Design, Modelling and Manufacturing aspects of Honeycomb Sandwich Structures: A Review

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Design, Modelling and Manufacturing aspects of Honeycomb Sandwich Structures: A Review

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***Abstract*: Honeycomb sandwich panels are widely used in automobile, aerospace and space structures due to unique characteristics like high strength to weight ratio and High stiffness. Honeycomb sandwich panels consist of honeycomb core made of either metal or thin paper like materials. Core is sandwiched with metallic or composite face sheets. Core gives high compressive strength in T direction whereas face sheet gives shear strength in T and W direction. Compressive strength of sandwich panel depends on foil thickness of honeycomb core, cell size, thickness of core in T direction and face sheet thickness. For nearly same weight honeycomb sandwich panels can give up to 30 times higher stiffness than metallic sheets. Face sheets of the sandwich structure facilitate mounting of the instruments as core has very high volume fraction of cavity and hence cannot hold fasteners alone.Modelling of Honeycomb sandwich structures with actual cell configuration is difficult and time consuming. Hence sandwich structure is generally modeled as equivalent homogeneous structure. This paper gives an insight about design, simulation and manufacturing aspects of honeycomb sandwich structures.**

***Keywords*: Honeycomb panel, thin walled structure, sandwich structure**

I. INTRODUCTION

The honeycomb structure is a type of cellular materials with regular and periodically repeated arrays of hexagonal cells and it is composed of two thin, stiff, strong sheets serving as primary load carrying elements and thick layer of low density core providing shear resistance and stiffness. [1,2] honeycomb has wide range of applications such as aerospace, shipbuilding, vehicle, construction, energy absorber, thermal isolators, packaging etc. Some of the unique characteristics which makes honeycomb structure a preferred choice for these applications are high stiffness to weight ratio, elimination of welding, superior insulation quality and design versatility.[3]

a. HISTORY

Honeycomb consist of arrays of cells formed from thin sheets of material. Mostly the cells are hexagonal but there are also other cell configurations like square and flex core. Some variations of these configurations are the over-expanded, under-expanded and reinforced. Honeycomb was first made from paper around 2000 years ago and it was used for ornaments by Chinese people. In 1919 first time aircraft primary structure was fabricated with sandwich panel made of thin mahogany facings bonded to end grain balsa wood core. Later between World War I and World War II, plywood skins and balsa wood core was used for aircraft structures by Italians. The manufacture of structural honeycombs began in late 1930s. In 1945 first aluminum sandwich panel was produced. Then with the development of better adhesives it was possible to achieve good bonding strength to the face sheets. Initially made adhesives had very high amount of volatile contents which can cause problem due to outgassing when used at temperature above 100°C. Hence initially core to be used in aerospace and space structures were kept perforated. Modern adhesives are purely solid and does not contain volatiles. Hence core manufacturing and curing is simplified.[4]

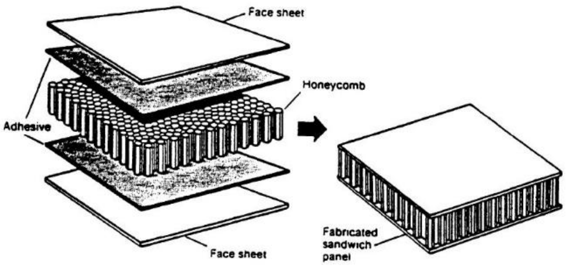


Figure 1 : Sandwich Construction

b. TERMINOLOGY

The following are some basic terms commonly used for honeycomb structures.[4]

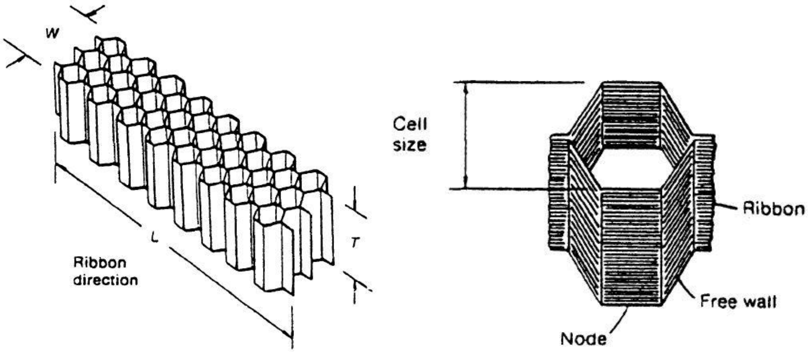


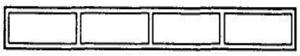
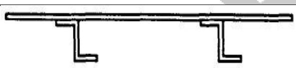
Figure 2 : Honeycomb Terminology

- Honeycomb density : the weight of one cubic meter of core expressed in kilograms (kg/m^3) or pounds per cubic feet (pcf)
- Cell : a single honeycomb unit
- Cell size: distance between two opposite sides of hexagonal cell.
- Ribbon : the flat sheet material constituting the honeycomb
- Node: the bonded portion of adjacent ribbon sheets.
- Free wall: cell wall sections of single bonded sheets.
- Foil thickness : thickness of free wall
- L direction : the core ribbon direction
- W direction : the core expansion direction
- T direction: the core direction parallel with cell openings.
- Honeycomb Before Expansion (HOBE): the solid block of bonded sheets.

c. Characteristics of honeycomb sandwich

There are some applications were light weight is a design criteria and usage of thin sheets causes buckling problem due to concentrated loads. In such applications honeycomb panels should be used. If the loads acting are very high then thick skins are required. In table 1 some of the standard structural panel constructions are compared for relative strength and stiffness.

Table 1 : Comparison of structural panels

Structural panel construction	Relative strength	Relative stiffness
 Honeycomb sandwich	100%	100%
 Foam sandwich	26%	68%
 Structural extrusion	62%	99%
 Sheet and stringer	64%	86%
 Plywood	3%	17%

Honeycomb works as energy absorbing material as it crushes uniformly at known load and has highest crush strength to weight ratio of all energy absorbing materials. Aluminum honeycomb is widely used in common energy absorption applications. Stainless steel honeycomb is used for high temperature application such as nuclear power plants.[5]

For mechanical structures which undergo repeated loads, fatigue properties of the core has to be investigated. Cell dimensions core density have significant influence on the fatigue strength.[6-9]

II. TYPES OF HONEYCOMB

The most common honeycomb are aluminum, Nomex, fiberglass and Kraft paper. However honeycomb can be manufactured from almost any thin sheet materials. The nonmetallic cores are resin dipped in phenolics, polyamide (for high temperatures), epoxy and thermoplastics (for toughness) resins.The corrugated aluminum honeycomb core manufacturing process is more time consuming than expansion method; hence the corrugated core is usually more expensive. Aluminum honeycomb is made of corrugation process because above 192 kg/m^3 (12pcf) it becomes very difficult to expand the HOBE. If strength and modulus requirement is very high in L direction, then reinforced cell configuration is used. Reinforcements can increase strength up to 35 MPa. If corrugated slice is roll formed in W direction then sometimes nodes are separated. In such cases staggering can be done as shown in R2S configuration in figure 3. Instead of each ribbon node contacting the entire opposite node, they are offset.[4]

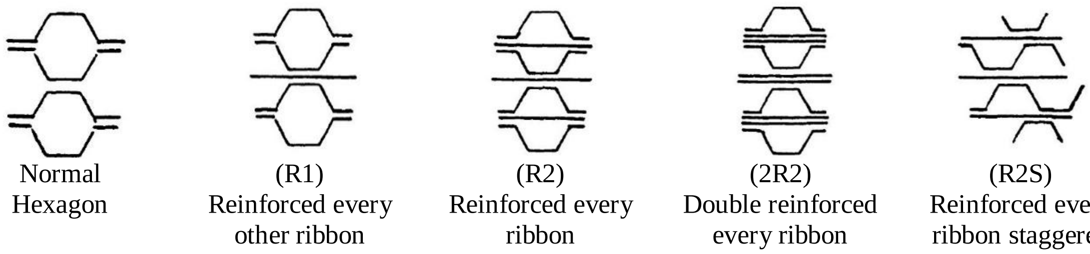


Figure 3 : Corrugated cell configurations

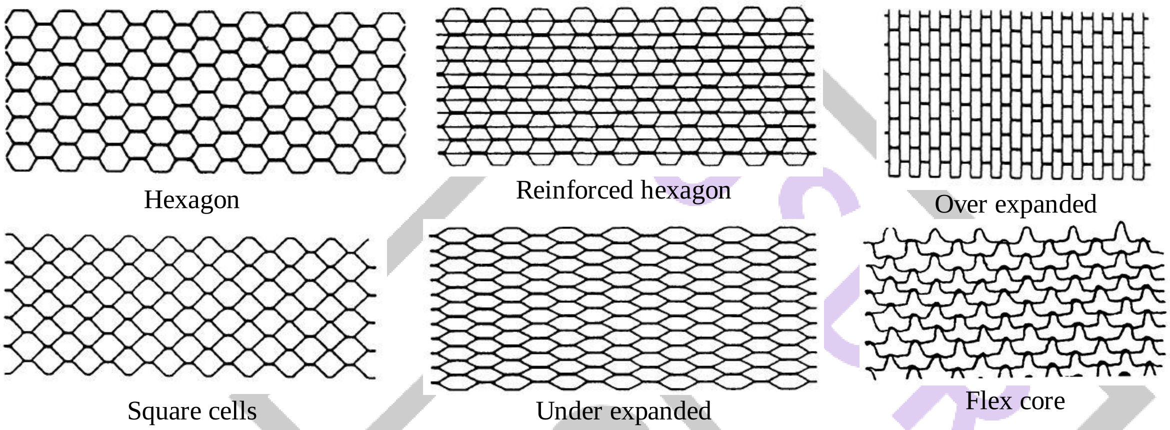


Figure 4 : Honeycomb cell configurations

a. CELL CONFIGURATIONS

The most common cell shapes are hexagon, square and flex core. Some variations of these configurations are overexpanded, underexpanded and reinforced. The hexagonal cell shape is most common for adhesively bonded honeycomb and mostly resistance welded and brazed cores have square cells.

The over expanded core allows to form cylinder in L direction. Hex cores does not easily form to curved shapes and must be roll formed or heat formed. Flex core is used when honeycomb must be formed with compound curves as this configuration can be wrapped around spherical shape as small as baseball.[4]

If honeycomb cells are irregular in shape with uniform wall thickness then modulus increases considerably while Poisson's ratios are insignificantly affected. But for regular honeycomb, the increase in the cell wall thickness non-uniformity substantially reduces the elastic modulus but has very little influence on the effective Poisson's ratio.[10]

III. HONEYCOMB PROPERTIES

Mechanical properties to be taken into consideration for honeycomb are bare and stabilized compressive strength, stabilized compressive modulus, L and W plate shear strength and modulus. For energy absorption application crush strength is considered which is 50 % of the bare compressive strength. In general practice, metallic honeycomb properties are specified for 15.9 mm thickness and nonmetallic honeycomb properties at 12.7 mm thickness. The compressive properties and shear modulus do not change with thickness but shear strength decreases with increase in thickness.[4] Typical mechanical properties for honeycomb core made of aluminum alloyis as shown in table 2.

Table 2 : Typical properties of Aluminum alloy honeycomb core

Core		Compression		L shear		W shear	
	Density (pcf)	Strength (psi)	Modulus (ksi)	Strength (psi)	Modulus (ksi)	Strength (psi)	Modulus (ksi)
5052 Al	1	55	10	45	12	30	7
5056 Al	1	60	15	55	15	35	7

2024 Al	2.8	320	40	200	42	120	19
3003 Al	1.3	70	16	55	14	40	7

Honeycomb core is orthotropic in nature. For hexagonal honeycomb, the L direction has twice the shear strength and modulus compared to W direction. When the core is over expanded the L and W shear strength are similar and the W shear modulus is about twice the L shear strength.

Poisson's ratio of honeycomb core cannot be determined in similar way to metals. If honeycomb core is compressed in T direction then cell walls can buckle inward or outward and this normal motion of one cell wall does not affect other wall. Also if core is compressed in L or W direction then it just deforms geometry. Hence honeycomb does not have single Poisson's ratio. One way to determine Poisson's ratio is to bend the core to a given radius in one direction and measure the anticlastic radius in other direction. The Poisson's ratio is equal to $-R_1/R_2$.[4]

Figure 5 : Anticlastic curvature of core

Usually honeycomb core modulus are very small compared to face sheets and hence Poisson's ratio of core does not matter for analysis of sandwich panel. L and W direction modulus properties are almost zero compared to T direction. Typical values of Poisson's ratio for commercially available core ranges from 0.1 to 0.6.

IV. FAILURE OF CORE

When honeycomb panel is loaded in out of plane direction then compression and shearing occur simultaneously. As the specimen is compressed buckling of honeycomb cell walls starts from both the end face sheets. Shearing occurs due to rotation of cell walls in combined loading conditions. Several researchers have observed effect of quasi-static and dynamic loading on honeycomb panels. There is no significant effect of loading velocity on rotational angle of core. Hence force displacement curve for static and dynamic loading conditions are nearly same. Plateau stresses are observed to increase with loading velocity.[11] The indentation resistance of honeycomb panel depends on nose geometry of indenter, cell dimensions and skin core adhesion.[12] The experimental results indicated that the normal crush strength under combined compressive and shear loads are lower than that under pure compressive loads. Hence honeycomb core is always orientated to be in pure compression along T direction.[13]

V. SIMULATION

For sophisticated analysis of structure considering sandwich panel to be subjected to combination of forces, techniques such as Finite Element Analysis can be used. In general shear forces normal to panel are carried out by honeycomb core and bending as well as in plane forces on panel are carried by facing skins. If very detailed and accurate results are required then solid geometry of honeycomb cells can be generated. But in general engineering analysis, individual cell modelling is avoided and core is simulated as solid equivalent plate.

The elastic properties of the homogeneous medium by which the sandwich core is replaced in the analysis can be determined by either experimental, analytical or numerical methods. Young's modulus in thickness direction can be determined by compression tests.[14] Shear characterization of the sandwich cores was carried out based on sandwich beam subjected to three point bending.[15,16] out of plane shear modulus can be determined by simple dynamic technique with four accelerometers.[17] A homogenization method is introduced by wang et al for linear elastic problems to analyze complicated distribution of the stresses and strains around core.[18]

When defining properties of honeycomb core following points should be taken into consideration. Modulus in L and W directions are nearly zero. But very small values may need to be applied to avoid singularity.

$E_L = E_W = 0$,$\mu_{LW} = \mu_{TW} = \mu_{LT} = 0$

The study of the mechanical behavior of a composite material commonly uses the homogenization concept. The equivalent characteristics of a honeycomb sandwich plate are determined by identifying its membrane and bending stiffness to those of an isotropic plate as shown in figure .[19]

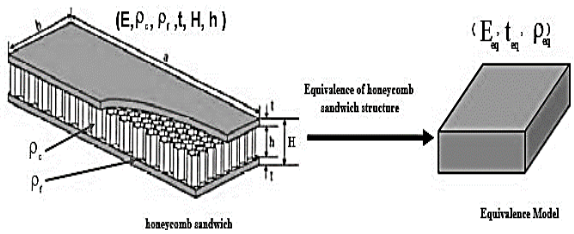
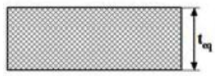


Figure 6 : Equivalent parameters of Honeycomb sandwich plate

Table 3 : Equivalent parameters of sandwich structure

	Honeycomb sandwich plate 	Equivalent isotropic plate 
Membrane stiffness	$\frac{2Et}{1-v^2}$	$\frac{E_{eq}\,t_{eq}}{1-v^2}$
Bending stiffness	$\frac{Eth^2}{2(1-v^2)}$	$\frac{E_{eq}\,t_{eq}^3}{12(1-v^2)}$

Where $t_{eq}= (3h^2)^{1/2}$

$E_{eq}= \frac{2}{\sqrt{3}}\frac{t}{h}\,E$

In anisotropic mechanical behavior, all honeycomb are closed cell structures. By identifying a unit cell and deriving the volume fraction occupied by metal, the equivalent density is given by [20]

$P_{eq} = \frac{2\varrho_t t+2\varrho_c(H-t)}{t_{eq}}$

VI. MANUFACTURING OF CORE

There are five basic ways of manufacturing honeycomb : adhesive bonding, resistance welding, brazing, diffusion bonding and thermal fusion.[4][21-24] Among these methods, most common manufacturing method is adhesive bonding. Resistance welding, brazing and diffusion bonding are only used for cores to be used at very high temperatures. There are two basic methods of manufacturing honeycomb core by adhesive bonding.

1. Expansion method
2. Corrugation method

A schematic of expansion process for honeycomb core manufacturing is shown in figure 7. Metallic sheet is cut into specified dimensions and strips of adhesive are printed on it. Adhesive is applied in such a way that adhesive prints on adjacent sheets are shifted by half of the distance between adjacent prints on the same sheet. After solidification and curing of the adhesive, HOBE block is sliced into required thickness of the core and then HOBE slice is expanded to form honeycombs.

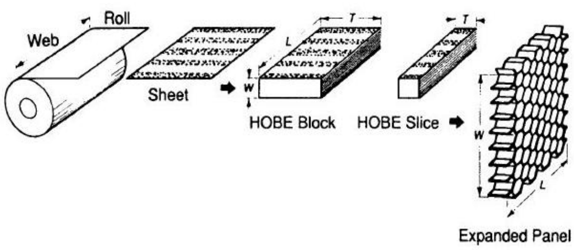


Figure 7 : Expansion method of core manufacturing

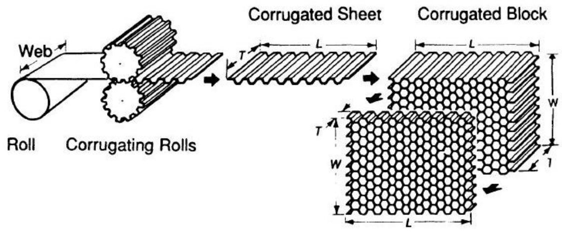


Figure 8 : Corrugation method of core manufacturing

Manufacturing of core by corrugation method is shown in figure 8. In this method corrugations are produced by pressing metallic sheet between toothed rollers. Corrugated sheets are then bonded, brazed or resistance welded to form honeycomb core. This method is generally preferred for high density cores which cannot be expanded due to thick and strong metallic sheets.[4]

VII. SANDWICH PANEL FABRICATION

The basic components of sandwich panel are core, facings and adhesive. Face sheets can be metallic or composite prepreg. Prepreg such as fiberglass, Kevlar and CFRP can be precured and bonded to honeycomb core with adhesive. Resin from the composite prepreg bonds fiber with core and therefore adhesive is not necessary for composite skins. The common methods of bonding panels are with the help of autoclaves,vacuum bagging and presses. Autoclaves and vacuum bagging are generally used for curved parts and presses for flat panels.

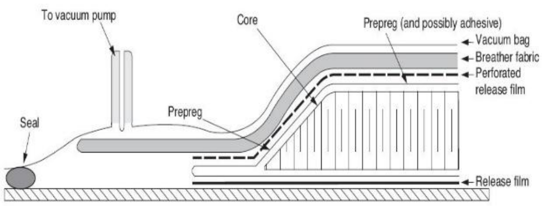


Figure 10: Autoclave or Vacuum bagging process

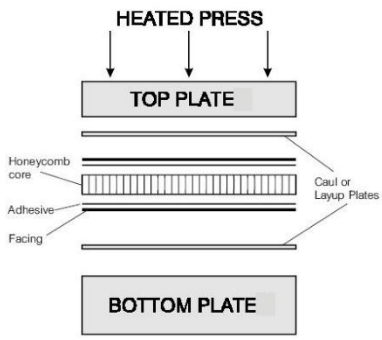


Figure 11 : Heated press method

When composite laminate is made in an autoclave generally either 121°C or 177°C cure cycle for 1 hour after heat up rate of 1.1-2.2°C per minute with pressure around 0.48 MPa is used. Similar cure cycles can be adopted for metallic facings however amount of pressure to be applied depends on compressive strength of core. Honeycomb cores cannot withstand any side pressures. Hence care must be taken to use seals on sides to prevent it from caving inward.

VIII. CONCLUSION

A summary of honeycomb sandwich panel terminologies, characteristics and properties are described. Various configurations of honeycomb cells and types of hexagonal honeycomb cores with reinforcements are studied and illustrated. To avoid modelling of actual hexagonal cells in CAD software, easier approach to model equivalent homogenized structure for FEA is described. Manufacturing processes for Honeycomb core and sandwich structures are explained.

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