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A study on the parameters affecting the properties of coated paper honeycomb

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Abstract. In this study, three parameters, namely the density of Kraft paper, the thickness of cell wall and the cell size of honeycomb were evaluated. A statistical analysis was performed to investigate the effect of the parameters on the specific compression strength(SCS) and specific energy absorption (SEA) of Kraft paper honeycomb. Based on the design of experiment, 27 configuration of Kraft paper honeycomb with different cell sizes (10mm,15mm,20mm), thicknesses of cell wall (1ply, 2ply, 3ply) and paper densities (80gsm,120gsm,175gsm) are subjected to quasi static compression loading. An analysis of variance (ANOVA) was used to examine the effect of each parameters and to obtain the optimum configuration of Kraft paper honeycomb. As a result, the thickness of cell wall shows as the most prominent parameter for specific energy absorption and specific compression strength. Meanwhile, the Kraft paper honeycomb with density 175gsm, 3 ply thickness of paper and 10mm cell size of honeycomb shows the optimum configuration with 724.80 J/kg of SEA and 9.35 MPa/kg of SCS.

1. Introduction

Sandwich panel containing commercial Kraft paper honeycomb core with resin pre-impregnated into the paper or no resin at all is widely used in furniture, doors, partitions, mobile homes, signs and similar construction. Meanwhile, special grade Kraft paper honeycomb core which dipped in a phenolic resin after expansion in order to increase its water resistance and strength is used in portable military shelter, aerospace and naval industry [1]. Some main advantages of these sandwich panel include reduced weight and production cost, lower materials usage and less damage during transportation [2]. Although honeycomb sandwich panels are widely used in engineering industries since many decades, there is limited information available concerning the properties and behavior of the lightweight paper honeycomb panel. Moreover, honeycomb core are the weakest part of sandwich panel and they may fail or collapse through cell material fracture or cell wall buckling, depending on the loading regime and the core configuration [3][4][5].

Up until today, many researchers investigated on honeycomb structure used for high technology application such as aerospace and naval industry like Nomex and metallic honeycomb[6][7][8]. Unfortunately, scarce studies can be found in the literature dealing with honeycomb sandwich panel used for low technology such as furniture or load bearing application. Recently, some manufacturers are aiming to use paper honeycomb panel or structure for load bearing application such as floor, decks, transportation pallet, load bearing wall and partition due to lower cost and material usage of paper honeycomb compared to solid wood based panel.

Investigation of the crushing phenomena of honeycomb structures under both quasi-static and dynamic loading conditions considering the effects of cell dimension and foil thickness have been performed earlier by Wu and Jiang [9] and Yamashita and Gotoh [10]. Wu and Jiang investigated the honeycomb specimens with cell size of 3.2 and 4.7 mm and Yamashita and Gotoh studied the quasi-static compression response of aluminium honeycomb in the thickness direction. Meanwhile, Dongmei wang [11] studied the impact behavior and energy absorption on the paper honeycomb sandwich panel where the effect of paper honeycomb structure factors on the impact behavior was analyzed.

In this research, honeycomb made from Kraft paper are manually manufactured with different parameters especially on the honeycomb cell sizes, thicknesses of cell wall and densities. Series of quasi static experimental tests were carried out to investigate the effect of the parameters on specific energy absorption and specific compression strength. The optimum configuration on specific energy absorption and specific compression strength were determined through statistical analysis of variance (ANOVA).

2.Specimen Fabrication and Methodology

Kraft Paper honeycomb coated with vanish were fabricated with different parameters by using honeycomb maker. The density of paper (80gsm, 120gsm, 175gsm), thickness of cell wall (1ply, 2ply, 3ply) and cell size of honeycomb (10mm, 15mm, 20mm) were taken as parameters (table 1).The height for all specimens was 45mm. According to full factorial design, 27 configuration are generated considering three parameters with three levels as shown in table 2. The paper honeycombs were subjected to quasi-static compression loading by using SHIMADZU Autograph AG-X 250 compression machine. As the bottom plate was fixed and the upper plate was subjected to vertical downward displacement of 22.5mm. The force acting on the specimens was measured by load cell, and the force-displacement curve was plotted. The rate of displacement was 0.5 mm/min. Then, statistical analysis of variance (ANOVA) was used to study the effect of parameters and to obtain the optimum configuration of Kraft paper honeycomb on the specific energy absorption (SEA) and specific compressive strength (SCS).

Table 1. Parameters and levels using in DOE.

Factor	Code	Unit	Level 1	Level 2	Level 3
Density of paper	A	gsm	80	120	175
Thickness of cell wall	B	ply	1	2	3
Cell size of honeycomb	C	mm	10	15	20

3. Results and Discussion of Compression Test

3.1. Force- Displacement curve

The sample of force-displacement curves of Kraft paper honeycombs tested in uniform compression are given in figure 1. The curves show that there is elastic behavior at the beginning of the indentation until a critical load is reached. After the peak load, a sharp drop is observed. Based on Aminanda et al [12], the sharp drop is corresponds to the beginning of vertical edge deformation. Then the force decreases to reach a plateau, which corresponds to the succession of fold forming and ends up by condensation of the honeycomb.

From the graph, the specific energy absorption (SEA) was determined by dividing energy absorption capability of specimen (EA) with mass of specimen (m). EA was estimated by the area

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under force-displacement curve and it was measured until 22.5mm of displacement. Meanwhile, specific compressive strength (SCS) was calculated by dividing maximum compressive stress (σ_{max}) with mass of specimen (m). Afterward, SEA and SCS will be analyze using ANOVA.

Table 2. The configuration of kraft paper honeycomb by general factorial.

Run	*A* *Density of paper (gsm)*	*B* *Thickness of cell wall (ply)*	*C* *Cell size of honeycomb (mm)*
1	175	2	10
2	80	2	20
3	80	2	10
4	120	3	15
5	175	3	20
6	80	3	15
7	120	2	10
8	120	1	20
9	120	2	15
10	120	3	10
11	80	1	20
12	80	3	20
13	175	2	20
14	80	1	10
15	175	1	20
16	175	2	15
17	120	1	10
18	120	1	15
19	80	2	15
20	80	3	10
21	175	1	10
22	120	3	20
23	175	3	20
24	175	1	15
25	120	2	20
26	175	3	10
27	80	1	15

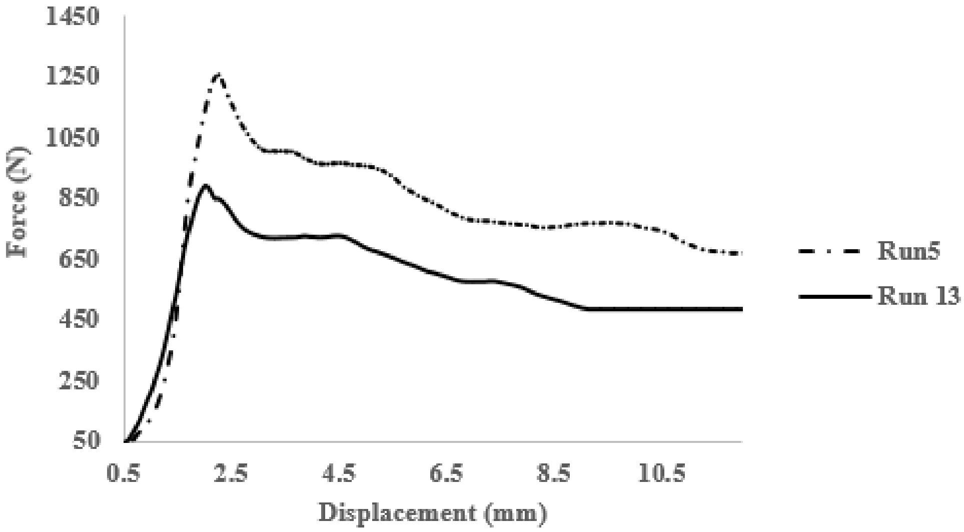

Figure 1. Force-displacement curves of selected kraft paper honeycomb.

3.2. Failure Mechanism

The final deformation of paper honeycomb after quasi-static compression can be observed in figure 2. From the figure, it can be seen that the failure mechanism of paper honeycomb consists of buckling of the cell walls and vertical edges, opening of the double thickness wall due to tearing, local wall buckling on the top and bottom surfaces, and tendency of unstable outer cells to buckle towards inward or outward direction. The mechanism is similar to Nomex honeycomb that reported by Aminanda et al. [1].

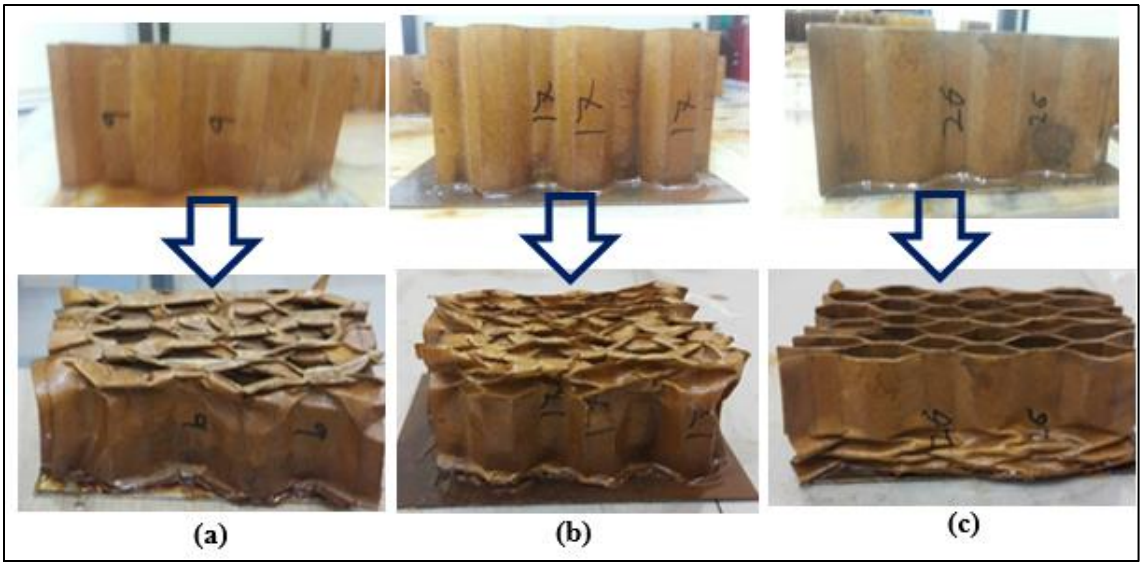

Figure 2. Condition of selected kraft paper honeycomb before (top) and after (bottom) quasi static compression test.

3.3. Analysis of Design of Experiment

3.3.1. Analysis of Specific Energy Absorption (SEA)

Table 3 shows the results of ANOVA associated with SEA obtained from Factorial method. The model for SEA was developed with 99% confident level and P-value less than 0.001 which indicated

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that this model is significant. *A*, *B* and *C* refers to density of paper, thickness of cell wall and cell size of honeycomb. From table 3, all parameters have significant effect on the SEA due to the P-value less than 0.05. The thickness of cell wall, *B* shows as most significant parameter with P-value less than 0.0001, following by density of paper, *A* and cell size of honeycomb, *C* with P-value of 0.006 and 0.0238, respectively. The P-value for interaction between density of paper and cell size of honeycomb is 0.1287 which indicates weak influence of the two parameters interaction to SEA value.

Figure 3 depicts the plot of main parameters to SEA. From the figure, It can be observed that SEA increases as the density of paper and thickness of cell wall increases. However, SEA decreases with decreasing of honeycomb cell size until 15mm. Then, SEA become constant as the bigger cell size. Eq. 1 showed the effect of density of paper, *A*, thickness of cell wall, *B* and cell size of honeycomb, *C* to the specific energy absorption.

$$SEA = 426.33 - 105.03A_1 + 27.55A_2 - 145.94B_1 + 31.68B_2 + 62.86\,C_1 - 8.35C_2 + 6.10A_1C_1 - 49.93A_2C_1 - 55.27A_1C_2 + 21.03A_2C_2 \quad (1)$$

Table 3. Analysis of variance (ANOVA) for SEA.

Source of data	Sum of square	Degree of freedom	Mean square	*F* value	Prob > *F*	Comment
Model	5.967E+005	10	59669	9.04	<0.0001	Significant
A	1.602E+005	2	80077.86	12.13	0.0006	
B	3.182E+005	2	1.591E+005	24.10	<0.0001	
C	62932.46	2	31466.23	4.77	0.0238	
AC	55395.17	4	13848.79	2.10	0.1287	

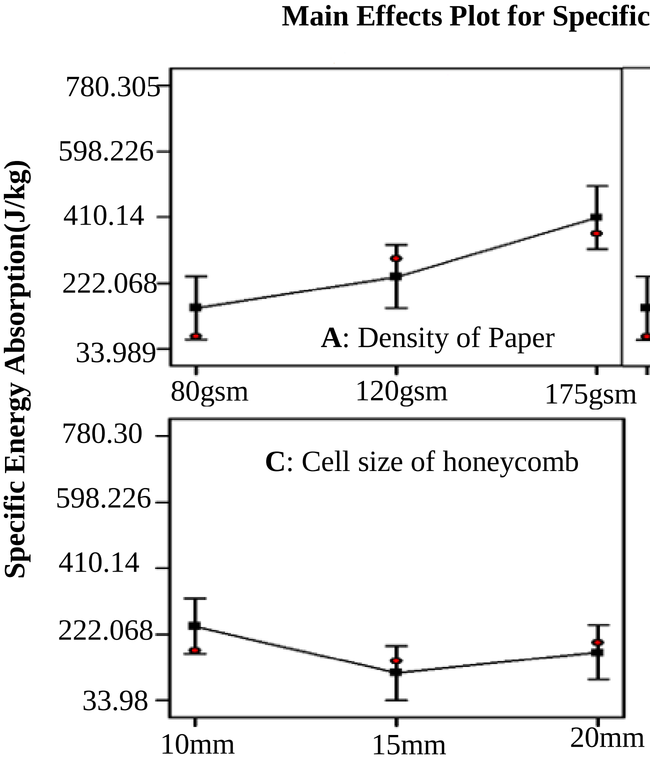

Figure 3. Main effect for specific energy absorption.

3.3.2. Analysis for Specific Compressive Strength (SCS)

The model for SCS was developed from ANOVA with 99% confident level and P-value less than 0.001 which indicated that this model is significant (table 4). The same parameters have been used for SEA analysis previously. From table 4, thickness of cell wall also displays as most significant parameter for SCS with P-value less than 0.0001 which similar to result of ANOVA for SEA. Meanwhile, both density of paper and honeycomb cell size showed the P-value of 0.003. There might have interaction between thickness of paper and cell size of honeycomb due to its P-value between 0.05 and 0.1. The P-value of 0.1348 for interaction between density of paper and thickness of paper implies no interaction between these two parameters. Main effect on the specific compression strength shows in figure 4 where it can be seen that the SCS increases with increasing of paper density and thickness. Meanwhile. SCS decreases with increasing the cell size of honeycomb. The effect of density of paper, *A*, thickness of cell wall, *B* and cell size of honeycomb, *C* on specific compression strength can be showed from Eq. 2.

$$SCS = 6.08 - 1.19A_1 + 0.49A_2 - 1.92B_1 + 0.40B_2 + 1.12C_1 - 0.23C_2 - 0.100A_1B_1 - 0.54A_2B_1 + 0.15A_1B_2 - 0.15A_2B_2 - 0.18B_1C_1 - 0.38B_2C_1 + 0.66B_1C_2 + 0.20B_2C_2 \quad (2)$$

Table 4. Analysis of variance (ANOVA) for SCS.

Source of data	Sum of square	Degree of freedom	Mean square	*F* value	Prob > *F*	Comment
Model	105.23	14	7.52	13.19	<0.0001	Significant
A	19.43	2	9.73	17.08	0.0003	
B	55.73	2	27.86	48.91	<0.0001	
C	18.98	2	9.49	16.66	0.0003	
AC	4.94	4	1.23	2.17	0.1348	
BC	6.12	4	1.53	2.69	0.0827	

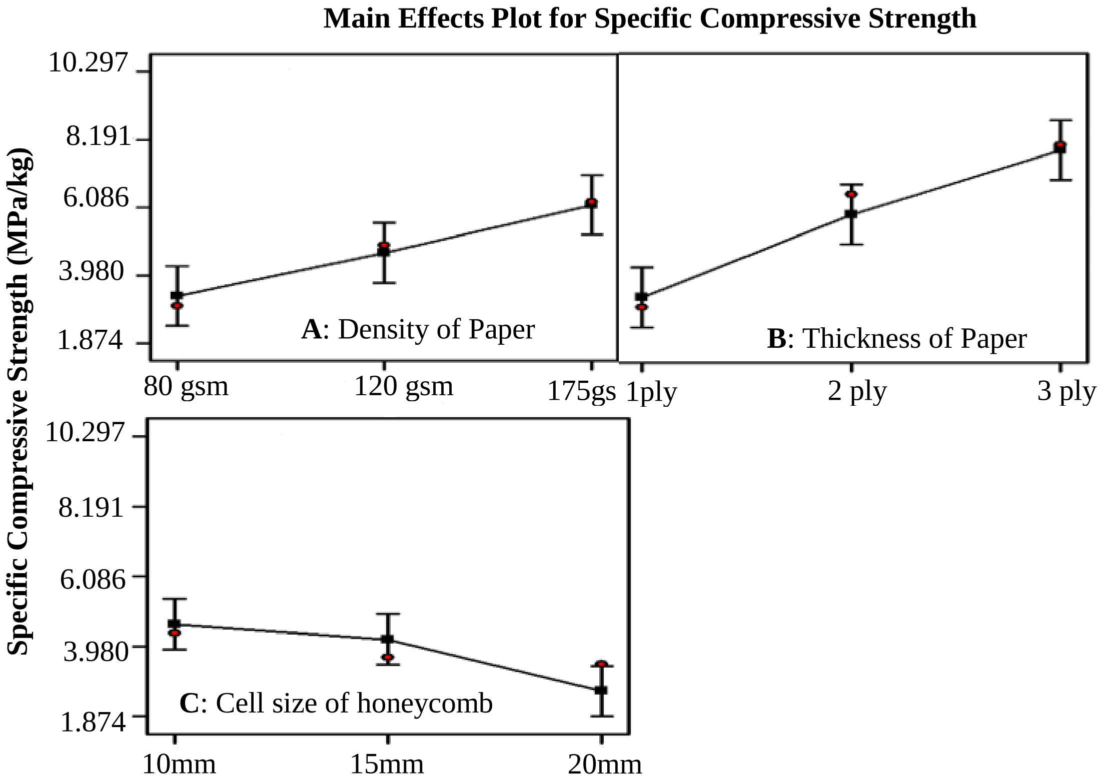

Figure 4. Main effect for specific compression strength.

3.3.3. Optimization Parameter of Paper Honeycomb

The optimum configuration parameters resulting higher SEA and SCS has been obtained through Design of experiments methods. As a result, the Kraft paper honeycomb with density 175gsm, 3 ply thickness of paper and 10mm cell size of honeycomb shows the optimum configuration with 724.80 J/kg of SEA and 9.35 MPa/kg of SCS. These finding was agreed with other researchers which found that the higher cell wall thickness and smaller cell size increase the energy absorption and crush strength [13][14].

4. Summary

In this study, the crushing behavior and effect of parameter under quasi -static compressive load was investigated. All three parameters are giving the significant effect on specific compression strength and specific energy absorption. The sample with highest density of paper, highest thickness of paper and smallest cell size of honeycomb shows the optimum performance for both specific compression strength and specific energy absorption.

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