers differ widely. In this study, a statistically based experiment was employed thoroughly in order to provide not only descriptive statistics data but also testing a specific hypothesis with inferential statistics analysis to obtain more information about the experiments conducted. There are a number of excellent software products to assist researchers in both design and analysis phase of experiment. Some of the software includes Design-Expert, JMP and Minitab [3]. The last two software-packages are widely available for general-purpose statistical software packages that have good data analysis capabilities. In this work, a Minitab version 15 has been employed thoroughly to analyse the experiment results.

Literature Review

Single factor experiment is probably the most common approach employed to explore the difference among more than two levels of a factor. Antony [4] addressed this type of experiment as a one-variable-at-a-time (OVAT), where one variable is varying during the experiment and all the rest variables are fixed. The method for analyzing the single factor experiment results is called as significance analysis that usually involving analysis of variance (ANOVA). Significance analysis is a mathematical tool that is commonly used to determine whether the outcome of an experiment is the result of a relationship between specific factors or solely the result of chance [5]. It is frequent to summarize statistical comparisons by declarations of statistical significance or non-significance [6]. In a simple expression, statistical significance means that there is a good a relationship exists between two variables [7]. However, statistical significance does not always mean that the finding is important or that it has any decision-making utility [8], hence the researcher must always examine both the statistical and the practical significance of any research finding.

Although significance or statistical analysis is rarely found as a primary approach in civil engineering research, it has been extensively used in the broad field of composite material research. Some case studies are provided as follow. A Taguchi method was used to analyse the dry sliding wear behaviour of red mud filled polyester composites which concluded that significant control factors and their interactions primarily influenced the results [9]. A study on the significance effect of microwave curing on tensile strength of carbon fibre composites was reported by Balzer and McNabb [10]. A two-level full factorial design of experiment was employed to study the abrasive wear behavior of bamboo powder filled polyester composites [11]. Aktas [12] used Weibull distribution analysis to investigate the bearing strength of glass fibre composites materials. A response surface methodology (RSM) was employed by Mathivanan et al. [13] to analyze the factors influencing deflection in sandwich panels subjected to low-velocity impact. In addition to these studies, Fajrin et al. [14] investigated the bending strength of sustainable hybrid sandwich panel using simple comparative experimental method. Also, a study on the flexural strength of sandwich panel with lignocellulosic composite intermediate layer was also conducted by Fajrin et al. [15] using statistic approach.

Theoretical Frameworks

The appropriate procedure for testing the equality of several means is the analysis of variance or abbreviated as ANOVA. The objective of the ANOVA is to identify important independent variables and determine how they affect the response [16]. When only one factor is investigated, the process is called the one-way or single factor ANOVA. The procedure for one-way ANOVA referred in this work is as described by Montgomery [3] as follows.

Considers different levels, or treatments, of a single factor are being compared. The observed response from each treatment is a random variable. A simple linear statistic model for describing the observation results in such experiment is shown as follows.

$$y_{ij}=\mu_i+\epsilon_{ij}\begin{cases} i=1, 2, \ldots, a \\ j=1,2,\ldots,n_i \end{cases} \tag{1}$$

where,

y_{ij} : The ij^{th} observation
μ_i : Mean of the i^{th} factor level or treatment
ϵ_{ij} : Random error component

Eq. 1 is called as a means model. Another alternative way to express the model for such data is to define:

$$\mu_i=\mu+\tau_i\ , \quad i=1, 2, \ldots\ldots a \tag{2}$$

So that Eq. 1 becomes

$$y_{ij}=\mu+\tau_i+\epsilon_{ij}\begin{cases}i=1, 2, \ldots, a\\ j=1,2,\ldots,n_i\end{cases} \quad (3)$$

where,
μ :Parameter common to all treatments called the overall mean
τ_i : Parameter unique to the ith treatment called ith treatment effect

The null and alternative hypotheses for this statistical analysis are as follows.

$$H_0: \mu_1= \mu_2=\ldots= \mu_a \quad (4)$$

$$H_1: \mu_i\neq \mu_j, \quad \text{for at least one pair (i,j)} \quad (5)$$

The analysis of variance is derived from partitioning of total variability into its components parts. The total corrected sum of squares, which is used as a measure of overall variability in the data, is define as:

$$SS_T= \sum_{i=1}^{a}\sum_{j=1}^{n}(y_{ij}-\bar{y}_{...})^2 \quad (6)$$

Note that the total corrected sum of squares may be written as:

$$\sum_{i=1}^{a}\sum_{j=1}^{n}(y_{ij}-\bar{y}_{...})^2 = n\sum_{i=1}^{a}\sum_{j=1}^{n}(\bar{y}_{i.}-\bar{y}_{...}) + \sum_{i=1}^{a}\sum_{j=1}^{n}(y_{ij}-\bar{y}_{i.})^2 \quad (7)$$

The above equation states that the total variability in the data can be partitioned into a sum of squares of differences between the treatments means and the grand mean denoted as $SS_{treatments}$ and a sum of squares of differences of observation within a treatment from the treatment mean denoted SS_E. This statement can be written symbolically as:

$$SS_t = SS_{treatments} + SS_E \quad (8)$$

where,
SS_t : Total corrected sum squares
$SS_{treatments}$: Sum squares due to treatments (i.e. between treatments)
SS_E : Sum squares due to error (i.e. within treatments)

There is also a partition of the number of degree of freedom that corresponds to the sum of squares in Eq. 7. That is there are $an = N$ observations; thus, SS_t has $an - 1$ degrees of freedom. There are a levels of the factor, So, $SS_{treatments}$ has $a - 1$ degrees of freedom. Also, within any treatment there are n replicates providing $n - 1$ degrees of freedom with which to estimate the experimental error. Since there are 'a' treatments, the degrees of freedoms for error become $a(n - 1)$. Therefore, the degrees of freedom partition is:

$$an - 1 = a - 1 + a(n - 1) \quad (9)$$

The ratio of$SS_{treatments}$ to the degree of freedom is called as the mean square for treatment, and may be written as follows.

$$MS_{treatments}=\frac{SS_{treatments}}{a-1} \quad (10)$$

Now, if the null hypothesis is true, $MS_{treatments}$ is an unbiased estimator of σ^2 because$\sum_{1=1}^{a}\tau_i = 0$. However, if alternative hypothesis is true, $MS_{treatments}$ estimates σ^2 plus a positive term that incorporates variation due to the systematic difference in treatment means. It should be noted that the error mean square is defined as:

$$MS_E = \frac{SS_E}{(N-a)} \tag{11}$$

The test statistic for the hypothesis of no differences in treatment means in analysis of variance is defined by the following equation.

$$F_0 = \frac{SS_{treatments}/(a-1)}{SS_E/(N-a)} = \frac{MS_{treatments}}{MS_E} \tag{12}$$

The H_0 hypothesis should be rejected and conclude that there are differences in the treatment means if:

$$F_0 > F_{\alpha,\ a-1,\ n-a} \tag{13}$$

Case Study on the Development of Hybrid Composite Sandwich Panel

Testing set-up. A case study in the implementation of the statistical based experiment is presented in the following section dealing with the development of hybrid sandwich panel. The panel was developed by incorporating intermediate layer within a conventional sandwich that normally consisted of skins and core only. An investigation with medium size samples has been reported in reference [17]. A larger size samples (full scale) were investigated in this study where the sandwich samples were cut and shaped into a span length of 900 mm and the size of 1150×100×52 mm for length, width and thickness, respectively. An aluminum5005 H34 sheet with the thickness of 1 mm was used as the skins for all samples. An expanded polystyrene (EPS) is used for the core of this hybrid sandwich panel. The thickness of EPS core for control level was 50 mm and 40 mm for the other two levels to maintain a constant overall thickness of 52 mm. Two types of intermediate layer have been investigated against control specimen which was a sandwich panel without intermediate layer.The hybrid composite sandwich panel were tested under static flexural load in accordance with the ASTM C 393-00 standard [18]. The actual set up of the testing is shown in Fig. 1.

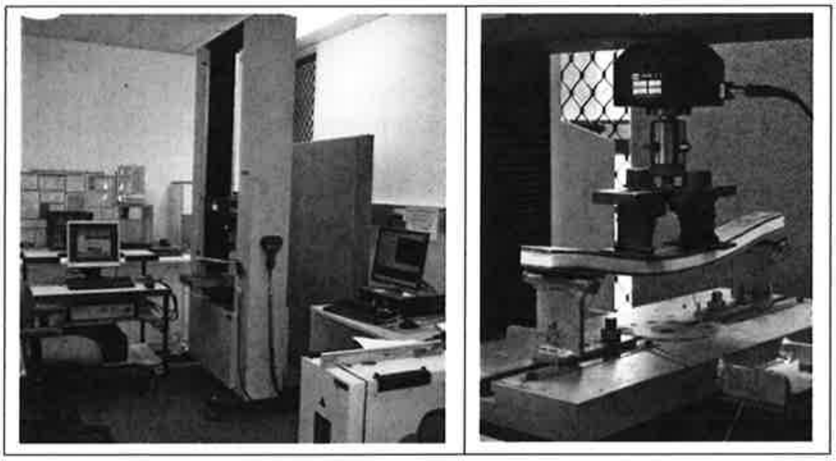

Fig. 1. The actual set up of flexural test

Analysis and Discussions

The experiments were arranged 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 and such factor was levelled as 0, 1 and 2 as required by Minitab 15 software.In the arrangement; level 1 and 2 refer to as Jute fibre composite (JFC) and medium density fibre (MDF) while level 0 was a control level (CTR) which is sandwich panel without intermediate layer. For the analysis purpose, the data for ANOVA are tabulated as shown in Table 1.

Table 1. Tabulated data for analysis of variance (ANOVA)

Factor levels	Observations				Totals	Average
	1	2	3	4		
Level 0 (CTR)	489	572	518	407	1986	496.50
Level 1 (JFC)	898	751	842	738	3229	807.25
Level 2 (MDF)	1241	1537	1275	1281	5334	1333.50

As it can be seen in Table 1, some important parameters for theoretical calculations can be defined such as replications (n = 4), total number of samples (N = 12), and number of levels or treatments (a = 3). Firstly, the theoretical total corrected sum squares (SS_T) and treatment sum square ($SS_{treatments}$) were calculated as per Eqs. 6 and 7, respectively. The sum of square of difference (SS_E) was then calculated based upon the results of the above two equations as defined by Equation 8. The subsequent steps were determining the mean square for treatment ($MS_{treatments}$) and the error mean square (MS_E) using Eqs. 10 and 11, respectively. At last, the value of F_0 can be obtained as per Eq. 12. The results of the theoretical calculations were then presented in Table 2, while the analysis obtained by statistical software Minitab 15 is summarized in Table 3.

Table 2. The theoretical results of ANOVA

Source of variations	Sum of square	Degrees of freedom	Mean square	F_0
Intermediate layer	1432098.00	2	716049.10	73.42
Error	87778.75	9	9753.19	
Total	1519877.00	11		

Table 3. Analysis of variance results obtained by statistical software minitab 15

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One-way ANOVA: Flexural Load versus Intermediate Layer

Source              DF       SS       MS      F      P
Intermediate Layer   2  1432098   716049  73.42  0.000
Error                9    87779     9753
Total               11  1519877
S = 98.76   R-Sq = 94.22%   R-Sq(adj) = 92.94%

                             Individual 95% CIs For Mean Based on
                             Pooled StDev
Level  N    Mean  StDev  -------+---------+---------+---------+--
0      4   496.5   68.9  (---*--)
1      4   807.3   76.2            (---*---)
2      4  1333.5  136.8                               (--*---)
                         -------+---------+---------+---------+--
                              600       900      1200      1500
Pooled StDev = 98.8
```

As it can be observed in Table 2 and Table 3, the value of F_0 was 73.42, while the F value obtained from the F-distribution table for $F_{(0.05;2,9)}$ was 4.26. The value of F_0 was much higher than the value of F table, accordingly the null hypothesis (H_0) should be rejected, which means that there are a significant difference in the average values of treatments. As the null hypothesis was rejected, it can be concluded that the load carrying capacity of conventional sandwich panel was much lower than those of hybrid sandwich panels. The theoretical calculations were in good agreement with the ANOVA results obtained by statistical software Minitab 15.

Conclusions

The primary conclusion drawn was that the statistical design of experiment used in this study has demonstrated its ability in drawing inferential results of an experimental work in civil engineering field. More specific outcomes are outlined as follows. The incorporation of intermediate layer has significantly enhanced the load carrying capacity of sandwich panels. The F_0 value was 73.42, while the F value obtained from the F-distribution table for $F_{(0.05;2,9)}$ was 4.26. The value of F_0 was much higher than the value of F table, accordingly the null hypothesis (H_0) should be rejected, which means that there are a significant difference in the average values of treatments. The inference statements suggested that the load carrying capacity of hybrid sandwich panels with JFC and MDF intermediate layer was significantly higher than the conventional sandwich panels.

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