THE CHARACTERISTICS OF LOAD VERSUS DISPLACEMENT OF PAPER HONEYCOMB : AN EXPERIMENTAL INVESTIGATION

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Mohd Khairir Ismail[1,a*] and Md Radzai Said[2,b]

[1,2] Faculty of Mechanical Engineering, Universiti Teknikal Malaysia Melaka.
[a]Email: khairir.ismail@gmail.com, [b]Email: radzai@utem.edu.my

Abstract—**The influence of paper honeycomb core on the energy absorption capability was studied. Simple mechanism for compression test was constructed. Maximum stress and deformation of each specimen were compared with the results from analyses of static compression stress-strain curves. The specimen under axial loading showed three zones. Zone 1 is the initial elastic state and the followed by the plateau region in zone 2. Zone 3 shows a monotonically stiffening region, associated with densification of the material. The locking strain is defined by intersection of two lines and the locking strain in experimental is 9 mm. Therefore, the value of locking strain each paper honeycomb stress-strain curves are used to define area under the curve to obtain energy absorption and mean load. The theoretical mean load used in metal honeycomb is adapted and compared with experimental results.**

Keywords—**Paper honeycomb, quasi-static axial loading**

NOMENCLATURE

P_m	*mean load*
P_c	*collapse load*
σ_0	*flow stress/yield stress*
h	*cell wall thickness*
D	*width of the cell wall*
s	*minor cell diameter*
θ	*angle*
l	*side cell length*
Eq. (1)	$P_m . 2H = E_1 + E_2 + E_3$
Eq. (2)	$\frac{P_m}{M_0} = 16.8\,\frac{b}{h} + 3\Pi\,\frac{D}{H} + 9.56\,\frac{H}{b}$
Eq. (3)	$\frac{\delta P_m}{\delta H} = 0,\ \frac{\delta P_m}{\delta b} \doteq 0$
Eq. (4)	$H = 0.821\,\sqrt[3]{hD^2}$
Eq. (5)	$b = 0.683\,\sqrt[3]{h^2 D}$
W	*energy absorption*
$\delta_{densification}$	*locking strain*

I. INTRODUCTION

Honeycomb structures with regularly shaped (usually hexagonal) cells, may be manufactured, usually in the form of panels, from a variety of materials such as metal, aramid or cellulose paper. Nomex honeycomb is constructed from ribbon of aramid paper running in the two ribbon direction. These are glue together at intervals along the ribbon and the stack of ribbons is then expanded into a honeycomb by pulling in 1 direction as shown in Figure 1. The paper substrate is finally dipped into phenolic resin to build up the walls of the honeycomb. Because of this construction method, the Nomex Honeycomb is anisotropic.

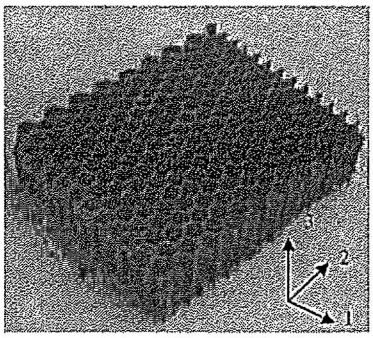

Figure 1: Nomex Honeycomb structure

Honeycombs are often used as cores in sandwich panels. The size/dimension of core are different depends on the function to used. Function of honeycomb core is to carry normal and shear loads in planes containing the axis of the hexagonal prisms the 3 direction in Figure 1. When loaded in this direction the cells walls are extended or compressed rather than bent. Honeycomb is an outstanding core material for sandwich structures and an efficient energy absorber. Honeycombs are much stiffer and stronger when loaded along the cell axis the 3 direction.

Foo et. al. [1] studied about the mechanical properties of Nomex material and Nomex honeycomb structure, which focus on this Nomex material. They performed tensile tests on the Nomex paper of the honeycomb to determine the mechanical properties in the fiber (or machine) direction and transverse (or cross-machine) direction. In order to determine the three fundamental Young's moduli, in-plane tensile tests and out-of-plane compressive tests were conducted.

Said and Fai [2] investigated about the effect of the aluminium honeycomb with the crushing load-displacement characteristics and the mode of deformation under quasi-static compressive loading. They focus on the experimental and performed compression test which applied in three principle direction under quasi-static condition (lateral compression across face, across corner and axial compression). The collapse load due to lateral loading is compared with mean load in axial compression loading.

Many aspect of the behaviour of cellular solids are described and summarized well in the book by Gibson and Ashby [3]. There is a great interest in the current and potential use of these materials for packaging, as impact energy absorbers and their use as core material in lightweight sandwich structures. Gibson and Ashby [3] devote a chapter of their book to the selection of material for low speed impact application. Honeycomb, in particular, has been used as a protective material for high velocity impact and is often used as an impact energy absorbing material. This paper presents the result of the study in which specimens of paper honeycomb were subjected to axial compression under quasi-static conditions.

Honeycomb cores have been studied by many researchers. Petras and Sutcliffe [4] are investigate a failure mode map of honeycomb for loading under three-point bending is constructed, and showing the dependence of failure mode and load on the ratio of skin thickness to span length and honeycomb relative density. Previous research on honeycomb mechanics and the behaviour of sandwich beams in 3-point bending have been combined to model the behaviour of honeycomb sandwich panels. It is assumed that the skin and core materials behave in a brittle manner. The failure mechanisms considered were face yield, face wrinkling, intra-cell buckling, core shear and indentation at the.

Paik et al. [5] had studied the strength characteristics of aluminium honeycomb sandwich panels using a series of strength tests, namely three-point bending tests, buckling/collapse tests and lateral crushing tests. They also carried out a theoretical study to analyze the elasto-plastic bending behavior, buckling/ultimate strength and crushing strength of sandwich panels subject to the corresponding load component. A sandwich construction, which consists of two thin facing layers separated by a thick core, offers various advantages for design of weight critical structures. Even if the concept of the sandwich construction is not very new, it has so far been applied to the design of light weight structures restrictively. The sandwich panels have primarily been used as non-strength parts of the structures in the last decade.

In this paper, the experimental data on paper honeycomb under compressive loading are presented. The main body of this work is concerned with the crushing load-compression (displacement) of honeycomb under quasi-static loading in axial condition from elastic to plastic collapse.

II. THEORETICAL

Honeycomb has the unique property of crushing in a uniform, predictable, and efficient manner. It is very reliable and lightweight, thus it is well adapted for energy absorption applications. A typical honeycomb crush strength curve is shown and explained below in Figure 2.

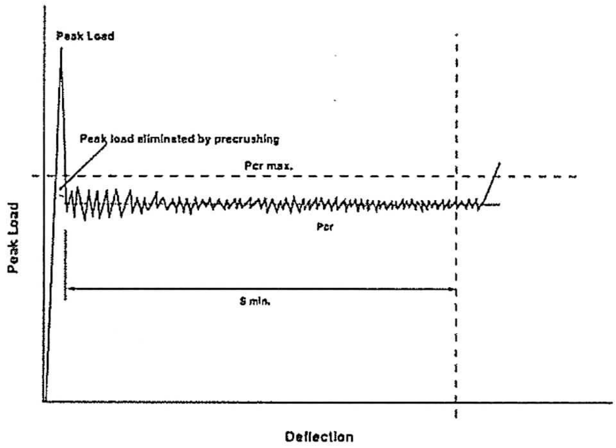

Figure 2: The theoretical load-deflection curve [6].

Wierzbicki [6] has provided the mean crushing force is defined from the requirement that the total internal dissipated energy is equal to the work of mean load, P_m on the crushing distance $2H$.

$$P_m . 2H = E_1 + E_2 + E_3 \quad (1)$$

$$\frac{P_m}{M_0} = 16.8\,\frac{b}{h} + 3\Pi\,\frac{D}{H} + 9.56\,\frac{H}{b} \quad (2)$$

The crushing strength of a honeycomb core is seen to depend on the yield stress, σ_0 , gauge thickness h, wall width D, all of which are considered as known and also on the unknown rolling radius b and half-wavelength H. It is reasonable to postulate that the free parameters of the collapse mode, which are actually formed and persist during the crushing process, would lead to a least possible value of the crushing force. These parameters can thus be determined from the optimally condition.

$$\frac{\delta P_m}{\delta H} = 0\,,\ \frac{\delta P_m}{\delta b} = 0 \quad (3)$$

The minimum of P_m with respect to H and b does exist and the solution of the above set of equations taken a simple form.

$$H = 0.821\,\sqrt[3]{hD^2} \quad (4)$$

$$b = 0.683\,\sqrt[3]{h^2 D} \quad (5)$$

Substituting (4) and (5) back into (2) and using the definition of M_0, finally arrive at an extremely simple formula for the mean crushing strength of hexagonal structures.

$$P_m = 8.61\,\sigma_0\,h^{5/3}\,D^{1/3} \quad (6)$$

Honeycombs are much stiffer and stronger when loaded along the cell axis the 3 direction. The same is true for honeycombs loaded in out-of-plane shear (sandwich panels loaded in bending). The initial linear-elastic deformation involves significant axial or shear deformations of the cell walls. In compression the linear-elastic regime is truncated by buckling and the final failure is tearing or crushing, giving a stress-strain curve like that shown in Figure 3. Energy *W* is dissipated through the cell bending, buckling of fracture, but the stress is generally limited by the long and flat plateau of the stress-strain curve.

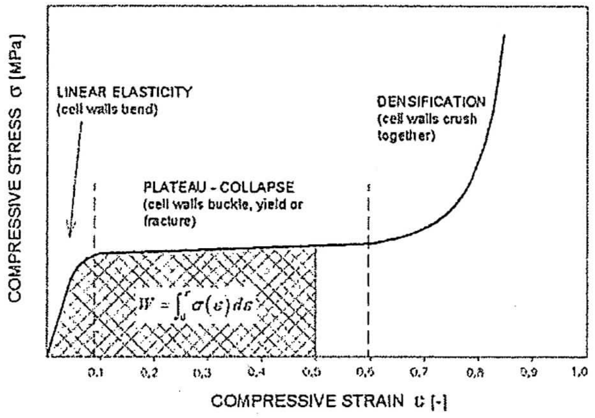

Figure 3: Stress-strain for the axial loading of honeycomb in compression [7].

III. EXPERIMENTAL DEVELOPMENT

Nomex honeycomb is made from Nomex Kevlar paper as shown in Figure 4a, which is a form of paper made of aromatic polyamide (aramid) fibers. The initial paper honeycomb is usually dipped in aphenolic resin to produce a honeycomb core with high strength and very good fire resistance. The cells of the honeycomb supplied by the manufacturer were slighty irregular hexagons with width cell wall, *D* of 2.96 mm, side length, *l* of 4.10 mm and cell wall thickness, *h* was 0.085 mm as shown in Figure 4b. The test specimens were compressed at 5 mm/min displacement rate.

The test was considered void whenever failure occurred at the ends, and a new test was performed. Each test specimen was being prepared in 75 mm x 75 mm x 10 mm of Nomex honeycomb and density is 31.82 kg/m^3. Compressive test were performed by using a universal testing machine Instron Floor Mounted Material Testing System (INSTRON 5585) with maximum load of 200 kN capacity.

IV. RESULT AND DISCUSSION

A. Axial loading on paper honeycomb

In order to determine the mechanical properties of paper honeycomb, compression way is preferred. This result will be earned. In total, fives specimen were performed for test to check the repeatability curves are shown in Figure 5. The test results are consistent and thus reliable.

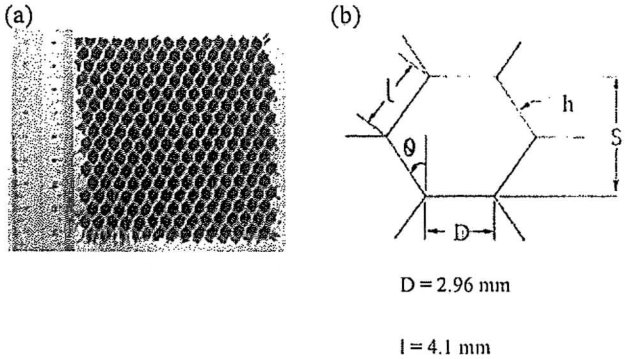

Figure 4: (a) Sample specimen Nomex Honeycomb (b) Dimensions of hexagonal cells (in mm)

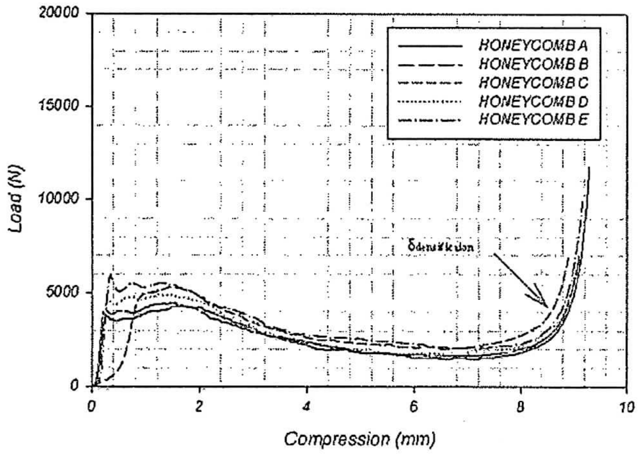

Figure 5: Graph of load against deflection for compression test of all paper honeycombs

The honeycomb specimens described in above were compressed between two rigid platens along the direction of cell axis using Instron Universal Testing Machine with 200 kN capacity. The load displacement curves were obtained from the displacement controlled at crosshead speed 5mm/min. The deformation can be divided into three zones as shown in Figure 6. Zone 1 is the initial, stiff, elastic state, which is followed by an elastic-plastic state that terminates with collapse signified by a zero slope of the load-compression (displacement) curve. Zone 2 is the plateau region where sequential crushing of lines of cells taken place at a nearly constant load, with very small, non-uniform load fluctuations. Finally, zone 3 starts with the termination of plateau (zone 2) and show a monotonically stiffening region, associated with densification of the material.

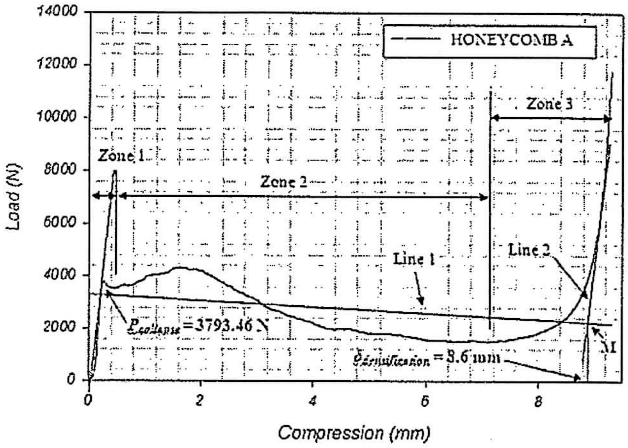

Figure 6: Graph of load against deflection for compression test of Honeycomb A specimen

When almost paper honeycomb are compresses completely, the load started to increase very rapidly. This is called as densification stage (zone 3) of deformation in the honeycomb. This zone is not useful for energy absorption, as the strain does not increase appreciably. This limiting value of strain is the so called locking strain, δ_l. Different definitions can be found for the locking strain. Here, locking strain is defined by the intersection of two lines. Line 1 is the linear regression and line 2 is parallel to the initial elastic line at a tangent to the stress-strain curve in the stiffening region. For example, point M in Figure 6 is a locking strain in the curve, which shows 8.6 mm.

Energy absorbed is the area under load compression curve up to $\delta_{densification}$. Very little energy is absorbed in the short, linear-elastic regime. The energy absorbed and specific energy is tabulated in Table 1. The experimental mean load is calculated by dividing the energy absorbed with $\delta_{densification}$ and compared with theoretical mean load [6]. The percent different is ranging between 12% and 28%. The different could be due the assumption made in theoretical development.

A summary of experimental result for paper honeycomb under axial compression is presented in Table 1. The collapse load, P_c of fives specimen shows the value are in range occurs between 3793N and 5937N and the load-compression curve are almost same when locking displacement, $\delta_{densification}$ is 9 mm. From Table 1 shows an out-of-plane deformation.

V. CONCLUSION

The results of paper honeycomb subjected to quasi-static (axial) compressive loading are studies and presented. Quasi-static compression test of Nomex honeycomb core with five specimens are observed. Compressive stress-strain curves were obtained. Honeycomb structures are used in energy absorbing structures. The theoretical mean load developed by Wierzbicki [6] for the metal honeycomb under compression is compared with the experiments. The results show the different of the mean load for experimental and theoretical is between 12% and 28%.

Table 1: Experimental result for compression test of paper honeycomb

Specimen	Honeycomb A	Honeycomb B	Honeycomb C	Honeycomb D	Honeycomb E
Mass (kg)	0.00168	0.00176	0.00183	0.00170	0.00179
Collapse Load, P_c (N)	3793.46	4207.69	4903.80	4784.73	5937.14
δ_c (mm)	0.26	0.24	0.93	0.29	0.33
Locking strain, $\delta_{densification}$ (mm)	8.6	8.7	8.6	8.9	8.7
Energy Absorbed, W (Nm)	23.033	22.985	25.089	25.504	28.095
Specific Energy (J/kg)	13.71 x 10^3	13.06 x 10^3	13.71 x 10^3	15.0 x 10^3	15.69 x 10^3
Mean Load experimental, P_m (N)	2678.25	2641.95	2917.32	2865.62	3229.31
Mean Load theory, P_m (N)	3676.306				
Different (%)	27	28	21	22	12

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REFERENCES

[1] C. Foo, G. B. Chai and L. K. Seah. "*Mechanical properties of Nomex material and Nomex honeycomb structure*". Composite Structure 80, pp 588-594 (2006).

[2] M. R. Said and T. C. Fai. "*Aluminium honeycomb under Quasi-static compressive loading: An experimental investigation*". Surnarce J. Sci. Tecnol. Vol 16 No 1; January-March 2009.

[3] Gibson, L.J. and M.F. Ashby (1997). Cellular solids: structure and properties. 2nd edition, Cambridge University Press, Cambridge.

[4] A. Petras and M. P. F. Sutcliffe. "*Failure mode maps for honeycomb sandwich panel*". Composite Structure 44, pp. 237-252 (1999).

[5] Joem Kee Paik, Anil K. Thayamballi and Gyu Sung Kim. "*The strength characteristics of aluminum honeycomb sandwich panels*". Thin-Walled Structures 35, pp. 205-231 (1999).

[6] Wierzbicki, T. "*Crushing analysis of metal honeycombs*". International Journal Impact Engineering. Vol 1 No 2, pp.157-174 (1983)

[7] Goga Vladimir, "Measurement Of The Energy Ansorption Capability Of Polyurethane Foam". Prosterus, 2010