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A COMPARATIVE ANALYSIS OF ORTHOTROPIC ELASTIC CONSTANT OF NOMEX HONEY COMB CORE

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In this research work, the modulus of elasticity was determined by analytical and numerical means and correlated with experimental results for Nomex paper hexagonal honeycombs. The analytical methods included continuum formulations and models based on strength of materials including a variety of beam theories. The numerical method is used for determination of orthotropic mechanical properties of honeycomb core using Isotropic material properties of Nomex paper by FEA simulations using ANSYS as a tool, and the experimental testing consisted of mechanical characterization of the honeycombs under both in-plane and out-of-plane loading by using tensile testing. The results obtained are very useful and have close agreement.

Keywords, Sandwich structure, Honeycomb, FEA simulation, Honeycomb testing, Nomex paper

1. Introduction

Due to high stiffness to mass ratio the composite structures are widely used in aerospace industry. Orthotropic core material properties are a major measuring parameter when analyzing sandwich structures. Composite sandwich construction is becoming more common in aircraft applications. Such panels offer optimal specific strength and stiffness. Honeycombs are discrete materials at the macro-scale that can be used as standalone materials or placed as cores between composite face-sheets to form sandwich structures. The prediction of their effective mechanical properties as a continuum material is essential to the analysis and design of honeycomb sandwich structures.

Honeycombs are discrete materials at the macro-scale level but their mechanical properties need to be calculated as a continuum material in order to simplify their design in engineering applications. Honeycombs can also be placed as cores between composite face-sheets to form sandwich structures and the prediction of the honeycomb effective properties is of key importance to model the overall mechanical response of the sandwich structures.

In the last few decades structural sandwich panels are widely used in light weight construction especially in wind blades and aerospace structures. Two-dimensional cellular structures are common as core materials. Each face-sheet may be an isotropic material or a fibre-reinforced composite laminate while the core material may either be of metallic/aramid honeycomb or metallic/polymeric foam [1]. A number of design factors that may affect the mechanical properties of honeycomb structures, e. g. cell size, cell shape, cell wall thickness, the density of cell, etc. and was described earlier [1-2]. For numerical impact analyses of honeycomb sandwich structures, several modelling approaches for the honeycomb core have been identified. One approach utilizes standard shell finite elements and is mainly used for approximation of the global behaviour in thin sandwich panels. In this study the honeycomb panel was modelled as a combination of solid and shell elements. A four-node shell element was used for modelling the composite facing skin while eight node solid elements were employed to model honeycomb core [3]. Another approach uses standard two-dimensional shell finite elements for the face-sheets and three-dimensional solid finite elements for the core [4]. Such models are used to predict both local and general responses in the

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sandwich panel. However, material properties have to be determined for each core type via mechanical testing or analytical approximation. The accuracy of the numerical solution depends on a variety of geometric and material characteristics of the constitutive materials in the core and face-sheets.

Computational expenses for finite element honeycomb sandwich models increase rapidly as the number of cells in the core increase. Therefore, to attain efficiency in numerical analysis, the honeycomb core is usually replaced with an equivalent continuum model. The sandwich panels are analyzed in terms of their effective properties rather than by consideration of their real cellular structure. Consequently, the determination of effective elastic properties for this continuum core becomes important [5].

Various analytical techniques have been proposed to predict the effective continuum properties of the core in terms of its geometric and material characteristics [6–8]. Meraghni et al. [7] modified the classical laminate theory and applied it on a unit cell to derive the equivalent elastic rigidities for the honeycomb core. He says that this hexagonal unit cell describes the entire honeycomb core. The unit cell is built up with one quarter of one central wall and one quarter of one inclined wall. This reduction in the size of the cell to be studied is because of the different symmetries. Hohe and Becker [8] also proposed a strain energy-based homogenization technique to derive the effective elastic properties of any general cellular structure by considering a representative volume element. Gibson and Ashby [9] published analytical formulations for the in-plane and out-of-plane stiffness, as well as the upper and lower limits of the transverse shear moduli for a regular hexagonal honeycomb. Their material properties models were investigated by Triplett and Schonberg [10], who conducted a numerical analysis for circular honeycomb sandwich plates subjected to low-velocity impact. They found that numerical results were inaccurate when honeycomb crushing was ignored for the finite element model. Schwingshackl et al. [11] examined several available analytic and experimental methods to determine the orthotropic material properties of the honeycomb. They found several theoretical methods for the pure honeycomb core. Out of plan elastic properties of honeycomb sandwich panels have been determined by Mujika et al. [12]. In their research work shear modulus was determined in the two principal directions of orthotropy of the honeycomb. Orthotropy of the constituent materials lead to much more complex and effective elastic characteristics of honeycomb sandwich composite shells has been earlier studied by Gobinda et al. [13]. Earlier Balawi and Abot [14] conducted series of uni-axial tension in order to understand the effect of relative densities on in plane elastic moduli of core structure. Experimental studies on mechanical properties of cellular structure using Nomex honeycomb core has been investigated recently [15].

During the last five decades, emphasis was placed on the effective out-of-plane normal and shear properties of honeycombs but more recently, the effective in-plane properties have been the focus of many studies. In this research work, the effective mechanical behaviour of honeycombs was studied by analytical and numerical means and correlated with experimental results for Nomex paper hexagonal honeycombs.

1.1. Specimen

This specimens consists of Nomex aramid-fiber paper dipped in a heat-resistant phenolic resin to achieve the final density. It features high strength and toughness in a small cell size, low density non-metallic core. It is available in hexagonal, OX-Core, and Flex-Core configurations. It is fire-resistant and recommended for service upto 350°F.

2. Theoretical and Numerical investigation

2.1. Theoretical Values

Theoretical values are calculated by using the following relationships

In-Plane Elastic Moduli

$$E_x = E_{paper}\left(\frac{t}{l}\right)^3 \frac{(\cos\theta)}{\sin^2\theta\left(\frac{h}{l}+\sin\theta\right)}$$

$$E_y = E_{paper}\left(\frac{t}{l}\right)^3 \frac{\left(\frac{h}{l}+\sin\theta\right)}{(\cos^3\theta)}$$

$$E_z = E_{paper}\left(\frac{t}{l}\right)\frac{\left(\frac{h}{l}+2\right)}{2\cos\theta\left(\frac{h}{l}+\sin\theta\right)}$$

For regular hexagonal honeycombs

If the hexagonal honeycomb is regular i.e all angles θ = 30°, h = *l* and wall thicknesses are equal then:

$$E_X = E_y = 2.3\left(\frac{t}{l}\right)^3 E_{paper}$$

$$E_Z = E_{paper}\left(\frac{t}{l}\right)$$

The theoretical values of modulus of elasticity of Nomex Honeycomb along X, Y & Z axis are 0.081, 0.081 and 31.83MPa respectively.

2.2. Finite Element Analysis of Honeycombs

A numerical investigation of a honeycomb core that consists of an array of hexagonal cells is presented. The finite element method (FEM) is used to find out the young's modulus in X,Y and Z direction of honeycombs. The commercial finite element analysis (FEA) software "Ansys" is used for this purpose. The FEA models are developed with *Shell 181* elements*.* It is a 4-node element with six degrees of freedom at each node: translations in each directions, and rotations about the X, Y, and Z-axes*.*

The honeycomb has orthotropic properties therefore, there are three modulus of elasticity of honeycomb core in three different directions i.e. E_x, E_Y and E_Z in X, Y and Z direction respectively.

In order to evaluate Young's modulus $E_{X,}$ Ey & Ez ,the following relation is used.

$E_i = F \times L / A \times \Delta L$

where

i = X, Y and Z directions.

F = Force applied on the end of the sample (N)

L = Gauge Length of the sample (mm)

ΔL = Change in Length of Paper (mm)

A = Cross Sectional area of the sample (mm^2*)*

The finite element model of the Honeycomb structure along X, Y and Z directions are shown in Fig. 1.

All applied boundary conditions are shown in Fig. 2. There are two ends plates attached to the end of the sample so that the force can be uniformly distributed over the whole face of sample. Total force of 2N is applied in the X-axis uniformly distributed over the nodes of the end plates in 10 sub-steps. Nodes on which force is applied are also constrained in UY and UZ, whereas the nodes of plates of the opposite sides are constrained in UX, UY and UZ.

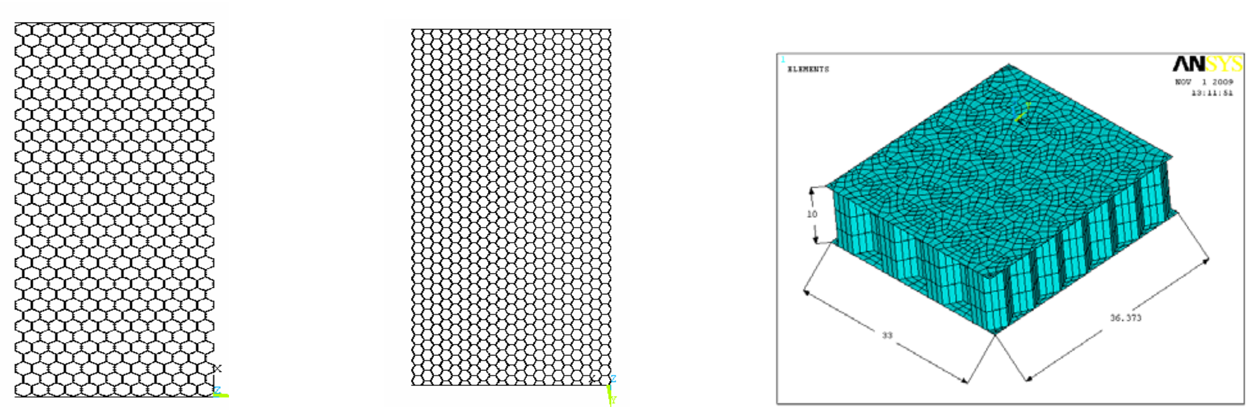
Table 1 shows the geometrical data of the tested samples for the determinations of Modulus of elasticity in three directions.

2.3. Experimentation of Honeycomb Core

The experimental portion of this study consisted of the mechanical characterization of the Nomex material that composes the honeycomb wall and the testing of the honeycombs under in-plane and out-of-plane static loading. To determine the two in-plane moduli for the bare honeycomb cores, E_x and E_Y, tensile tests were carried out in accordance to the ASTM standard for delamination test [11]. The test specimens measured 29 mm wide by 120 mm long with a test section of 75 mm between the locating pins. Two wooden end plates were fabricated for the tensile tests and holes were drilled in them. The locating pins were inserted in each pair of end plates for the tests. The honeycomb specimen was then mounted onto the pins.

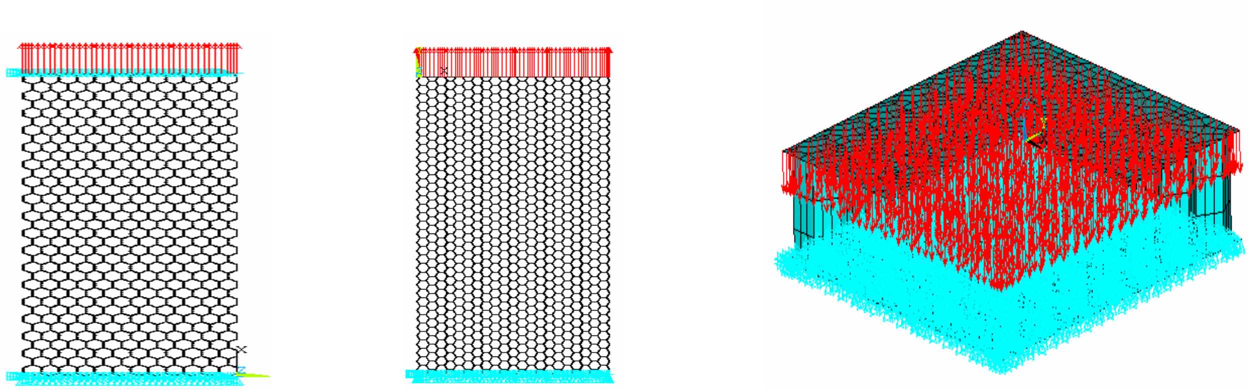
For these tests, the universal testing machine 100 kN, together with a 5 kN load cell and an accompanying computer with data logging software, was used. To eliminate the slack in the honeycomb specimen, a preload was also applied prior to the test. The test specimens were then pulled at a displacement rate of 10mm/min. The test was considered void whenever failure occurred at the ends, and a new test was performed.

The compression testing of honeycomb core specimens were conducted for Ez by compressing the specimens in between two cylindrical steel platens. One of the steel platens (bottom platen) was fastened to the actuator of the testing machine while the other (upper platen) was fastened to the load cell which was in-turn fastened to the fixed



(a) In X Direction (b) In Y Direction (c) In Z Direction

Figure 1. Finite Element Model of the Honeycomb Structure in X ,Y and Z Directions



(a) In X direction (b) In Y direction (c) In Z Direction

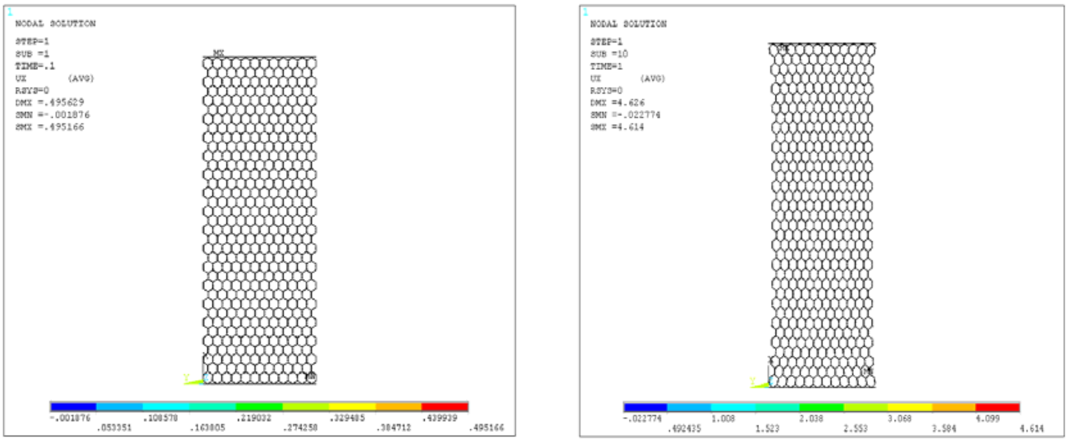
Figure 2. Applied Boundary Conditions for calculation of Ex, Ey and Ez.

Table 1. Used Data of sample for determination of E_x, E_y &E_z

Description	Notation	For E_x	For E_y	For E_z
No. of cells in width	q	12	22	7
No. of cells in length	p	35	36	7
Side Length of cell	*l*	3 mm	3mm	3mm
Theta	θ	30^o	30^o	30^o
Thickness of core	b	10 mm	10mm	10mm
Total Tensile Force	F	2 N	4N	10.79N
Cross Sectional Area	A	623.5 mm^2	990.2 mm^2	1200 mm^2
Original Length	L	159 mm	99mm	10mm

cross-head of the testing machine. On the surface of the bottom platen, a square measuring 35x35 mm^2 was marked with its centre coinciding with that of the platen. The specimen is aligned with the marked square to ensure that the specimen is co-axial with the load. The specimens are fixed to the bottom platen with the help of a double sided tape so that they do not move/slide during the test.

A thin layer of grease is applied on the surface of the top face sheet of the specimen to accommodate sliding of the top-face sheet relative to the surface of the platen. This sliding occurs due



(a) For substep-1 (b). For substep-10

Figure 3. Deformation of FEA model in X-Directional for the Sub-step 1&10

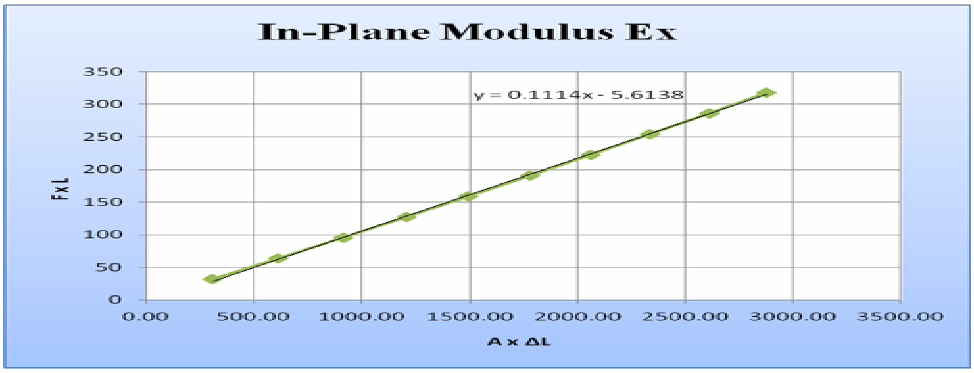


Figure 4. In-Plane Modulus E_x (by FEA).

to the extension-shear deformation coupling present in the off-axis specimens. If the sliding is constrained due to friction or by other means, the deformation field will be distorted with significant end effects. It was assumed that during crushing, the change in cross-sectional area of the cell walls was negligible, and it would not affect the elastic modulus significantly.

3. Results and Discussions

As discussed earlier that the force is applied in 10 sub-steps, therefore, results have been read at the end of every sub-steps. The produced displacement due to the application of force for the sub-step is shown in Fig. 3.

On the basis of FEM analysis data has been calculated and results are given in Table 2.

The average value of the in plane modulus Ex is 0.1067 MPa from FEA simulation. The graph between F x L and the A x ΔL shows a straight line and its slope give also the value of Ex 0.1114 MPa as shown in Fig. 4.

Forces applied along Y-axis which are uniformly distributed over the nodes of the end plates in 10 sub-steps. The nodes of opposite sides are constrained in UX, UY and UZ.

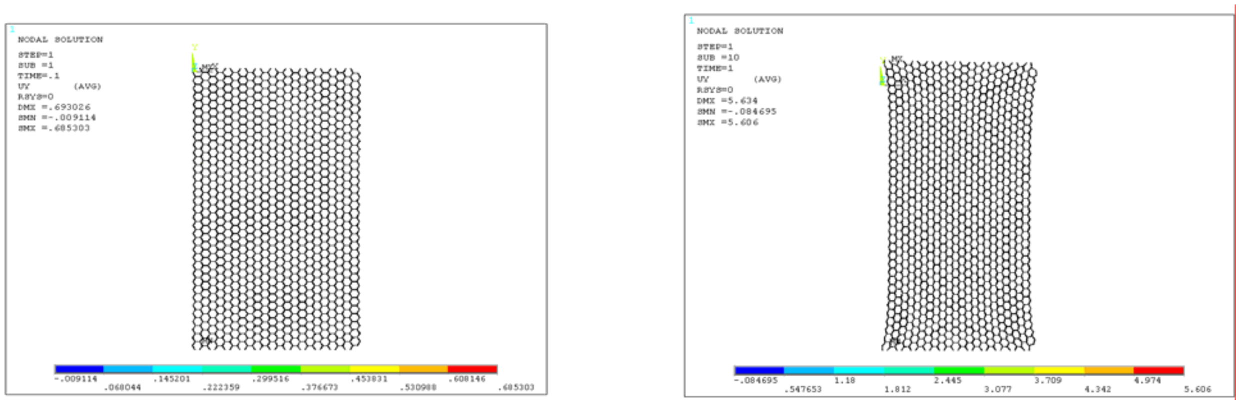
As discussed earlier that the force is applied in 10 sub-steps as in previous case, therefore, results have been read at the end of every sub-steps. Overall linear displacement calculated by using ansys and by considering the data reflected in Table 3 ,the modulus of elasticity in Y direction is calculated. Deformed shape of substep-1 and substep-10 along y axis are shown in Fig 5.

Table 2. Calculation of E_X by Ansys (FEA).

Sub-Step	Force Applied (N)	Displacement (mm)	A x ΔL	F x L	E_x (MPa)
1	0.2	0.495	308.72	31.795	0.1029
2	0.4	0.982	612.59	63.590	0.1038
3	0.6	1.462	911.50	95.385	0.1046
4	0.8	1.934	1205.78	127.18	0.1054
5	1	2.398	1495.06	158.97	0.1063
6	1.2	2.855	1779.99	190.77	0.1071
7	1.4	3.305	2060.54	222.56	0.1080
8	1.6	3.746	2335.49	254.36	0.1089
9	1.8	4.185	2609.19	286.15	0.1096
10	2	4.614	2876.66	317.95	0.1105
Average Ex					0.1067

Table 3. Calculation of E_Y by Ansys (FEA).

Sub-Step	Force Applied (N)	Displacement (mm)	A x ΔL	F x L	E_y (MPa)
1	0.4	0.685	677.90	72.4	0.1068
2	0.8	1.336	1322.80	144.8	0.1094
3	1.2	1.956	1936.68	217.2	0.1122
4	1.6	2.548	2522.83	289.6	0.1147
5	2	3.114	3083.24	362	0.1174
6	2.4	3.655	3618.89	434.4	0.1200
7	2.8	4.173	4131.77	506.8	0.1226
8	3.2	4.669	4622.87	579.2	0.1253
9	3.6	5.145	5094.17	651.6	0.1279
10	4	5.601	5545.66	724	0.1305
Average E_Y					0.1187



(a) For substep-1

(b) For substep-10

Figure 5. Deformation of FEA model in Y-Direction at the end of Sub-step 1&10

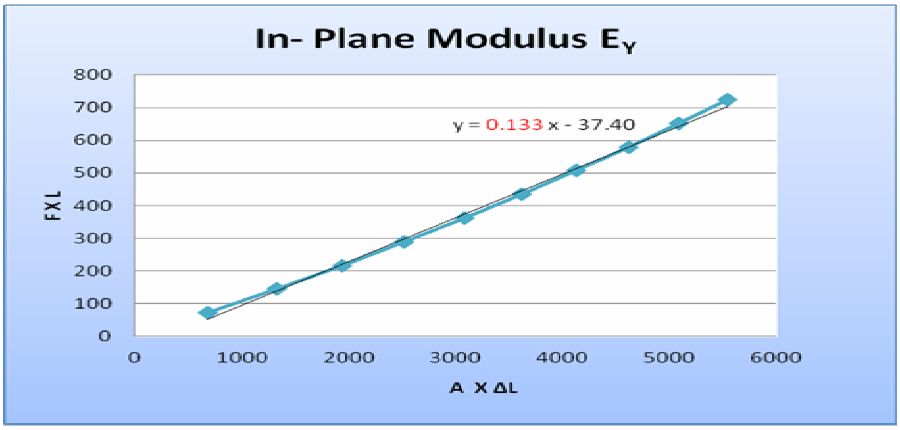


Figure 6. In- Plane Modulus E_Y (by FEA)

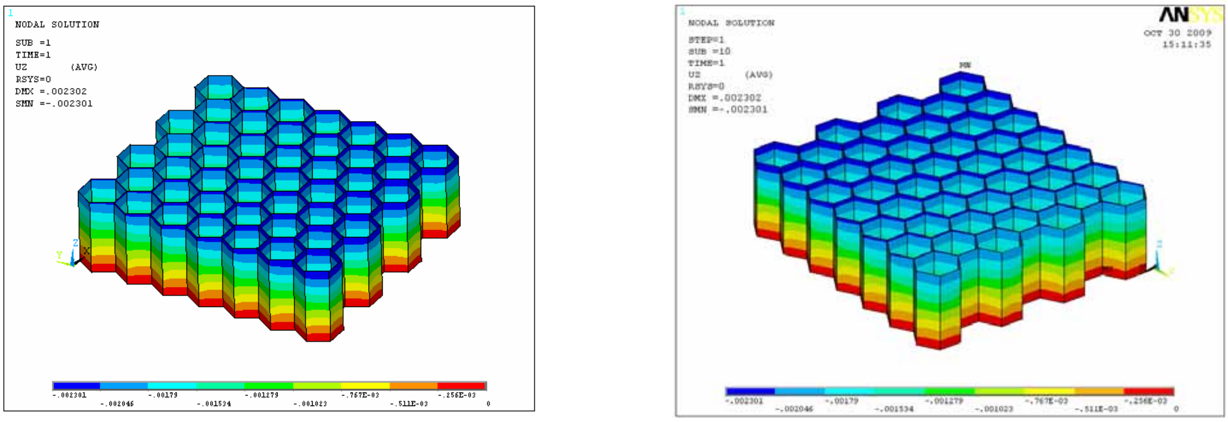


Figure 7. Deformation of FEA model in Z-Directional at the end of Sub-step 1&10

The average value of the in plane modulus E_Y is 0.1187 MPa from FEA simulation. The graph between F x L and the A x ΔL shows a straight line and its slope gives also the value of E_Y is 0.133 MPa as shown in Fig. 6.

Overall linear displacement of the model in Z-direction for the substep-1 and substep-10 is shown in Fig. 7. Along the Z direction there are two face plates attached to the sample so that the force can be uniformly distributed over the whole face of sample. Total compressive force of 10.79N (0.01N force per node) is applied in the Z-axis uniformly distributed over the nodes of the end plates in 10 sub-steps whereas the nodes of opposite sides are constrained in UX, UY and UZ. All values are tabulated in Table 4. The average value of the out-plane modulus E_Z is 39.036 MPa. The slope of the curve gives the value of E_Z 39.03 MPa and is shown in Fig. 8.

The experimental, numerical (FEA) and theoretical values Ex, Ey and Ez for a Nomex honeycomb core are presented in Table 5. The numerical and experimental results compare well. However, most of the experimental values are greater than the theoretical and FEA values. One reason for this large discrepancy could be that the theoretical formulations were derived for an isotropic material, but Nomex paper is anisotropic. Another reason could be due to the size effect of the whole honeycomb core. For the theoretical formulations in [16], a unit honeycomb cell was considered. However both numerical and experimental results indicate that Young's moduli in Z direction exhibit a dependency on the size of the honeycomb core. Interestingly, the theory states that the in-plane moduli (E_X and E_Y) are independent of the core size, and E_X is equivalent to E_Y. However, the numerical values for E_X and E_Y show otherwise.

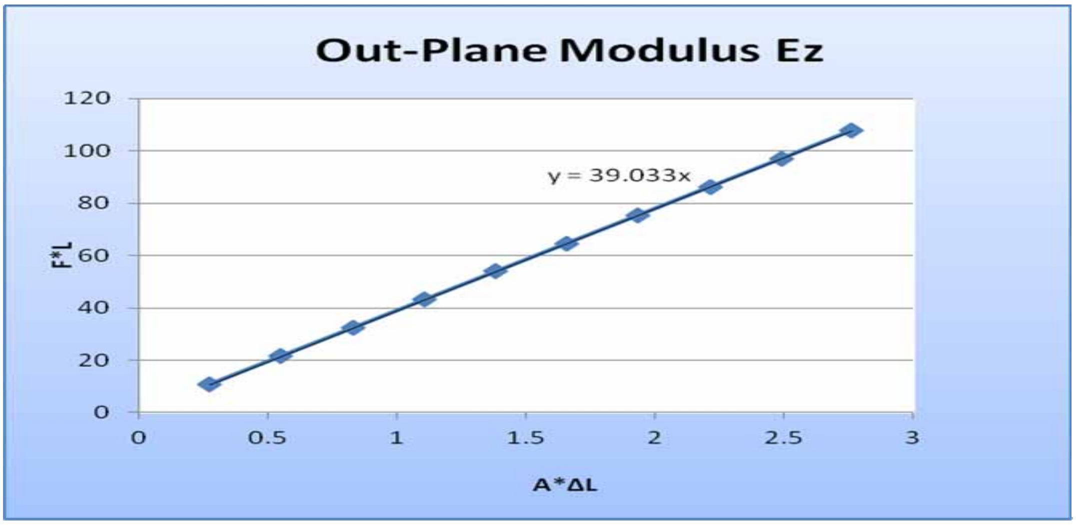


Figure 8. Out-Plane Modulus E_z (by FEA)

Table 4. Calculation of E_z by Ansys (FEA).

Sub-Step	Force Applied (N)	Displacement (mm)	A x ΔL	F x L	E_z (MPa)
1	1.079	0.00023	0.2760	10.79	39.084
2	2.158	0.00046	0.5521	21.58	39.084
3	3.237	0.000691	0.8294	32.37	39.027
4	4.316	0.000922	1.1066	43.16	38.999
5	5.395	0.001152	1.3827	53.95	39.016
6	6.474	0.001382	1.6588	64.74	39.027
7	7.553	0.001613	1.9360	75.53	39.011
8	8.632	0.001843	2.2121	86.32	39.020
9	9.711	0.002073	2.4882	97.11	39.027
10	10.79	0.002301	2.7619	107.9	39.067
Average Ez					39.036

Table 5. Comparison of Elastic Properties of Nomex Honeycomb Core.

Parameter	Theoretical values(MPa)	FEA values(MPa)	Experimental values(MPa)
E_x	0.081	0.1067	0.1863
E_y	0.081	0.1187	0.1863
E_z	31.83	39.036	45.12

The analytical methods included continuum formulations and models based on strength of materials. The results are very useful for the modelling of such structures and FEM has a significant role in designing of honeycomb structures before fabrication of actual component to save time and money.

Using the existing theories the orthotropic mechanical properties of Nomex Honeycomb Core were calculated theoretically. Then experimental tests were performed on the base material of Nomex honeycomb to ascertain its properties. These findings were then used in numerical analyses as input for static tension on bare honeycombs. As a result of these analyses the orthotropic elastic constant was found using FEA. For this purpose an FEA tool Ansys was used. The finite element discretization was also precise and the analysis was repeated to examine the effect of element size. During all these analysis Non linear and large displacement effects were on. All other orthotropic properties like V_{xy} , V_{yx}, V_{xz} , V_{zx}, V_{yz}, V_{zy}, G_{xy} , G_{yx}, G_{xz} , G_{zx} have been carried out in another research work.

4. Conclusion

The elastic constants of Nomex Honeycomb core were found experimentally and compared with the theoretical and numerical values. It was concluded from the above research that instead of performing time consuming and costly testing of honeycomb, simulated mechanical properties can be obtained for any material or sizes of hexagonal honeycomb samples. These simulated homogenized properties can be used in subsequent FE analyses of different sandwich structures with a very little compromise on accuracy and enough time saving for both testing, modelling and solution time. There is scope of work in considering the determination of other mechanical properties with different orientations.

References

[1] A.H. Nayfeh, Wave Propagation in Layered Anisotropic Media with Application to Composites. Elsevier Publishing Company, Applied Mathematics and Mechanics Series, Amsterdam (1995).

[2] S. Balawi and A.H. Nayfeh, Effective Mechanical Properties of Triangular and Hexagonal Cellular Composites. 11th International Conference on Composites / Nano Engineering, Hilton-Head Island, South Carolina (2004).

[3] M. Meo, A.J. Morris, R. Vignjevic and G. Marengo, Composite Structure **62** (2003) 353.

[4] A. Levent, A. Johnson and F. H. Martin, Comput. Material Science **32** (2005) 252.

[5] C.C. Foo, G.B. Chai and L.K. Seah, Composite Structures **80** (2007) 588.

[6] W.S. Burton and A.K. Noor, Comput. Meth. Appl. Mech. Eng. **145** (1997) 341.

[7] F. Meraghni, F. Desrumaux and M.L. Benzeggagh, Composites Part A **30** (1999) 767.

[8] H. Jorg and B. Wilfried, Comput. Mater. Sci. **19** (2000) 108.

[9] L.J. Gibson and M.F. Ashby, Cellular Solids: Structures & Properties, Pergamon Press (1988).

[10] M.H. Triplett and W.P. Schonberg, Struct. Eng. Mech. **6** (1998) 95.

[11] C.W. Schwingshackl, G.S. Aglietti and P.R. Cunningham, Journal of Aerospace Engineering ASCE (2006) 177.

[12] F. Mujika, J. Pujana and M. Olave, Polymer Testing **30** (2011) 222.

[13] G.C. Shah, A.L. Kalamkrov and A.V. Georgiades, Composites: Part A **38** (2007) 1533.

[14] S. Balawi and J.L. Abot, Composite Structures **84** (2008) 293.

[15] A. Karakoc and J. Freund, Composite Structures (2012)

[16] ASTM. General Products, Chemical Specialities and End use Products (1998).