

Effect of Cell Size on the Fundamental Natural Frequency of FRP Honeycomb Sandwich Panels

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ABSTRACT

In the present work, the effect of hexagonal cell size of the core on the fundamental natural frequency of FRP honeycomb sandwich panels has been analyzed both experimentally and by finite element technique. Experimental Modal tests were conducted on hexagonal cell honeycombs ranging in size from 8 mm to 20 mm maintaining the facing thickness constant at around 1 mm with two different boundary conditions viz C-F-F-F and C-F-C-F. The traditional “strike method” has been used to measure the vibration properties. The modal characteristics of the specimens have been obtained by studying its impulse response. Each specimen has been subjected to impulses through a hard tipped hammer which is provided with a force transducer and the response has been measured through the accelerometer. The impulse and the response are processed through a computer aided FFT Analyzing test system in order to extract the modal parameters with the aid of software. Theoretical investigations have been attempted with appropriate assumptions to understand the behavior of the honeycomb sandwich panels during dynamic loading and to validate experimental results. Finite Element modeling has been done treating the facing as an orthotropic laminate and Core as orthotropic with different elastic constants as recommended in the literature. The results are presented which show that the theoretical model can accurately predict the fundamental frequency and how honeycombs with different cell size will perform under dynamic loads.

Keywords: Honeycomb; Modal Testing; FRP; Impulse; Frequency

1. Introduction

Sandwich structures that employ a honeycomb core between two relatively thin skins are desirable in several engineering applications that require high strength to weight ratios. Because of their ability to absorb large amounts of energy, they are also often used as a “cushion” against external loads. Honeycomb sandwich structures are currently being used in many engineering applications, both within and outside of aerospace engineering. Lightweight honeycomb materials can be used in the construction of composite panels, shells, and tubes with high structural efficiency.

In recent years, the researches pertaining to honeycomb sandwich structures have been focused on effective numerical modeling methods, vibration properties, crashworthiness, damage, failure and impact response [1,2]. Burton and Noor [3,4] investigated the continuum modeling of honeycomb sandwich for computation. Nieh [5] also studied the processing and modeling of cellular solids for lightweight structures. Maheri and Adams [6]

investigated the damping of composite honeycomb sandwich beams in steady-state flexural vibration using the method extended from that for monolithic beams. Goldsmith *et al.* [7,8] studied the crashworthiness of honeycomb under impact loads. Neilsen [9] discussed the continuum representations of cellular solids, including honeycomb materials, to relate localized deformations to appropriate constitutive descriptions. But the role of anisotropic properties of honeycomb core in elasticity on the structure was not addressed.

Damping contributions due to its components, particular skin fiber orientations, were considered. They also investigated the dynamic shearing property of both Nomex and aluminum honeycomb core [10]. The dynamic shearing properties of honeycomb were shown to be different in various directions from static properties. It has long been realized that honeycomb materials are anisotropic in nature. The ability to predict the properties of these cellular materials depends on the knowledge of microstructural mechanism that contributes to macroscopic behavior. The traditional Nomex and aluminum cores have great capability of withstanding compression

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load in thickness (T) direction and shear load in longitudinal (L) and width (W) directions. The material properties such as elastic moduli and strengths are various in different directions, and even the compressive and tensile properties are different in the thickness-direction, primarily due to the initial deflection of cell walls. Vibration frequencies and mode shapes of honeycomb sandwich panels with various structural parameters were studied by Qunli Liu and Yi Zhao [11] using computational and experimental methods. Two computational models were used to predict the mode shapes and frequencies of honeycomb sandwich panels. Plate elements were used for honeycomb cell walls to reflect the geometric nature of the hexagonal cells. The quantitative effect of the anisotropic core on the vibration properties of the sandwich panels were studied and presented.

Most studies in the literature are related to one of the attributes (high strength/weight or increased energy absorption) mentioned above. With regard to the development of a honeycomb panels, one issue that has been overlooked is the scaling of honeycomb properties with respect to cell size. The variation in cell size may have a large influence on the dynamic properties of honeycomb panels. The current paper expands upon this study. The results from the experimental program will be presented and discussed. The theoretical literature available [12] on sandwich panels in evaluating fundamental frequency with a non-dimensional parameter will also be discussed in this work. Of interest in this study is to understand the effect of cell size on the fundamental frequency of honeycomb panels.

2. Experimental Techniques

2.1. Fabrication of Honeycomb Panels

FRP honeycomb sandwich panels have been fabricated through vacuum bag molding technique, which uses the vacuum to eliminate the entrapped air and excess resin. The adhesive used is epoxy resin LY 556 mixed with hardener HY 951. The resin and hardener is mixed in the weight ratio of 10:1. To maintain optimum strength of the matrix, the ideal resin to glass ratio is found to be 35:65. The mold used is a "hexagonally machined split molding tool" made of chromium plated mild steel. After ensuring the surface is clean and free from foreign particles, a coat of release agent is applied. A coat of resin mixture is then applied on the molding surface and the plain weave glass "E" fabric is impregnated against the first half of molding tool surface, by ensuring thorough wetting of glass cloth. Subsequently the hexagonal mandrel is placed in the respective slots by pushing the glass cloth down into the half hexagonal slot of the molding tool (**Figure 1**). Pressure is applied to the wet laid-up laminate in order to improve its consolidation. This is

achieved by sealing the wet laid up laminate with a perforated plastic film and placing an absorbent over the perforated plastic film. Above this, a film is placed and sealed which constitutes vacuum bagging process. At one corner of the bag, a port for vacuum is arranged and subjected to a pressure of 450 - 500 mm Hg is applied for 120 minutes to consolidate and to increase the inter laminar shear strength of layers.

2.2. Specimen Details

Four different cell sizes viz 8, 16, 20 and 25 mm honeycomb sandwich panels were prepared to study their influence on the dynamic characteristics. **Figure 2** below depicts the honeycomb panel preparation.

After the cure process, test specimens are cut from the size 1000 mm \times 1000 mm \times 8 mm by using a diamond-impregnated wheel, cooled by running water. The types of specimens investigated in this study are in the form of plates. The specimens are cut with effective dimensions 100 \times 100 mm to obtain cantilever condition (**Figure 3**). Similarly, another specimen was prepared for C-F-C-F condition and is as shown in **Figure 3**.

2.3. Modal Test Method

The modal characteristics of the specimen have been obtained by studying its impulse response. The specimen was fixed at one end to simulate the clamped-free-free (C-F-F-F) condition as shown in **Figure 3**. The

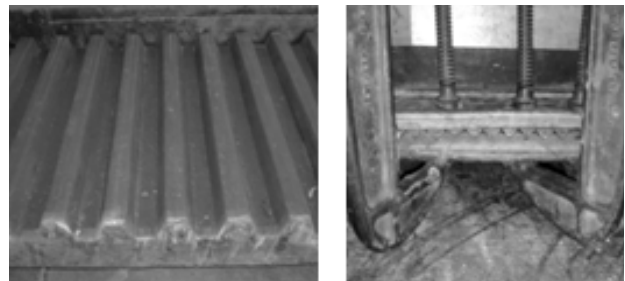
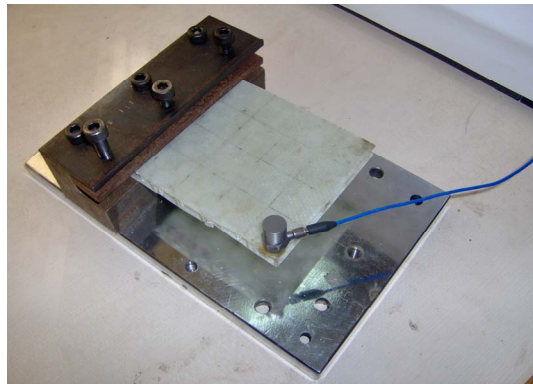


Figure 1. Mould for making the honeycomb core.



Figure 2. Preparation of honeycomb panel.



C-F-F-F condition



C-F-C-F condition

Figure 3. Specimens attached to fixture for simulating C-F-F-F & C-F-C-F condition.

specimen has been subjected to impulses through a hard tipped hammer which is provided with a force transducer (PCB make) with a sensitivity of 2.25 mV/N and the response has been measured through the accelerometer (PCB make) with an accelerometer of sensitivity 10 mV/g. The impulse and the response are processed on a computer aided FFT analyzer test system (LMS Inc.) in order to extract the modal parameters with the help of built in software.

The sandwich specimen has been subjected to impulses at 25 station locations. The response has been measured by placing the accelerometer at station 1. Due to inherent damping in the specimen, the test was restricted to fundamental vibration mode with the impact hammer. The test was conducted for all the types of specimen with two different boundary conditions and the results recorded.

3. Results & Discussions

The physical and chemical tests such as density test, Glass transition test and chemical tests conducted on FRP face sheet is indicated in **Table 1**. The geometric details of the specimens used for C-F-F-F and C-F-C-F boundary conditions in the modal tests are indicated in **Tables 2 and 3**.

The elastic properties of the fiber and resin are indicated in **Table 4**. The elastic constants of the FRP bi-woven laminate are obtained from the equations listed in

Table 1. Physical and chemical test of FRP face sheet.

Specimen designation	Specimen dimensions in mm	Volume in m ³	Mass in Kg	Density in Kg/m ³
Density as per ASTM C 271				
FRP	25.2 × 25.3 × 2.1	1.3389 × 10 ⁻⁶	2.156 × 10 ⁻³	1610
Glass content in FRP: 70%; Resin content: 30%				
Glass Transition (T_g) Temperature of FRP as per ASTM D 3418 - 99: 111.29°C				

Table 2. Geometric details of the sandwich panel (C-F-F-F).

Designation	Length × width mm	Facing thickness mm	Core cell size mm	Wall thickness mm	Core thickness mm
C-8	100 × 100	0.92	8	0.1	7.96
C-16	100 × 100	1.00	16	0.1	8.35
C-20	100 × 100	0.96	20	0.1	6.48

Table 3. Geometric details of the sandwich panel (C-F-C-F).

Designation	Length × width mm	Facing thickness mm	Core cell size mm	Wall thickness mm	Core thickness mm
C-8	100 × 100	0.95	8	0.1	7.38
C-16	100 × 100	0.94	16	0.1	8.32
C-20	100 × 100	0.98	20	0.1	6.74

the appendix and are tabulated in **Table 5**.

The elastic constants of the FRP honeycomb core have been determined as per the equations listed in the appendix and are tabulated in **Table 6**.

For the FE modeling, 20 noded SOLID 95 element was used. The elastic constants and mass density for Facing layer and core layer were appropriately given. Finite Element analysis results are indicated in **Figures 4-9** and the consolidated results of the predicted and experimental results are indicated in **Table 7**. It can be

Table 4. Elastic properties of fiber and resin of Unidirectional FRP facings.

Material	Properties	Value
Glass fiber	E_f (GPa)	74
	G_f (Gpa)	30
	ρ_f (Kg/m ³)	2600
	ν_f	0.25
Epoxy resin	E_m (Gpa)	4.0
	G_m (Gpa)	1.4
	ρ_m (Kg/m ³)	1200
	ν_m	0.40

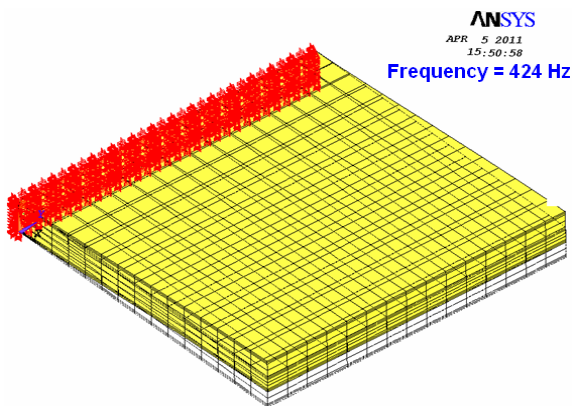


Figure 4. FE model cell size 8—C-F-F-F.

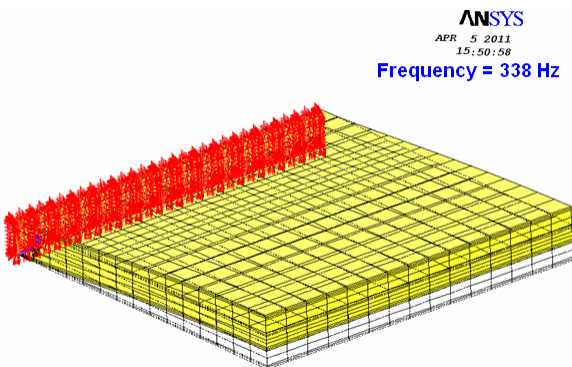


Figure 5. FE model cell size 16—C-F-F-F.

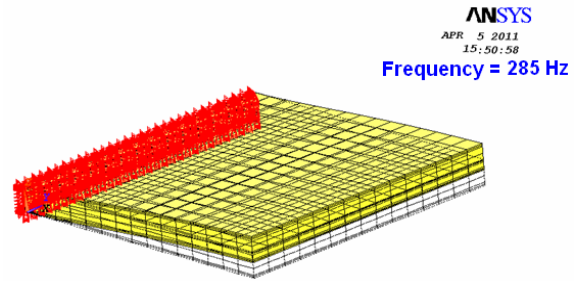


Figure 6. FE model cell size 20—C-F-F-F.

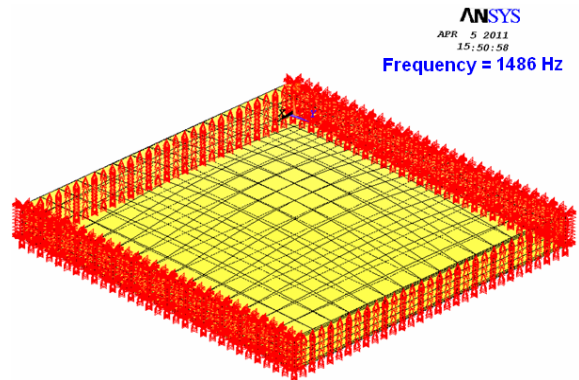


Figure 7. FE model cell size 8—C-F-C-F.

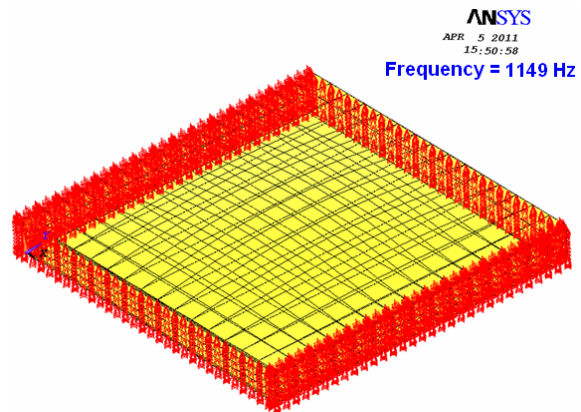


Figure 8. FE model cell size 16—C-F-C-F.

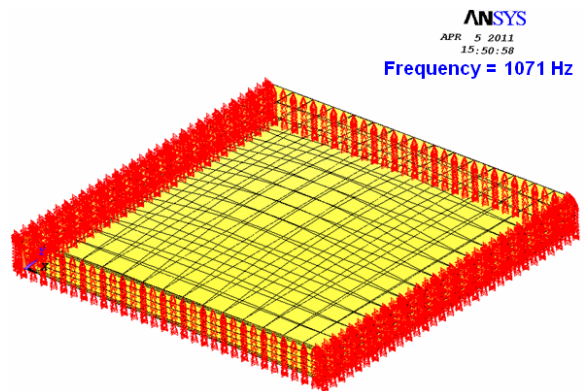


Figure 9. FE model Cell size 20—C-F-C-F.

Table 5. Elastic properties of the bi-woven FRP facings.

E_1 (N/m ²) $\times 10^9$	E_2 (N/m ²) $\times 10^9$	E_3 (N/m ²) $\times 10^9$	G_{12} (N/m ²) $\times 10^9$	G_{23} (N/m ²) $\times 10^9$	G_{13} (N/m ²) $\times 10^9$	ν_{12}	ν_{23}	ν_{13}
16.84	16.84	7.78	2.46	2.38	2.38	0.15	0.49	0.49

Table 6. Elastic properties of FRP honeycomb core.

Cell size and density (Kg/m ³)	E_x (N/m ²) $\times 10^5$	E_y (N/m ²) $\times 10^5$	E_z (N/m ²) $\times 10^8$	G_{xy} (N/m ²) $\times 10^4$	G_{yz} (N/m ²) $\times 10^6$	G_{xz} (N/m ²) $\times 10^6$	ν_{xy}	ν_{yz}	ν_{xz}
C-8 (53.7)	3.940	3.940	3.64	5.92	18.4	12.7	0.994	0.0001	0.0001
C-16 (26.8)	0.490	0.490	1.82	68.3	9.22	6.15	0.994	0.0001	0.0001
C-20 (21.47)	0.252	0.252	1.46	0.379	7.38	4.92	0.994	0.0001	0.0001

Table 7. Comparison of experimental and predicted first natural frequency.

Cell size	CFFF			CFCF		
	f_{Ansys}	f_{Actual}	Error	f_{Ansys}	f_{Actual}	Error
C-8	424	404	4.95%	1486	1492	0.04%
C-16	338	326	3.7%	1149	1291	11.9%
C-20	284	278	2.2%	1071	1194	11.7%

$$\text{Error} = \left| \frac{f_{\text{Actual}} - f_{\text{Ansys}}}{f_{\text{Actual}}} \right| \times 100.$$

seen that the predicted results are in close agreement with the experimental results, the error being less than 12%. It can be inferred that the elastic constants of the core and facings have to be rigorously worked out to predict the fundamental frequency.

4. Conclusion

The fundamental frequencies of FRP honeycomb core with different cell sizes under two different boundary conditions viz. C-F-F-F and C-F-C-F have been determined by experimental modal analysis using impulse—strike technique. Finite Element analysis with appropriate elastic constants rigorously worked out for the facings and the core predicts the fundamental frequencies which are quite close to the experimentally determined values.

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Appendix

Density of unidirectional lamina

$$\rho_c = \rho_f * v_f + \rho_m * v_m = \rho_f * v_f + \rho_m (1 - v_f - v_m) \quad (1)$$

$$\rho_{core} = \rho_{frp} \frac{8t}{c} \quad (1a)$$

Elastic constants of Uni-directional lamina

$$E_1 = E_f * v_f + E_m * v_m \quad (2)$$

$$E_2 = E_m * \left[\frac{E_f + E_m + (E_f - E_m) * v_f}{E_f + E_m - (E_f - E_m) * v_f} \right] \quad (3)$$

$$\nu_{12} = \nu_f v_f + \nu_m v_m \quad (4)$$

$$\nu_{23} = \nu_f v_f + \nu_m v_m * \left[\frac{1 + \nu_m - \nu_{12} E_m / E_{11}}{1 - \nu_m^2 + \nu_m \nu_{12} E_m / E_{11}} \right] \quad (5)$$

$$G_{12} = G_m * \left[\frac{G_f + G_m + (G_f - G_m) * v_f}{G_f + G_m - (G_f - G_m) * v_f} \right] \quad (6)$$

$$G_{23} = \frac{E_{22}}{2(1 + \nu_{23})} \quad (7)$$

Elastic constants of Bi-woven fibers

$$\left[\frac{2 E_1 (E_1 + (1 - \nu_{12}^2) E_2) - \nu_{12}^2 E_2^2}{E_1 E_1 (E_1 + 2E_2) + (1 + 2\nu_{12}^2) E_2^2} \right]^{UD} = \left[\frac{1}{E_1} \right]^{WF} \quad (8)$$

$$\left[\frac{4 \nu_{12} E_2 (E_1 - \nu_{12}^2 E_2)}{E_1 E_1 (E_1 + 2E_2) + (1 + 2\nu_{12}^2) E_2^2} \right]^{UD} = \left[\frac{\nu_{12}}{E_1} \right]^{WF} \quad (9)$$

$$\left[\frac{1 E_1 (\nu_{12} + \nu_{23} + \nu_{12} \nu_{23}) + \nu_{12}^2 E_2}{E_1 E_1 + (1 + 2\nu_{12}) E_2} \right]^{UD} = \left[\frac{\nu_{13}}{E_1} \right]^{WF} \quad (10)$$

$$\left[\frac{(1 - \nu_{23}^2) E_1^2 + (1 + 2\nu_{12} + 2\nu_{12} \nu_{23}) E_1 E_2 - \nu_{12}^2 E_2^2}{E_1 E_2 (E_1 + (1 + 2\nu_{12})) E_2} \right]^{UD} \quad (11)$$

$$= \left[\frac{1}{E_3} \right]^{WF}$$

$$\left[\frac{1}{G_{12}} \right]^{UD} = \left[\frac{1}{G_{12}} \right]^{WF} \quad (12)$$

$$\left[\frac{1 + \nu_{23}}{E_2} + \frac{1}{2G_{12}} \right]^{UD} = \left[\frac{1}{G_{13}} \right]^{WF} \quad (13)$$

Elastic constants of FRP honeycomb core [Ref. 13]

$$E_x = \left(\frac{4}{\sqrt{3}} \right) \left(\frac{t}{l} \right)^3 E_1 \quad (14)$$

$$E_y = \left(\frac{4}{\sqrt{3}} \right) \left(\frac{t}{l} \right)^3 E_1 \quad (15)$$

$$E_z = \left(\frac{t}{l} \right) E_1 \quad (16)$$

$$G_{xy} = \left(\frac{\sqrt{3}\gamma}{2} \right) \left(\frac{t}{l} \right)^3 E_1 \quad (17)$$

$$G_{xz} = \left(\frac{\gamma}{\sqrt{3}} \right) \left(\frac{t}{l} \right) G_{12} \quad (18)$$

$$G_{yz} = \left(\frac{\sqrt{3}\gamma}{2} \right) \left(\frac{t}{l} \right) G_{12} \quad (19)$$

$$\nu_{xy} = 1 \quad (20)$$

$$\nu_{xz} = 0.001 \quad (21)$$

$$\nu_{yz} = 0.001 \quad (22)$$

Nomenclature

Symbol	Description
ρ_f	Density of fiber
ρ_m	Density of matrix
ρ_c	Density of composite
v_f	Volume fraction of matrix
v_m	Volume fraction of matrix
E_f	Elastic modulus of fiber
E_m	Elastic modulus of matrix
G_f	Shear modulus of fiber
G_m	Shear modulus of matrix
ν_f	Poisson's ratio of fiber
ν_m	Poisson's ratio of matrix
E_1	Elastic modulus of FRP lamina in x direction
E_2	Elastic modulus of FRP lamina in y direction
ν_{12}	Poisson's ratio of FRP lamina in plane 1-2
ν_{13}	Poisson's ratio of FRP lamina in plane 1-3
ν_{23}	Poisson's ratio of FRP lamina in plane 2-3
G_{12}	Shear modulus of FRP lamina in plane 1-2
G_{13}	Shear modulus of FRP lamina in plane 1-3
G_{23}	Shear modulus of FRP lamina in plane 2-3
<i>UD</i>	Uni-directional composite
<i>WF</i>	Woven fiber composite
t, c	Thickness of cell wall, size of cell
l	Side of hexagon
θ	Half angle between inclined sides
γ	Technology coefficient (0.4 to 0.6)
E_x	Young's modulus of FRP honeycomb core in x direction
E_y	Young's modulus of FRP honeycomb core in y direction
E_z	Young's modulus of FRP honeycomb core in z direction
G_{xy}	Shear modulus of FRP honeycomb core in x-y plane
G_{xz}	Shear modulus of FRP honeycomb core in x-z plane
G_{yz}	Shear modulus of FRP honeycomb core in y-z plane
ν_{xy}	Poisson's ratio of FRP honeycomb core in x-y plane
ν_{xz}	Poisson's ratio of FRP honeycomb core in x-z plane
ν_{yz}	Poisson's ratio of FRP honeycomb core in y-z plane