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Experimental investigations and finite element analysis of composite sandwich structures with honeycomb core – Evaluation for strength and quality

S. A. Abdul Sukkur[a], P. Palanisamy[b], K. R. Vijayakumar[b]

a) Research Scholar, Mechanical Engineering Department, Dr MGR Educational and Research Institute University, Maduravoyal, Chennai-600095, India.
b) b. Mechanical Engineering Department, Advanced Research Institute, Dr MGR Educational and Research Institute University, Maduravoyal, Chennai-600095, India.
Phone: +919380283490, shaikabdulsukkur@gmail.com

Abstract: Honeycomb cores in composite sandwich structures are economical and appropriate scheme to absorb impact in engineering applications. Hexagonal honeycomb that are conventionally being used displays greater Poisson's ratio and are typically used for their light weight and higher axial stiffness. Auxetic honeycombs exhibit contradictory properties such as high in plane shear stiffness and shows negative Poisson's ratio with lateral extension instead of contraction when axially stretched. The research reports suggests the need for greater research evolutions in the field of honeycomb composites structures still considered to be in its naïve state. This study involves analysis of the dynamic response of an aluminum composite panel with a honeycomb core constrained within two thin face subjected to impact with a rigid ball. Parametric analysis and finite element analysis are performed to investigate the governing factors, their interdependencies and the deformations occurring for various loads.

Keywords: Honeycomb, Impact strength, Energy, Elastic, Stress-Strain Modulus

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1. **Introduction:** Employment of lightweight structures for vehicles such as airplanes, trains, ships, and automobiles is mounting gradually owing to its ability to mitigate the air pollution, carbon emissions and improved energy efficiency or enhanced yield capacity by providing an increased payload. This task promotes the research on identifying advanced materials to cater to the demands of light weight structures and their applications. Composite materials possessing features that present high specific stiffness and strength than conventional materials have been proposed in many industrial sectors to address and suit lightweight structures. In particular, the sandwich structure that includes a composite laminated face sheet and a core material, provides better bending stiffness and longer fatigue life cycles aptly suits the insulating applications, as well as in noise covers, which promotes its widespread applications in airplanes, trains, ships, and automobiles. Employability of materials in vehicle of the sandwich composite panel offers the merit of weight reduction of transit, increases the speed while improving its energy efficiency. Taking the global facts, honeycomb sandwich panels are predominantly employed for absorbing the noise (Aluminum honeycomb cores absorb 70~80% of the impact energy) and to parallelly augment the crashworthiness of structures, such as the bumper of automobile and cab-mask in railways. Generally, honey comb structures are manufactured with wall partitions that are perpendicular to the surface of face sheet material as shown in Figure (1). Nevertheless, if the wall partition of honeycomb core is fabricated for an inclined surface of face sheet, the ability of sandwich structures to absorb impact energy may be drastically improved. Therefore, it is imperative to determine

the optimum angle of wall partition of honeycomb core before it is employed as shock absorber of transit vehicle [1].

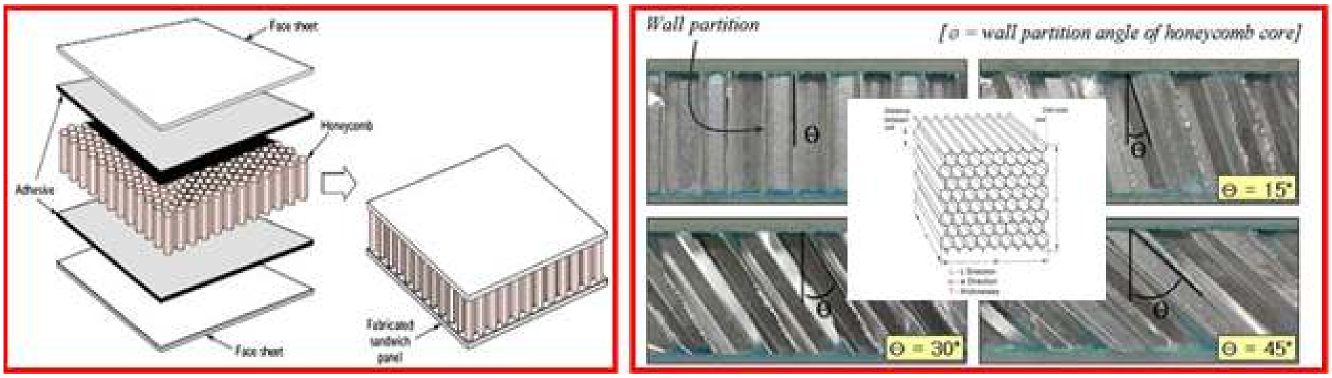

Figure (1): Honeycomb composites with wall partition angle (ϴ) **[1]**.

It's a conclave of several phenomenon and parametric governs and hence stipulates an optimization to capture the conclave of concepts of physics which include: (1) Slender front face plate will result in significant concave deformation under load that will increase the momentum on the structure which is detrimental, (2) front and back face plate thicknesses must ensure proper load transfer to the core to enable crushing, (3) the core itself must be stiff enough to minimize peak backface displacement and soft enough to crush and absorb energy to minimize acceleration, (4) total mass and space or envelope constraints must be satisfied, and (5) face plates must be thick enough to maintain integrity [2]. With these fundamentals, the literatures directly contributing to this study is also briefed in this section.

Sandwich construction is preferred in several engineering applications as it offers weight reduction and high stiffness features [1]. Masashi Hayase and Richard Eckfund [2] developed a metallic sandwich structure in which metal sheets were intermittent or discontinuous welded. Sun and Zhang [3] in 1995 presented the use of thickness-shear mode in adaptive sandwich structure with piezoelectric materials. In 2001, V. Dattoma and R.Marcuccio [4] discussed some typical defects prevailing in composite material sandwich structures by using thermo graphic technique. Other research group highlighted the reason for the greater fatigue resistance of the honeycomb wherein the panels are continuously bonded to the core which evades stress concentrations. Other major reason suggested by researchers indicates the fact of high stiffness with considerable weight reduction making up the state-of-art choice for weight sensitive applications such as aircraft and satellites [5, 6]. Each component is relatively weak and flexible but provides a stiff, strong and lightweight structure when working together as a composite structure. Auxetic honeycombs are cellular structures basically designed to invert the angle of a unit cell to negative. This change of angle is reported to have negative Poisson's ratio in the cell plain [7]. Found and his co-researchers [8] applied a modal analysis in auxetic structure. Ruzzene [9] investigated the wave propagation in sandwich beams with auxetic honeycomb core. Abrate [10] designed and developed numerical models for the impact analysis between a foreign object and a composite structure. This promoted the exploration of the auxetic honeycomb behavior by applying a resonance to the model and observed that the predominant mode of cell wall deformation is always flexural [11]. After thorough understanding of the fundamentals pertaining to honeycomb, an attempt is made in this study to develop a honeycomb composite and subject it to loads for accessing the deformation physically. This is followed by development of preliminary finite element model to analyze the performance while evaluating the deformation.

1.0 EXPERIMENTATION

The test specimen consisted copper core with hexagonal cells. Stainless steel sheets of 2 mm thickness are used for making the sandwich panel faces. Varying core heights, 5 mm, 10 mm and 15 mm are selected for this investigation. The core is spot welded to the face plates. Figure (2) show the spot weld locations (dark spots). The cell size of the honeycomb is 30 mm. Figure (2) also shows the image of the copper honeycomb core fabricated.

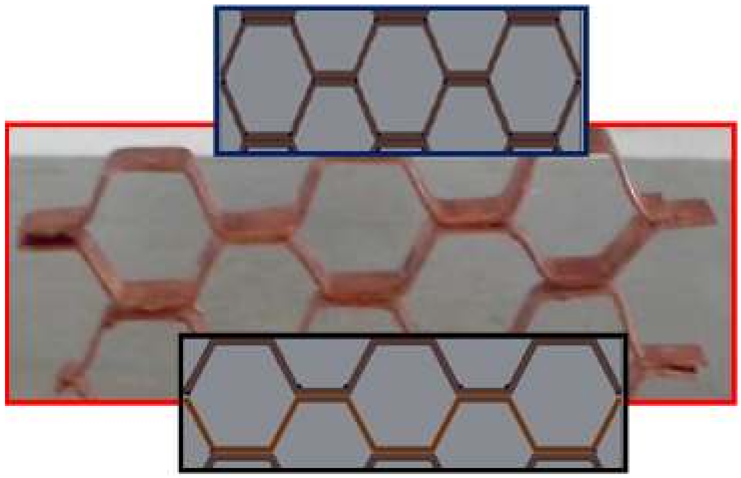

Figure (2): Copper honey comb structures with spot welded plates indicating dark locations.

3.0 EVALUATION AND TESTING OF THE SPECIMENS

The fabricated honey comb structures are subjected to various loading conditions and the corresponding responses are used to estimate the strength and the quality of the honey comb structures. The specimens are basically subjected to static loading and drop test. Figure (3) shows the specimens subjected to various loading conditions.

Figure (3): Specimens getting subjected to various loads.

4.0 RESULTS AND DISCUSSION

4.1 Static Test Results: Tests were carried out at room temperature (22 °C) in displacement control at a cross-head speed of 0.5 mm/min. Failure load was taken as the peak of the load vs. displacement curves. The corresponding values of shear stress were found using the following expression.

$$Ss = \frac{L}{l \times W}$$

where **Ss** is the shear stress, **L** is the load applied to the coupon, **l** is the length of the coupon, and **W** is the width of the coupon.

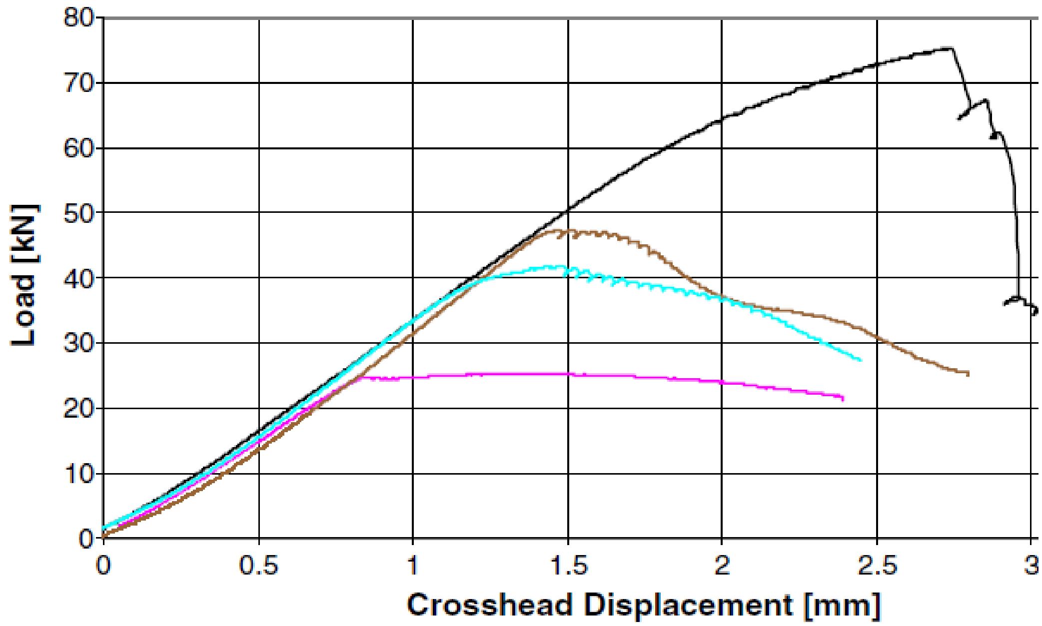

Figure (4): Plot of Crosshead displacement Vs Load.

Load versus cross-head displacement curves obtained by testing the two core types in the principal orientations is shown in Figure (4). It is observed that the crosshead displacement increases upto a particular load and attains saturation. This is followed by the decrease in the curve. The point at which the displacement reaches the peak and starts decreasing is the threshold and indicates the maximum load bearing capability. From Figure (5), it is clearly observed that the shear strength decreases prominently as the degree of orientation increases. Hence, it is imperative to maintain the degree of orientation in an optimized range in order to attain higher shear strength.

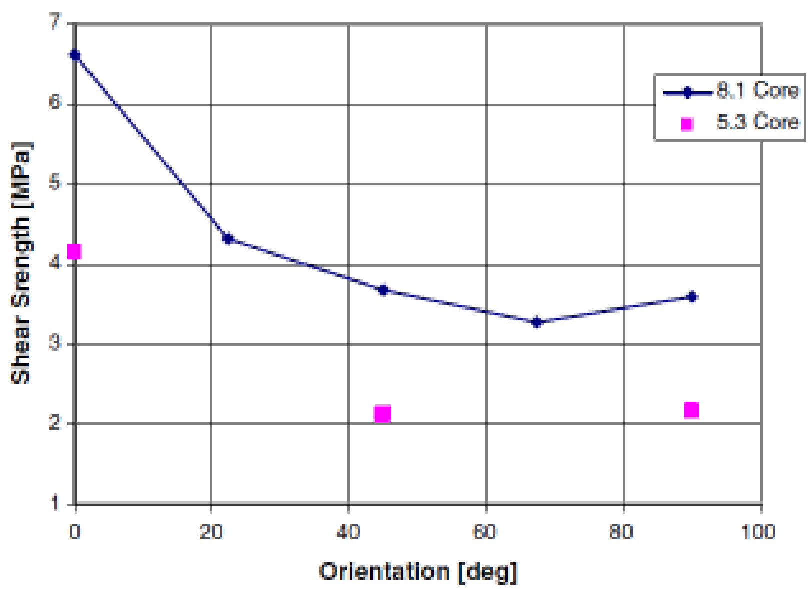

Figure 5 Variation of measured shear strength with cell orientation.

All tests were conducted at room temperature in load control at load amplitude values chosen on the basis of the static test results. For all the tests the applied load was sinusoidal with a ratio R=−1 (i.e.

fully reversed). Alternating compressive and tensile stresses was chosen as it induces the highest fatigue damage and hence is representative of the most severe loading scenarios. The fatigue life of the coupons is characterized in terms of the number of cycles to ultimate failure. Figure (6) illustrates that, as the displacement increases, there is corresponding increase in the equivalent shear stress. This establishes the fact that, there exists proportionality relationship between stress and displacement. However, it is also to be noted that, after reaching the threshold stress value, it would start decreasing irrespective of the increase in the displacement. It may be concluded that, the displacement has insignificant effect after the stress reaches its threshold value.

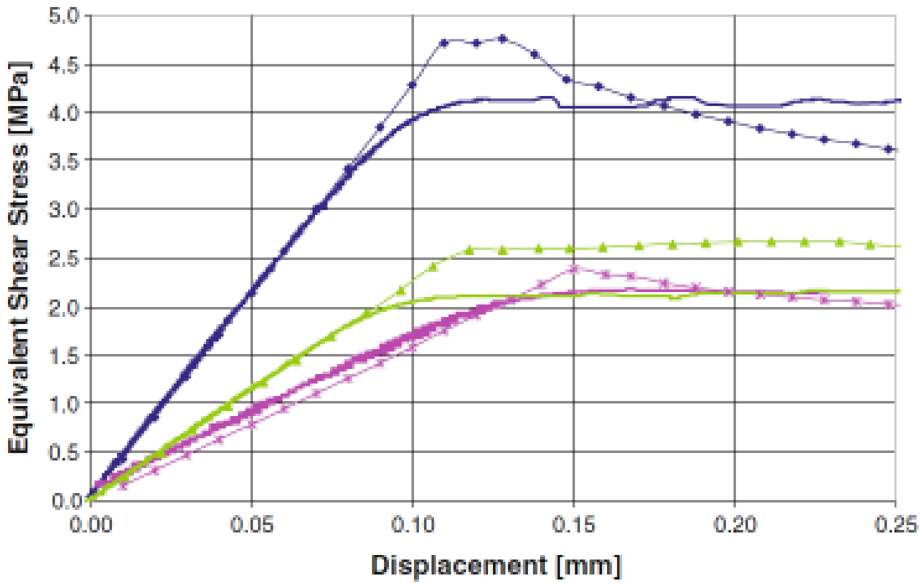

Figure (6): Shear stress vs. Displacement curves.

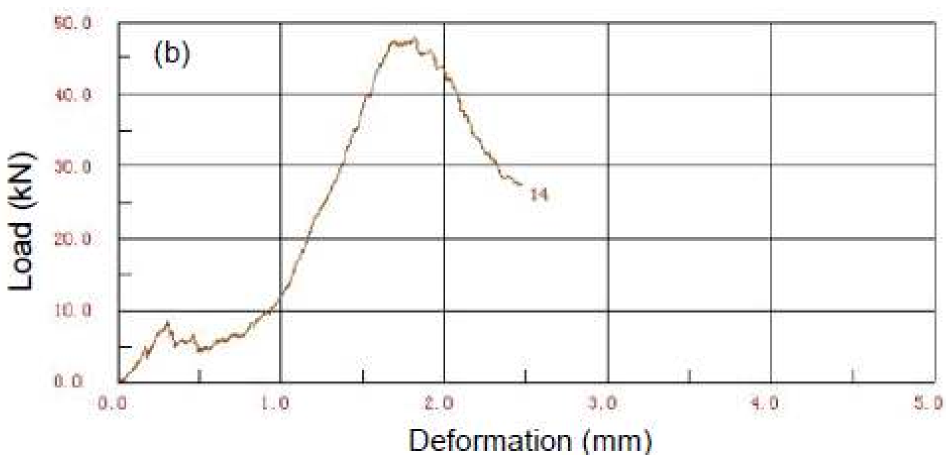

Figure (7): Deformation vs. Load curve.

Figure (7) illustrates that, with the increase in the load, there is an increase in the deformation. The load and the deformation are exponentially related to each other.

5.0 THERMAL STRUCTURAL BEHAVIOUR FOR HONEYCOMB STUCTURES

A non-linear transient thermal analysis is performed for various loading conditions to predict the temperature history of the domain for complete thermal cycle multi pass welding along the thickness. Computer based simulations offer the prospectus to examine different aspects of the process without having a physical prototype of the product. In this work, main parameters of the honey comb materials properties are considered and the finite element simulation is performed using ANSYS.

5.1 Mathematical Model for deformation analysis

The heat transfer in the base material is conceived to be three dimensional models in nature considering the radial, circumferential and axial directions [Bag S et al (2009)]. Figure (8) shows the three dimensional model which typically depicts the honeycomb layers and configurations along with the associated boundary conditions. Figure (8) shows the FEM model of honeycomb layered structure with the triangular meshing adopted for this study.

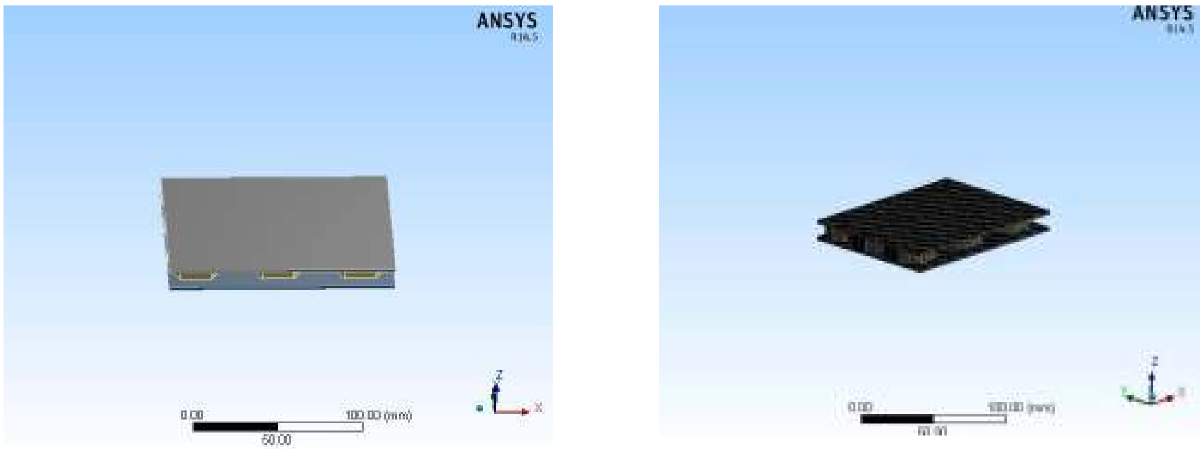

Figure (8): FEM model for thermal analysis with meshing.

Welding simulation procedure is depicted in Figure (9).

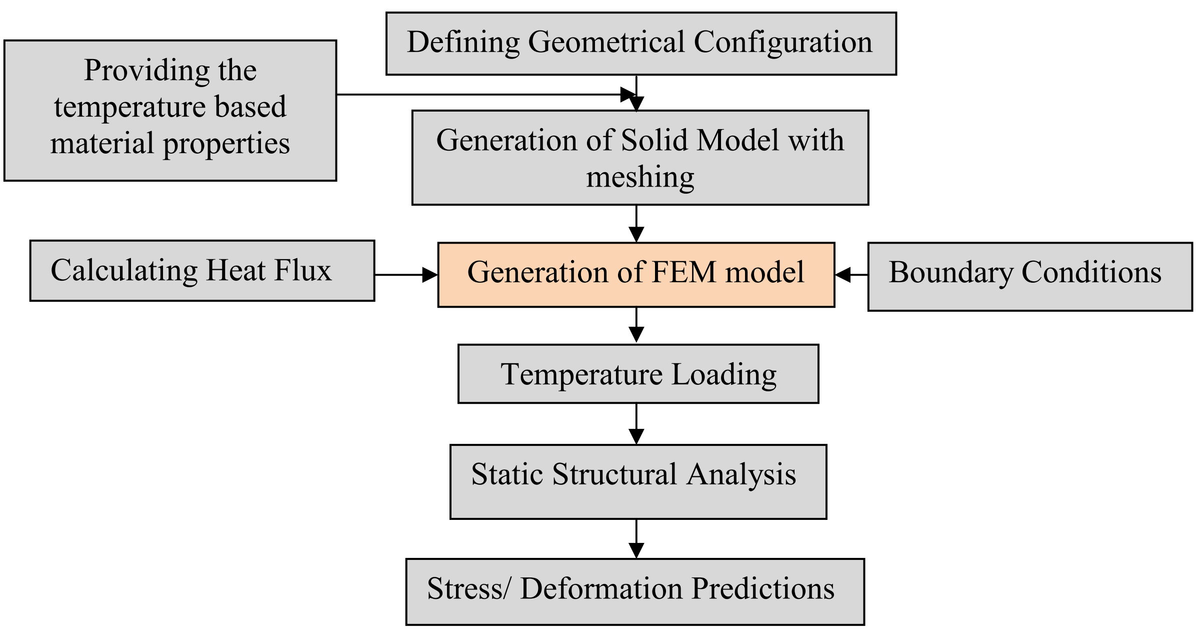

Figure (9): Welding simulation procedure.

The dimensions of all the specimens considered for this study is 25 mm thick. The length of each specimen is approximately 100 mm. A free mesh is adopted for the calculation which includes a total of 76,590 nodes and 25043 elements for the calculation domain as shown in Figure (9). The calculation domain is increased and selected through a series of calculations for this size, which shows a uniform distribution of heat flux.

5.2 Material Properties: The materials used for the study are copper alloy and structural steel. The material properties Viz., thermal and mechanical properties of the joint for Cu alloy and Structural Steel material are used for the numerical analysis. The material properties of copper alloy and Structural Steel are presented in Table (1) and (2) respectively.

Table (1): Properties of Cu alloy.

Density	8.97e-006 kg mm^{-3}
Coefficient of Thermal Expansion	1.8e-005 C^{-1}
Specific Heat	3.85e+005 mJ kg^{-1} C^{-1}
Thermal Conductivity	0.401 W mm^{-1} C^{-1}
Compressive Yield Strength Mpa	280
Tensile Yield Strength Mpa	70
Tensile Ultimate Strength Mpa	200
Young's Modulus MPa	1.2e+005
Poisson's Ratio	0.3
Bulk Modulus MPa	1.e+005
Shear Modulus MPa	46154

Table (2): Properties of Structural Steel.

Density	8.19e-006 kg mm^{-3}
Coefficient of Thermal Expansion	1.2e-005 C^{-1}
Specific Heat	4.34e+005 mJ kg^{-1} C^{-1}
Thermal Conductivity	6.05e-002 W mm^{-1} C^{-1}
Compressive Yield Strength Mpa	250
Tensile Yield Strength Mpa	520
Tensile Ultimate Strength Mpa	860
Young's Modulus MPa	2.e+005
Poisson's Ratio	0.3
Bulk Modulus MPa	1.6667e+005
Shear Modulus MPa	76923

5.3 Boundary condition and heat input: For this study, an assumption is made that the loading condition is carried out at room temperature with air as the medium in the set up. The necessary mathematical equations for the FEA are adopted here.

5.4 Theoretical Estimation

A simply supported honeycomb sandwich panel Kelsey *et al*.(1958) evolve a formula of the mid-span deflection, δ for the sandwich panel for aluminium honeycomb in the linear elastic regime as follows: $\boldsymbol{\delta=Pa3/48EfIf+Pa/4AcGca}$ (1)

The expression relates bending effect and accounts for the shear effect. It is seen that equation (1) predicts the linear elastic bending response of copper honeycomb sandwich beam well. The critical load P, is obtained when the bending stress of facing skin reaches the yield stress. Therefore, by replacing P by Po, equation (2) leads us to the following critical load: $\boldsymbol{P=CPt2fo/d\ \{1-(tc/t)}$ (2) where C is a constant representing the shear effect due to honeycomb core on the resistive bending moment [5].

The constant C in the above may be obtained from eq. (1) by assuming that the shear effects of cores for panel strength are likely to be similar to those for panel stiffness. These results in $C=C1/C1+C2$ (3) Where, $C1=d3/48EfI$, $C2=d/4AcGca$ (4) Deflection of copper honey comb panel under different loads: Central deflection of honey comb panel is given by: Sample calculation: $\boldsymbol{w=(Pa3/48EfIf)+(Pa/4AcGca)}$.

5.5 Results and Discussion

Static analysis was performed to obtain the response of the hexagonal honeycomb sandwich panel with three different loads, i.e. 2 kN, 5 kN, 7 kN for three different core heights i.e. 5 mm, 10 mm and 15 mm. The outcome reveals an increase in deflection with increase in load when the core height is 5mm when compared to that of 15 mm. Figure (10, 11, and 12) shows the variation in deflection for various core heights.

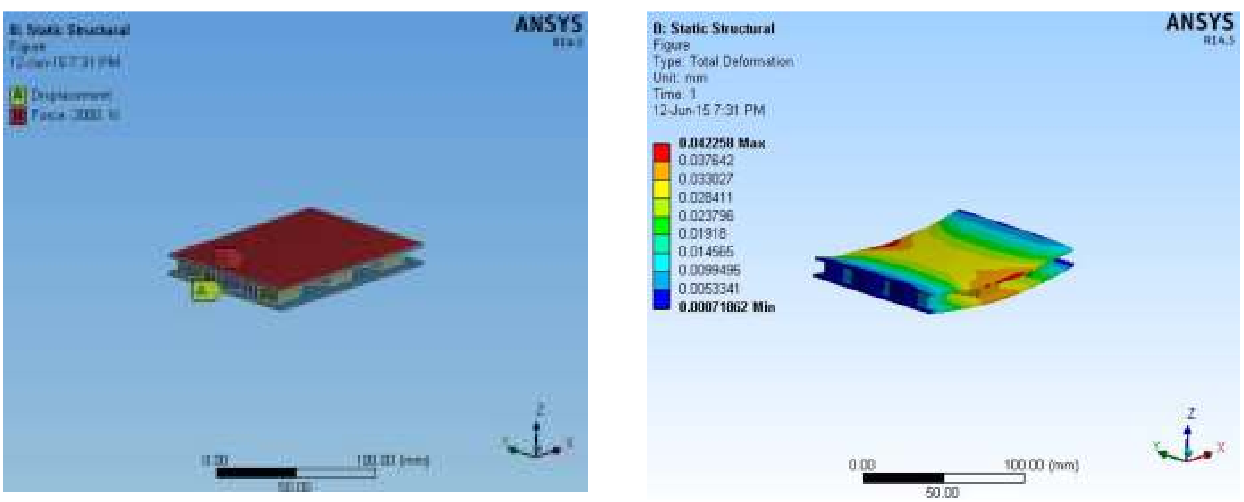

Figure (10): Deflection plots for various loads with core height of 5 mm.

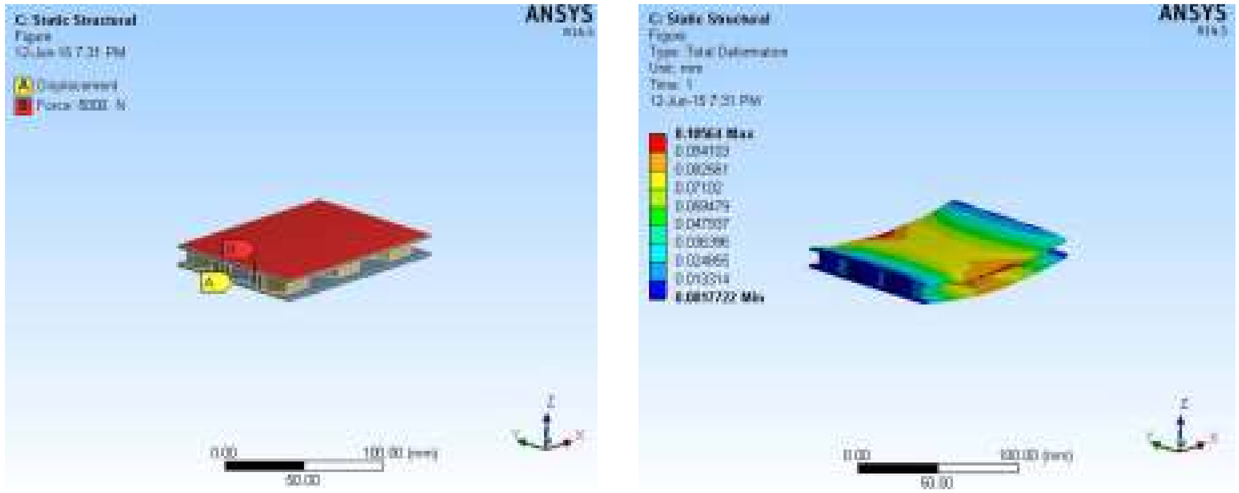

Figure (11): Deflection plots for various loads with core height of 5 mm.

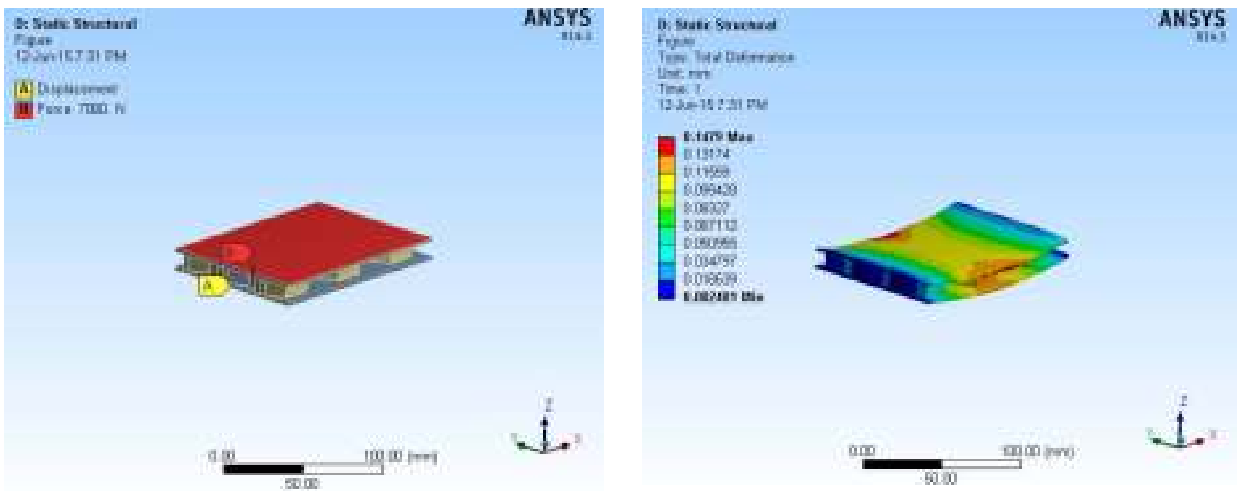

Figure (12): Deflection for various loads with core height of 5 mm.

Stress and corresponding strain plots and the corresponding safety factor are to be taken into consideration before subjecting the honeycomb composite to various loading condition is also estimated through FEM analysis. It may be clearly noticed that the strain distribution is uniform and is maximum at the point of application of load. The maximum deformation is also observed at this point which increases the brittleness of the composite. The strain distribution is uniform and reducing at equidistant positions from the point of load application. The safety factor is estimated in order to confine the application of the composite based on the safety factor values. Strain and safety factor for various loads are presented in the Figures (13-15) respectively.

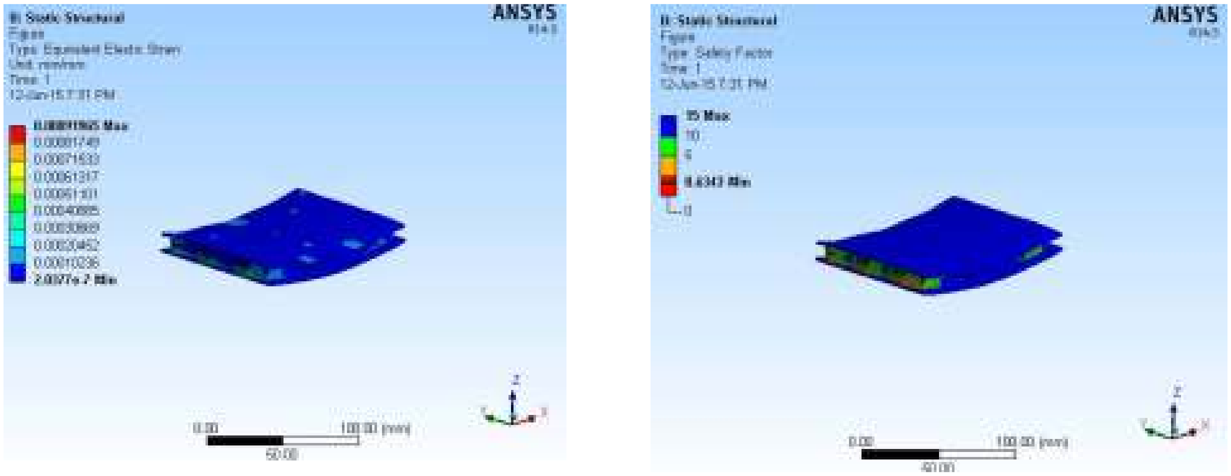

Figure (13): Strain and safety for various loads with core height of 5 mm.

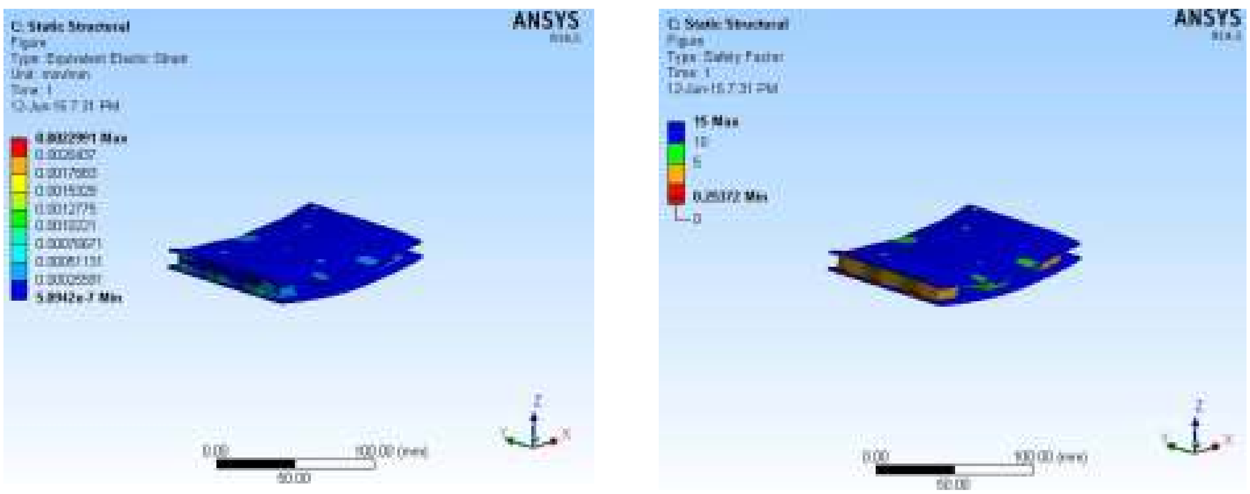

Figure (14): Strain and safety for various loads with core height of 5 mm.

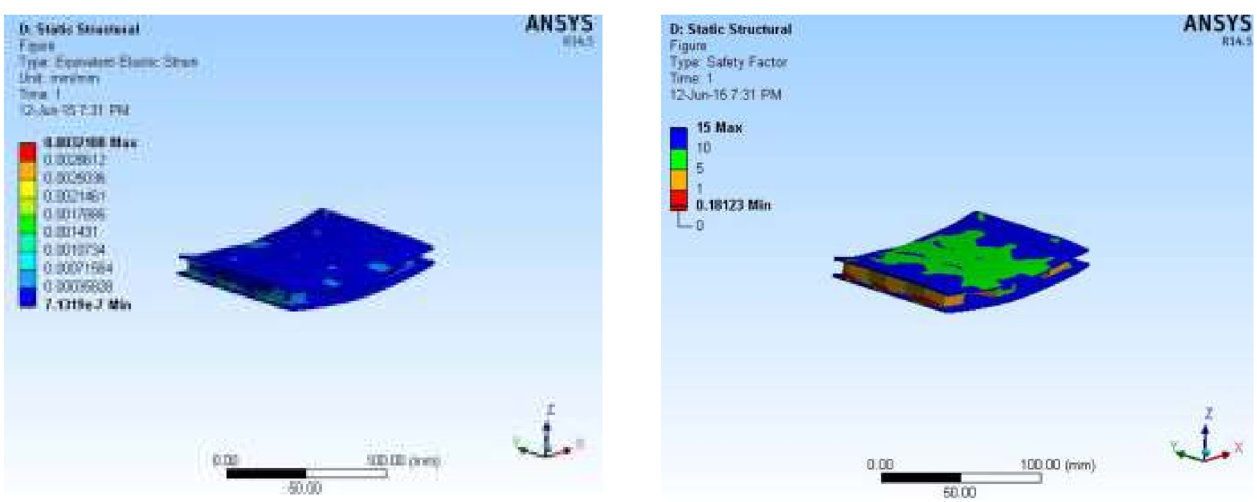

Figure (15): Strain and safety for various loads with core height of 5 mm.

6.0 VALIDATION OF EXPERIMENTAL AND FEM RESULTS

Destructive Testing was performed on the honeycomb composite structure using universal testing machine. Various loading conditions were tested and the results were recorded. Those results reveal good correlation with the FEM results indicating that the FEM analysis procedure adopted and the model is suitable for predicting the behaviour of honeycomb composites.

7.0 CONCLUSIONS

In this study, bending behaviour of copper core honeycomb composite panel with stainless steel facing under 3-point bending was studied experimentally for various core heights and loads. Finite Element simulation was used to predict the deflection. The predicted Design and Analysis of Copper Honeycomb Sandwich Structure values and experimental values were compared. Based on the results it is found that the gradient of deflection curve is high for lower core height and stress is low for higher value of core height. These results can be used as input when designing sandwich panels.

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