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Flexural Strength of Sandwich Panel with Lignocellulosic Composites Intermediate Layer - a Statistic Approach

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ABSTRACT
In this study, three different types of lignocellulosic composite materials have been incorporated in sandwich panel structure as an intermediate layer. The experiment was statistically designed based on single factor analysis scheme. The results of experiments have been analyzed using analysis of variance (Anova) followed by Tukey's, Fisher's and Dunnet's tests to obtain the information of how significant those materials contribute to the flexural strength of sandwich panel structure. The total number of samples tested was 48 beams. The results show that the introduction of lignocellulosic composites materials, that are hardboard, medium density fibre (MDF) and plywood, has significantly improved the flexural strength of sandwich panel. The range of improvement contributed by the presence of lignocellulosic composites intermediate layer was around 100-150% for samples with balsa core and 130-150% for samples with polystyrene core. The result of this study shows the potential of lignocellulosic composite material to be developed further for producing more sustainable sandwich panel.

Keywords: Lignocellulosic composites, intermediate layer, flexural strength, statistics

1. INTRODUCTION

A sandwich structure is formed by bonding a relatively thick and low density core material in between top and bottom thin face skin layers. The role of the skin is to hold bending stresses, while the primary function of core component is to maintain the skins separated and thus keep a high section modulus or moment of inertia and also carrying transverse shear load (Kampner *et al*. 2008). Although sandwich panels offer high strength and stiffness to weight ratio as their primary advantages, which has been highlighted by many investigators (Zenkert *et al*. 1995; Zhou *et al*. 2005; Schwarts-Givli *et al*. 2007, Moreira *et al*. 2010), they also have a critical drawback that is subjected to a strong stress concentration at the interfaces among the skin and core which may cause a premature failure at load level much

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lower than the ultimate load (Icardi *et al*. 2009). This observable fact should be taken into account particularly when using lightweight-thin laminate or metal skin for sandwich panel. The core must be capable of handling a compressive loading without premature failure which helps to prevent the thin skins from face wrinkling, and failing in other mode of failures such as buckling or core shear.

Having considered this typical weakness of sandwich panel structure, some researchers proposed different concepts to cope with this phenomenon. A fibrous core sandwich panel which is thin, lightweight structures with face sheet separated by an irregular arrangement of independent fibres was introduced by Zhou *et al*. (2004). Grenesdet *et al*. (2007) and Kampner *et al*. (2007) reported their works on using a corrugated skin to increase the wrinkling strength under compression load and to carry shear in sandwich beam. Some authors used honeycombs core (Grediac *et al*. 1993; Masters *et al*. 1996; She *et al*. 1995; Meraghni *et al*. 1999; and Balawi *et al*. 2008). A relatively new effort in this topic was carried out by Mamalis, *et al*. (2008) who proposed a new hybrid concept for sandwich structures. The concept is the introduction of intermediate layer between two conventional sandwich materials, skin and core, with a material which is stiffer than core, lightweight and preferably much thinner than the core material. They claimed that their work have been successfully improving the bending and impact behavior of sandwich panel. Fajrin *et al*., (2011) reported their work on further investigation Mamalis's concept using statistics approach. A simple comparative experimental design was employed to plan the experiment and the results of *two-sample t-test* using statistics software, Minitab 15, were discussed. The results show that, with the level significance of 0.05 and degree of freedom (DF) 10, the t-value of all sample categories exceeded the corresponding values provided from relevant table t-distributions, verifying that the bending strength of sandwich panel with intermediate layer are significantly higher than the conventional one.

The intermediate layers employed in the current research were plywood and balsa wood which impregnated with epoxy resin prior to use. The utilization of plywood as an intermediate layer, which is a lignocellulosic composite, seems more appropriate to be used as their properties are relatively consistent and also gives higher bending strength. Hence, there is a need to further investigate different types of lignocellulosic composites as the intermediate layer. This paper presents the result of statistical analysis to the flexural strength of sandwich panels containing three different types of lignocellulosic composites as the intermediate layer. The experiment was statistically designed as a single factor experiment to obtain comparative analysis between variables and control.

2. LIGNOCELLULOSIC COMPOSITES

A lignocellulosic material is any substance that contains both cellulose and lignin. Wood, agricultural crops and agricultural residues are included in this material category. Generally, a composite can be defined as any combination of two or more materials to form a new constituent material, in any form, and for any use. The composite products have a distinct performance that combine the positive attributes of each constituent component. Hence, a lignocellulosic composite is a composite product made from any combination of lignocellulosic materials. The term of composite and reconstituted wood is frequently used to describe any wood product that is glued together to produce a widely range of final wood-based product from fiberboard to laminated beams and structural components (English, 1994). Traditional lignocellulosic composites can be categorized into three main groups based on particle size; veneer, particle and fiber based materials. Plywood and laminated veneer lumber (LVL) is a veneer-based material. The class of particle board includes waverboard, oriented strand board (OSB), chipboard and particleboard. Meanwhile, other wood-based products such as hardboard and medium density fiberboard (MDF) are categorized as fiber-based panel materials.

Plywood is a type of manufactured wood which made with an odd number of plies and usually with the grain of alternating veneer plies at right angle (Biblis, 1970). Meanwhile, a fiber composite material comprising of refined wood fibers, adhesive (resin), process additives, and minor amount of wax produced in a dry fiber process is called as medium density fiber (MDF). This typical panel has a density ranges from 450 to 800 kg/m^3 and the strength of MDF depends on its fibers. The most common types of resins used for MDF products are based on formaldehyde (Halvarsson, 2008). In addition, hardboard is an engineered made out of interfelted lignocellulosic fibers that have been highly compressed and manufactured primarily from wet or dry formed to a specific gravity of 0.50 to 1.45. Hardboards are classifieds by density, surface finish, thickness and minimum physical properties (English, 1994).

3. SINGLE FACTOR ANALYSIS

Single factor analysis is the most common approach employed by many researchers to explore the difference among more than two levels of a factor. Antony (2003) 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. Basically, there are two types of factor, quantitative and qualitative. A quantitative factor is a factor where some levels that can be quantified such as 0%, 10%, 20% and 30% are of interest. When the levels of a factor cannot be quantified such as different type of methods or materials, this kind of factor is classified as a qualitative factor.

A single factor analysis is a process of analyzing data obtained from experiment with different levels of a factor, usually more than two levels of factor. The appropriate procedure for testing the equality of several means is the analysis of variance or abbreviate as Anova. As the name implies, the Anova procedure attempts to analyze the variation in a set of responses and assign portions of this variation to each variable in a set of independent variables. The objective of the Anova is to identify important independent variables and determine how they affect the response (Wackerley, 2008). When only one factor is investigated, the process is called the one-way or single factor analysis of variance. The procedure for one-way Anova is as described by Montgomery (2009) as follows. The model for this statistical analysis is

$$y_{ij} = \mu + \tau_i + \in_{ij} \left\{ \begin{matrix} i=1,2,\ldots,a \\ j=1,2,\ldots,n \end{matrix} \right. \tag{1}$$

where,

y_{ij} : response of the ijth observation
μ : overall mean
τ_i : ith treatment effect
$\in_{ij}$: random error component

The null and alternative hypotheses for this statistical analysis are
H_0: $\mu_1 = \mu_2 = \cdots = \mu_a$ or equivalently, H_0: $\tau_1 = \tau_2 = \cdots = \tau_a = 0$
H_1: $\mu_i \neq \mu_j$ for at least one pair (i,j)

The next procedure for this analysis process is to calculate:

$$SS_T = \sum_{i=1}^{a} \sum_{j=1}^{n} y_{ij}^2 - \frac{y_{..}^2}{n} \tag{2}$$

$$SS_{treatments} = \frac{1}{n} \sum_{i=1}^{a} y_i^2 - \frac{y_{..}^2}{n} \tag{3}$$

$$SS_E = SS_T - SS_{treatments} \tag{4}$$

$$MS_{treatments} = \frac{SS_{treatments}}{a-1} \tag{5}$$

$$MS_E = \frac{ss_E}{n-a} \tag{6}$$

Then, the appropriate test statistic for this one-way Anova process is

$$F_0 = \frac{MS_{treatments}}{MS_E} \tag{7}$$

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)
$MS_{treatments}$: mean squares of treatments
MS_E: mean squares of errors
F_0: response of the *ij*th observation

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

$$F_0 > F_{\propto,a-1,n-a} \tag{8}$$

4. EXPERIMENTAL PROGRAM

The single factor used in this experiment refers to the type of material for intermediate layer which is a qualitative factor. Three different materials were employed for intermediate layer, i.e. Hardboard, Medium Density Fiber (MDF) and Plywood. However, for the purposes of analysis, this factor was leveled as 0, 1, 2 and 3 as required by Minitab software. Level 0 was the sample with no intermediate layer which used as the control level while level 1, 2 and 3 refer to as hardboard, MDF and plywood, respectively. The sandwich panel samples were fabricated in accordance with ASTM C 393-00 which is a standard test method for flexural properties of flat sandwich constructions.

The samples were cut and shaped into the size of 312.5 × 25 × 12.5 mm for length, width and thickness, respectively. The span length was 250 mm and two types of core materials were employed; balsa wood and polystyrene (EPS). An aluminium coil with the thickness of 0.3 mm was used as the skins for all samples. The overall thickness of sandwich panels was kept constant to 12.5 mm. This experiment was designed as a single factor with 4 levels. Each level was replicated 6 times; hence the total of samples tested was 48 beams. The arrangement of experiment is shown in Table 1 and the test set-up is shown in Figure 1.

5. RESULT AND DISCUSSIONS

5.1 STATISTICAL INFERENCE ANALYSIS

The primary concern here is to find out the inference of how significant the difference among all means of factor levels and also between levels of factor. The results of experiment are shown in Table 2.

The appropriate procedure for testing the equality of several means like this case is by performing the analysis of variance (Anova). The results of Anova using Minitab are shown

Table 1. Experimental arrangements for single factor analysis

Groups	Levels	Intermediate layer		Skin		Core	
		Material	Thickness	Material	Thickness	Material	Thickness
Group 1	Level 0	None	-	Aluminium	0.3 mm	Balsa	11.9 mm
	Level 1	Hardboard	3 mm	Aluminium	0.3 mm	Balsa	5.9 mm
	Level 2	MDF	3 mm				
	Level 3	Plywood	3 mm				
Group 2	Level 0	None	-	Aluminium	0.3 mm	Polystyrene	11.9 mm
	Level 1	Hardboard	3 mm	Aluminium	0.3 mm	Polystyrene	5.9 mm
	Level 2	MDF	3 mm				
	Level 3	Plywood	3 mm				

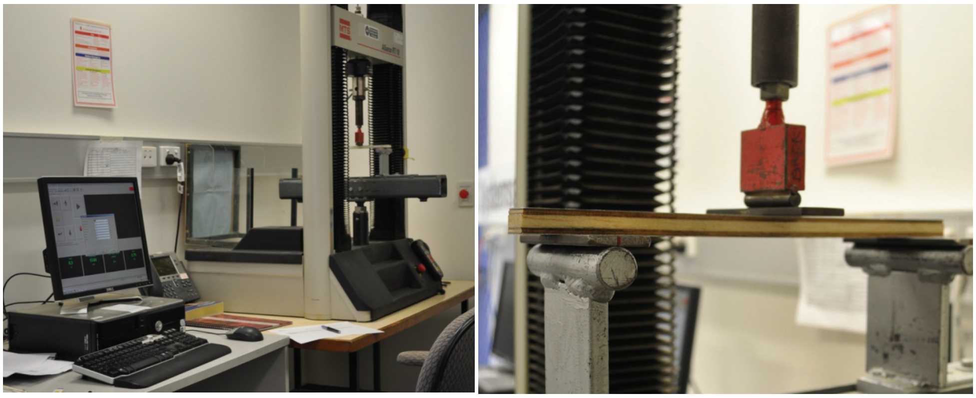


Figure 1. Test set-up for three-point-bending load

Table 2. Bending strength (MPa) of sandwich panel beam samples with three types of intermediate layer material using two different core materials.

Core Material	Intermediate Layer	Replications						Avrg	Stdv
		1	2	3	4	5	6		
Balsa core	None	62.66	76.38	43.98	56.56	62.18	51.2	58.83	11.12
	Hardboard	141.83	151.84	145.37	164.37	159.20	139.35	150.33	9.95
	MDF	108.81	136.69	118.14	124.02	91.52	125.98	117.53	15.71
	Plywood	113.94	107.80	117.41	105.83	127.67	105.36	113	8.63
Polystyrene core	None	10.12	8.66	9.99	6.46	6.65	10.78	8.78	1.85
	Hardboard	13.66	26.71	17.15	16.74	27.75	27.90	21.65	6.48
	MDF	20.01	20.39	25.50	23.17	24.64	23.64	22.89	2.24
	Plywood	22.34	21.30	23.81	21.30	17.86	19.08	20.95	2.16

Table 3. Computer output using Minitab 15 for the analysis of variance (Anova)

```
One-way ANOVA: Bending stress versus Intermediate layer type

Source                   DF     SS    MS      F      P
Intermediate layer type   3  25864  8621  63.41  0.000
Error                    20   2719   136
Total                    23  28583
S = 11.66   R-Sq = 90.49%   R-Sq(adj) = 89.06%
                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level  N    Mean  StDev  ----+---------+---------+---------+-----
0      6   58.83  11.12  (---*--)
1      6  150.33   9.95                                (--*--)
2      6  117.53  15.71                     (--*--)
3      6  113.00   8.63                   (---*--)
                         ----+---------+---------+---------+-----
                            60        90       120       150
Pooled StDev = 11.66
```

in Table 3. The rule of making a decision in this type of experiment is based on Equation 8; whenever the value of calculated F (F_0) exceeds the value of F table $F_{\propto,a-1,n-a}$ then a null hypothesis should be rejected and it can be concluded that the level means differ. For example, as it can be seen in Table 3, the F-value obtained by Minitab, (F_0) = 63.41. If a significancy level of 95% ($\alpha = 0.05$) was selected, 6 replications ($a = 6$) and 24 number of samples ($n = 24$) then from table F-distribution it can be found that $F_{(0.05;5,19)} = 2.74$. Because the value of $F_0 = 63.41 > 2.74$, H_0 will be rejected which means the level is different; that is, the introducing of intermediate layer signifficantly affects the bending stress of sandwich panel. We could also use the P-value to draw a conclusion; if the P-value is less than α (0.05, error tolerance level) we can conclude that there has factor levels or treatments which have different means. Clearly, the p-value is very small in this case as obtained by Minitab presented in the Table 3.

At the lower part of the Anova output, there has also information about the mean and standard deviation of all factor levels as well as their matrix. Based on the graph presented there, a rough decision of what factor levels differ can be obtained. But the decision made is going to be very subjective and unsatisfied. Therefore, a pairwise comparison between all factor levels need to be conducted. There are few possible test methods for this purpose such as Dunnet's test, Tukey's test and Fisher's test. Many statisticians prefer to use the Tukey method because it does control the overall error rate (Montgomery, 2009).

The Tukey's test compares all possible pairs of means and can be used to determine which means amongst a set of means differ from the rest. This typical test is normally conducted after Anova leads to a conclusion that there is evidence that the group means are different. The results are presented as a matrix showing the result of each pair as a confidence interval.

Table 4. Summary of the Tukey's test result using Minitab 15

Descriptions	**Treatments**	**Convidence Interval**		
		lower	**centre**	**upper**
Comparison between level 0 to level 1, level 2 and level 3	Level 0 vs Level 1	72.65	91.50	110.35
	Level 0 vs Level 2	39.85	58.70	77.55
	Level 0 vs Level 3	35.32	54.17	73.03
Comparison between level 1 to level 2 and level 3	Level 1 vs Level 2	–51.65	–32.80	–13.95
	Level 1 vs Level 3	–56.18	–37.32	–18.47
Comparison between level 2 and level 3	Level 2 vs Level 3	–23.38	–4.53	14.33

If none of the Tukey confidence intervals equals zero, it indicates that all of the means are different. The output of Tukey's test for this experiment is summarised in the the following Table.

Table 4 shows that for the first level comparison, there is no confidence interval contains zero, all results are positive numbers, which means that the level 1, 2 and 3 have a significant difference with level 0. All the confidence interval in the second process contains negative numbers, which means that level 1 has a large difference with level 2 and level 3. In the last step, the interval confidence is –23.38 for the lower and +14.33 for the upper, which means there has a zero number in between the lower and upper confidence interval. This figure leads to a conclusion that there has no significant difference between level 2 and level 3. The results of this test are extremely important to drawing a conclusion, particularly the last one. Although the mean bending strength of level 2 (117.53 MPa) and level 3 (113 MPa) are different, the statistical analysis shows that those two means are substantially similar.

There are other kinds of pairwise comparison tests that usually conducted simultaneously with Tukey's test, such as Dunnet's test and Fisher's test. They are basically similar to the Tukey's test. The Dunnet's test is specifically designed for situations where all levels are to be pitted against one reference level. It is commonly used after Anova has rejected the hypothesis of equality of the means of the distributions. Its goal is to identify levels whose means are significantly different from the mean of reference level. The result of Dunnet's test is presented in the following Table.

The Dunnet's test only compares the control with the rest of factor levels. There are two possible ways to make judgement through this type of test. The first way is to compare the critical value of control level with other levels. As can be seen in Table 5, the critical value of control (level 0) is 2.54. Meanwhile, the critical value of level 1, level 2 and level 3 was 91.5, 58.7 and 54.17, respectively. Those three critical values of levels were much higher than the critical value of control. This result confirms that the bending stress of sandwich panel with intermediate layer is significantly higher than conventional sandwich panel. The second way is by checking whether the confidence interval contains zero or not. The result in Table 5 shows that none of the three levels contains zero which means that they are substantially different. In addition, The Fisher's test is similar to the Tukey's test in term of goal and rules. For the comparison purpose, the Fisher's test was also performed using Minitab 15 and the results are shown in Table 6.

As indicated in the Table, for the first and second comparisons, none of the confidence interval contains zero number, which means that they are different to each other. For the third process, however, the confidence interval has a zero number between –18.57 and 9.52. This means that the level 2 and level 3 are not significantly different.

Table 5. The result of Dunnet's test using Minitab 15

```
Dunnett's comparisons with a control

Family error rate = 0.05

Individual error rate = 0.0195

Critical value = 2.54

Control = level (0) of Intermediate layer type

Intervals for treatment mean minus control mean

Level  Lower  Center   Upper  -+---------+--------+--------+--------

1      74.40   91.50  108.60                      (--------*-------)

2      41.60   58.70   75.80    (-------*--------)

3      37.07   54.17   71.28  (-------*--------)

                              -+---------+--------+--------+--------

                              40        60       80       100
```

Table 6. Summaration of the Fisher's test result using Minitab 15

Descriptions	Treatments	Convidence Interval		
		lower	centre	upper
Comparison between level 0 to level 1, level 2 and level 3	Level 0 vs Level 1	77.46	91.50	105.54
	Level 0 vs Level 2	44.66	58.70	72.74
	Level 0 vs Level 3	40.13	54.17	68.22
Comparison between level 1 to level 2 and level 3	Level 1 vs Level 2	–46.84	–32.80	–18.76
	Level 1 vs Level 3	–51.37	–37.32	–23.28
Comparison between level 2 and level 3	Level 2 vs Level 3	–18.57	–4.53	9.52

6. STATISTICAL DESCRIPTIVE ANALYSIS

The inferential statistic analysis is basically can only be used for drawing a conclusion and provide the information about the quality of comparison among the levels of factor, whether they are significant or not. In order to provide descriptive information, a descriptive statistical analysis needs to be done. This typical statistical analysis is employed to describe the basic features of the data in a study. They provide simple summaries about the sample and the measures in the form of graphical analysis. In general, descriptive statistics describe the main features of a collection of data quantitatively. The results of this work can be descriptively presented in the following figure.

Figure 2 shows the bending stress of sandwich panels with different types of intermediate layer, i.e. hardboard, medium density fibre (MDF) and plywood against sandwich panel with no intermediate layer. There are two categories of samples; one group of samples with balsa core and the other group of samples with polystyrene core. It is clearly demonstrated in this figure that the sandwich panels with intermediate layer have superior bending stress capacity than the control group with no intermediate layer. The range of improvement contributed by the presence of intermediate layer was around 100–150% for samples with balsa core and

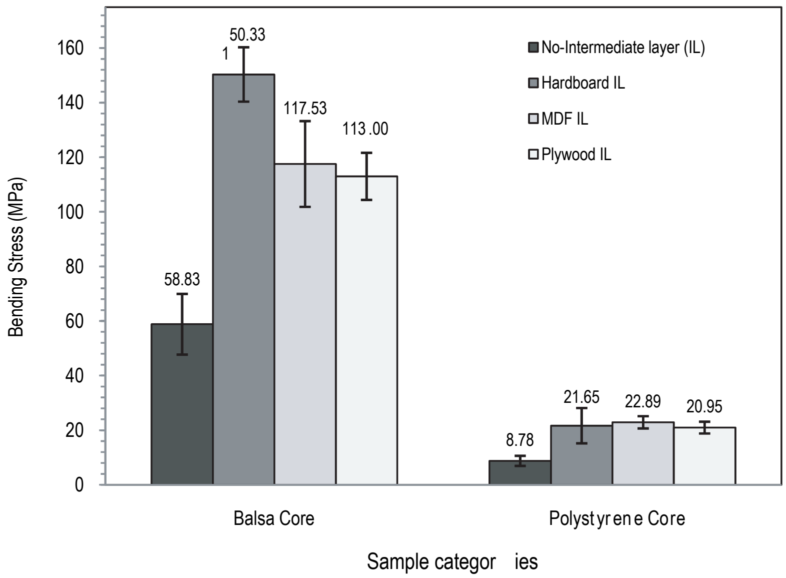


Figure 2. Bending stress (MPa) of sandwich panel beam tested under single factor experimental design

130–150% for samples with polystyrene core. In addition, it is also evident that the core material has a significant role to distribute some amount of bending stress in order to prevent a premature failure. The average bending stress that can be hold by a sandwich panel with intermediate layer and polystyrene core was only ranged from 20.95–21.65 MPa. This is quite far less than the capacity of sandwich panel with intermediate layer and balsa core, which was about 113–150 MPa. There are indeed other possible potential factors that can affect the bending stress of this new hybrid sandwich panel such as the interaction between intermediate layer and core material. The most disadvantage of single factor experimental design is that it is unable to consider any possible interaction between the factors in sample population. A factorial design of experiment could be a better way to overcome this limitation.

Figure 3 shows the specific strength to weight ratio of the sandwich panels with and without intermediate layer. The introduction of intermediate layer in a sandwich structure will allow the use of very thin face sheets, e.g. metals and very cheap cores at the expense of a slightly heavier structure. However, the improvement achieved will compensate all those costs. As indicated in Figure 3, the specific strength to weight ratio was reduced up to 35% when intermediate layer was used, while the bending strength increased up to 150%. Although weight is important, other priorities such as the structural integrity and the cost are followed. If a common material is chosen, e.g. plywood, this intermediate layer will also decrease the cost considerably while maintaining a very similar strength to weight ratio.

As can be seen from Figure 3, using plywood as intermediate layers seems the appropriate choice as it can improve the bending strength up to 92.08% for balsa core and 138.61% for polystyrene core, while maintaining the similar specific strength to weight ratio. However, using plywood will costmore as the price of plywood almost doubled the price of MDF and hardboard.

The typical failure modes of sandwich panel shown in the Figure 4 clearly demonstrated how the introduction of intermediate layer has prevented the existence of premature failure modes. Sandwich panel with balsa core without intermediate layer was mostly collapsed in

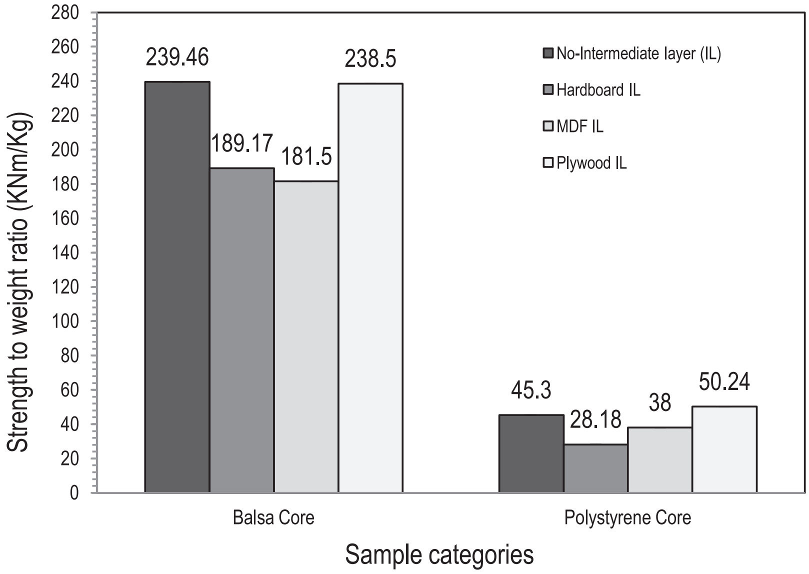


Figure 3. Strength to weight ratio (specific stregth) of sandwich structures for two different sample categories

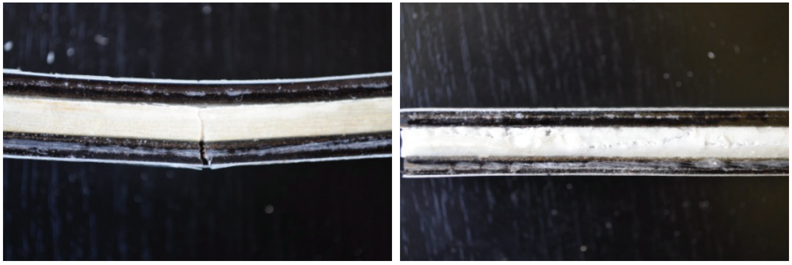
wrinkling at the top skin. The addition of hardwood, MDF and plywood intermediate layer give some additional strength to sandwich panel to remain withstand and then collapsed under other types of failure mechanism such as tensile, shear and delamination that resulted in higher load carrying capacity. Meanwhile, the indentation failure mode existed mostly for the sandwich panel with polystyrene core. The low strength properties of polystyrene have resulted in a very early failure of the sandwich panel structures. The presence of intermediate layers in the structures improves the flexural behaviour to such extent but not as much as when the sandwich panel using balsa core. Core shear and delamination were the typical failure modes for sandwich panel with polystyrene core containing lignocellulosic composites intermediate layers. The typical failure patterns of some specimens are as illustrated in the following figure.

7. CONCLUSIONS

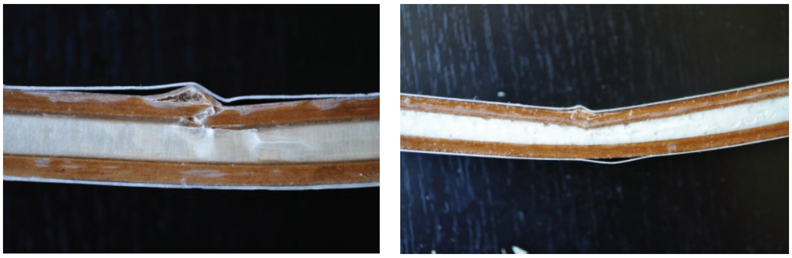
The introduction of lignocellulosic composites materials, that are hardboard, medium density fibre (MDF) and plywood, has significantly improved the flexural strength of the sandwich panel. The results of statistics inferential analysis using software Minitab 15 confirmed that sandwich panel containing lignocellulosic composite materials are significantly different to the conventional sandwich panel that employed no intermediate layer. The Tukey's and Fisher's test showed that all confidence levels were positive when compared other levels to the control (level 0). The result of Dunnet's test showed that the critical value of level 0 (control) was far less than those of other levels, which means that the bending stress of sandwich panel with intermediate layer is significantly different (higher) than conventional sandwich panel.

Graphical descriptive statistics clearly demonstrated that the sandwich panels containing lignocellulosic composites intermediate layer have superior bending stress capacity than the control group with no intermediate layer. The range of improvement contributed by the presence of intermediate layer was around 100–150% for samples with balsa core and 130–150% for

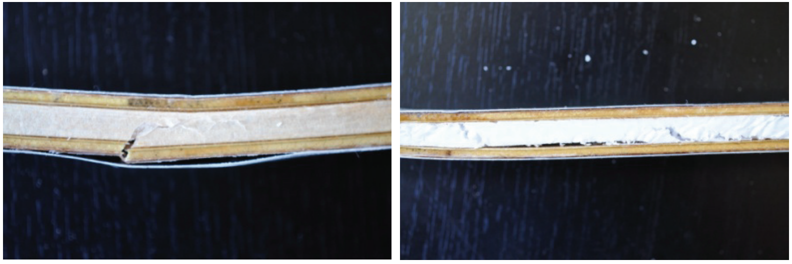
Aluminium + Balsa Aluminium + Polystyrene (EPS)



Aluminium + Hardwood + Balsa Aluminium + Hardboard + Polystyrene (EPS)



Aluminium + MDF + Balsa Aluminium + MDF + Polystyrene (EPS)



Aluminium + Plywood + Balsa Aluminium + Plywood + Polystyrene (EPS)

Figure 4. Typical failure patterns of sandwich panels-sandwich panel with balsa core (left)and sandwich panel with polystyrene core (right)

samples with polystyrene core. Although the weight of sandwich structure was increased by the introduction of intermediate layer, the strength to weight ratio is only slightly less than or the same as the unmodified panel. The result of this study shows the potential of lignocellulosic composite materials to be developed further for producing more sustainable sandwich panel.

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