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# Experimental modal testing of a honeycomb sandwich plate

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**Abstract.** Honeycomb structures have been widely used in several applications and industries in the past decades. Such structures have a significant role in aerospace engineering especially in building up the satellite structures. Honeycomb structures provide key benefits represented in high specific strength, high specific stiffness, and superior dimensional stability. Detailed finite element modelling of such structures is a great challenge as it involves high computational expense. Thus, equivalent modelling is mandatory. The detailed and equivalent finite element models of a honeycomb plate are introduced intensively throughout analyzing its dynamic behaviour using the modal analysis module in ANSYS workbench software. The equivalent modelling is carried out via the three-layered sandwich theory and leads to the calculation of the first four natural frequencies and the related mode shapes. An experimental modal testing of the honeycomb sandwich plate is implemented for the sake of validating the computational results. A good agreement is obtained when comparing both experimental and computational results with mean error not exceeding 5%. Finally, a parametric study is performed to relate the modal analysis results with different boundary conditions cases. The results show that the model can be a reliable basis for satellite honeycomb sandwich structures design.

## 1. Introduction

In the past decades, honeycomb sandwich structures were used extensively in many applications, especially aerospace engineering [1]. Such structures are composed of two stiff facing sheets bonded to a more flexible honeycomb core. They comprise excellent mechanical properties represented in their high strength, stiffness and low mass. However, the detailed finite element modelling (FEM) of these structures is still a great challenge due to complexity and high computational time. Many researchers in the past years tried to use different equivalent modelling approaches to overcome the aforementioned difficulties.

In 2001, Xia et al. [2] introduced three modeling theories that can be used for equivalent modeling of sandwich structures. These theories are the sandwich theory, the equivalent plate theory, and the honeycomb plate theory. The authors validated the results of the modal analysis using the three theories by comparing them with analytical work.

In 2012, A. Boudjemai et al. [3] proposed the usage of the equivalent plate theory in the FEM of a satellite honeycomb sandwich structure. They carried out modal testing in order to validate the



numerical results. They received a good agreement between experimental and numerical modal results.

In 2014, Jiang et al. [4] employed the sandwich theory during the computation of natural frequencies and their related mode shapes. They performed a dynamic testing to assess the use of sandwich theory in modeling sandwich structures with acceptable accuracy.

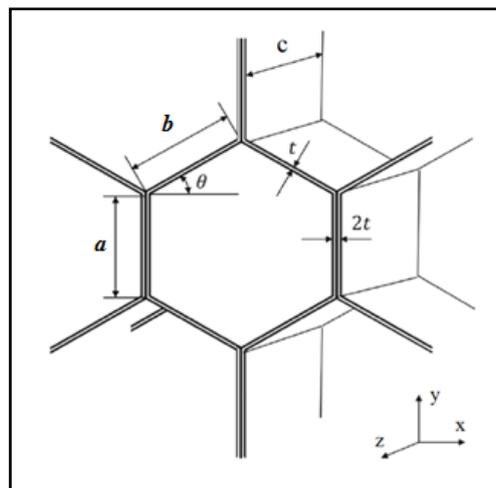
In 2017, Fu et al. [5] presented the dynamic response of a spacecraft solar blanket using the sandwich theory. They compared the results with analytical work to ensure the availability of using such theory in modeling sandwich structures.

Recently, sun et al. [6] implemented both modal testing and analysis of a honeycomb sandwich plate. Based upon results, they performed a FEM updating so as to efficiently estimate the accurate equivalent properties of the honeycomb core.

In this research, the modeling of honeycomb sandwich plate is introduced extensively via modal analysis module in ANSYS workbench using free-free boundary conditions. Detailed FEM is carried out; such model exhibits a high computational time. Consequently, an equivalent FEM is built, using the three-layered sandwich theory, to overcome such problem. Both detailed and equivalent results are validated using experimental modal testing results, where the first four natural frequencies are measured and compared to those computed numerically.

## 2. Detailed FEM of a honeycomb sandwich plate

Such type of modelling relies on representing all the geometric details of the utilized honeycomb core. These details includes the foil thickness ( $t$ ), the cell vertical length ( $a$ ), the cell inclined length ( $b$ ), and the cell angle ( $\theta$ ) as shown in figure 1.



**Figure 1.** Honeycomb core geometry.

The modal analysis is implemented on a honeycomb sandwich plate utilizing free-free boundary conditions. The mentioned plate dimensions are 400mm x 400mm x 13 mm. the plate thickness includes 2 mm thickness for each facing sheet and 9 mm for the honeycomb core thickness. Both facing sheets and core are fabricated of Aluminum alloys. The geometric and material specifications of the selected core are shown in table 1 and table 2 respectively.

**Table 1.** Geometric properties of the core

Type	Material	Cell length ( $a=b$ )	Cell thickness ( $t$ )	Cell angle ( $\theta$ )
Regular hexagon	AL-3003	4 mm	0.04 mm	$30^{\circ}$

**Table 2.**Core material specifications

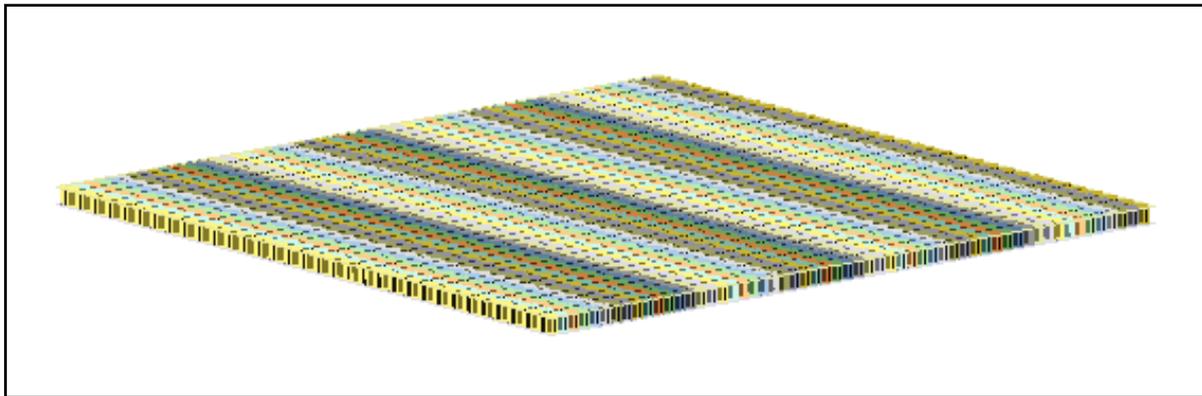
Young's modulus ( $E_c$ )	Shear modulus ( $G_c$ )	Density ( $\rho$ )
70000 MPa	27000 MPa	2700 kg/m <sup>3</sup>

The facing sheets are fabricated of AL-6061-T6, their material properties are displayed in table 3.

**Table 3.**Material properties of the facing sheets.

Young's modulus ( $E_c$ )	Shear modulus ( $G_c$ )	Density ( $\rho$ )
71000 MPa	27000 MPa	2770 kg/m <sup>3</sup>

The detailed geometry of the core is performed via computer-aided design (CAD) software and then exported to ANSYS workbench "Design Modeler section" using "parasolid.x\_t" format as shown in figure 2.

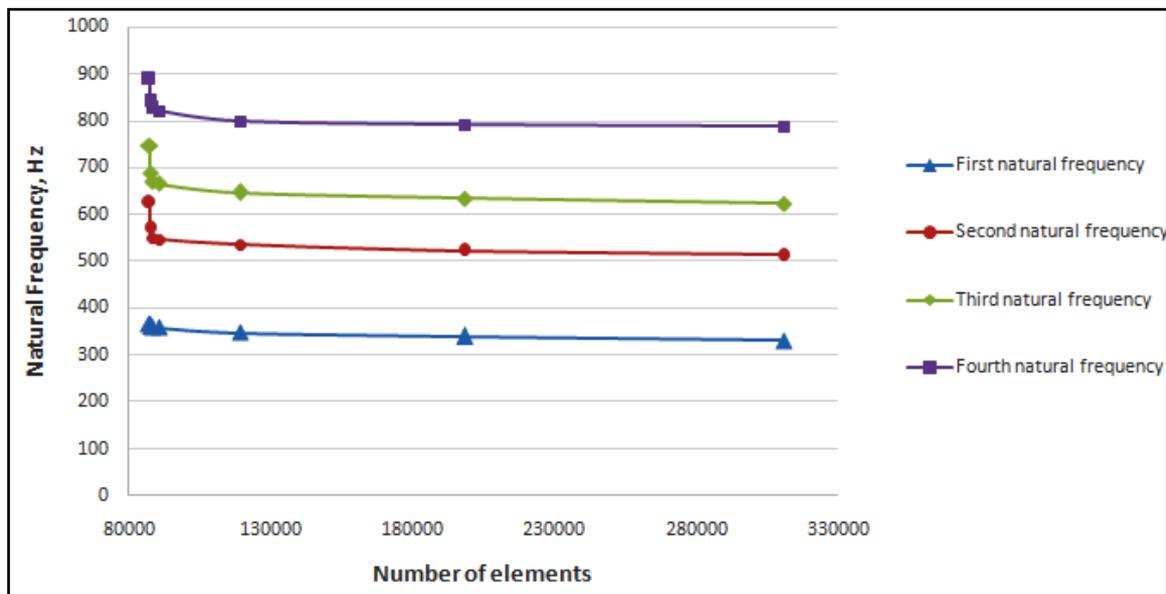
**Figure 2.**Imported detailed honeycomb sandwich plate.

Both facing sheets and core are meshed via shell finite elements "shell 181". Such element is a 4 node element with 6 degrees of freedom at each node. The Free-Free boundary conditions are employed to compute the four natural frequencies and the corresponding mode shapes. Meshing is performed using a fine mesh of element size 3 mm, where results converge and there is no more need to reduce the element size as shown in figure 3. Table 4 shows the total number of elements and nodes.

**Table 4.**Detailed model elements and nodes.

Element size, mm	Number of elements	Number of nodes
3	310643	249735

It can be noted that the CAD and FE detailed modeling is a time-consuming process and needs a computers of high computational resources.



**Figure 3.** Mesh convergence study of detailed FEM.

### 3. Equivalent FEM of a honeycomb plate

The equivalent modelling helps in solving the problems encountered during the detailed modelling of honeycomb sandwich structures. In this research, the three-layered sandwich theory is used in the honeycomb sandwich plate modal analysis using free-free boundary conditions. The main difference between sandwich theory and detailed modelling is the way of representing the honeycomb core. In this theory, the core is dealt with as homogeneous continuum with orthotropic material properties. Thus, sandwich theory needs to calculate the equivalent properties of the core. The calculation of these properties depends on the geometric properties of the core in addition to the material properties of core material as shown in table 1 and table 2.

In this research, Gibson and Ashby formulas [7], with minor modification [8, 9], are utilized to calculate the core equivalent properties as follows:

$$\rho_{eq} = \rho_c \frac{8}{3\sqrt{3}} \left(\frac{t}{a}\right) \quad (1)$$

$$E_x = E_y = \frac{4}{\sqrt{3}} \left(\frac{t}{a}\right)^3 E_c \quad (2)$$

$$G_{xy} = \frac{4}{5\sqrt{3}} \left(\frac{t}{a}\right)^3 E_c \quad (3)$$

$$u_{xy} = v_{yx} = 1 \quad (4)$$

$$E_z = \frac{8}{3\sqrt{3}} \left(\frac{t}{a}\right) E_c \quad (5)$$

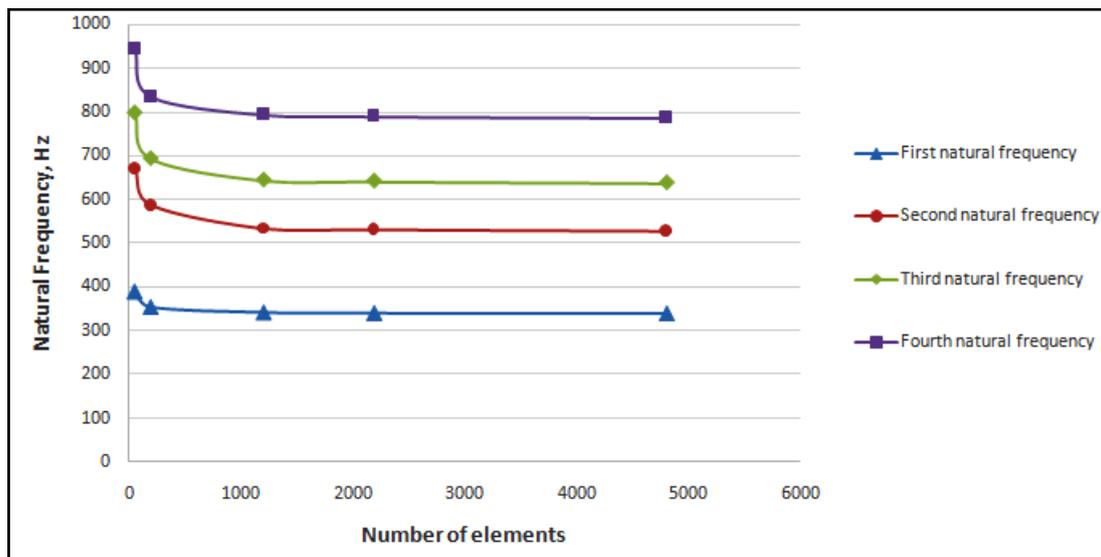
$$v_{xz} = v_{yz} \approx 0 \quad (6)$$

$$G_{xz} = \frac{1}{\sqrt{3}} \left( \frac{t}{a} \right) G_c \quad (7)$$

$$\frac{\sqrt{3}}{2} \left( \frac{t}{a} \right) G_c \leq G_{yz} \leq \frac{5}{3\sqrt{3}} \left( \frac{t}{a} \right) G_c \quad (8)$$

$$G_{yz} = \frac{\sqrt{3}}{2} \left( \frac{t}{a} \right) G_c + \frac{0.787}{(c/a)} \left( \frac{5}{3\sqrt{3}} \left( \frac{t}{a} \right) G_c - \frac{\sqrt{3}}{2} \left( \frac{t}{a} \right) G_c \right) \quad (9)$$

In order to apply the sandwich theory in the finite element modeling using ANSYS software, shell-volume-shell (SVS) approach is employed[4, 6, 10], where the facing sheets are meshed using solid finite elements "solid 186", while the core is meshed using shell finite elements "shell 181". Meshing is performed using a fine mesh of element size 10 mm, where results converge and there is no more need to reduce the element size as shown in figure 4. Table 5 shows both elements and nodes total number.



**Figure 4.** Mesh convergence study of Equivalent FEM.

**Table 5.** Equivalent model elements and nodes.

Element size, mm	Elements number	Nodes number
10	9604	32200

Based upon the aforementioned formulas, the equivalent properties of the utilized honeycomb core are estimated as shown in table 6.

**Table 6.** Equivalent properties of the core.

$\rho_{eq}$	41.56 kg/m <sup>3</sup>	$E_z$	1077.7 MPa
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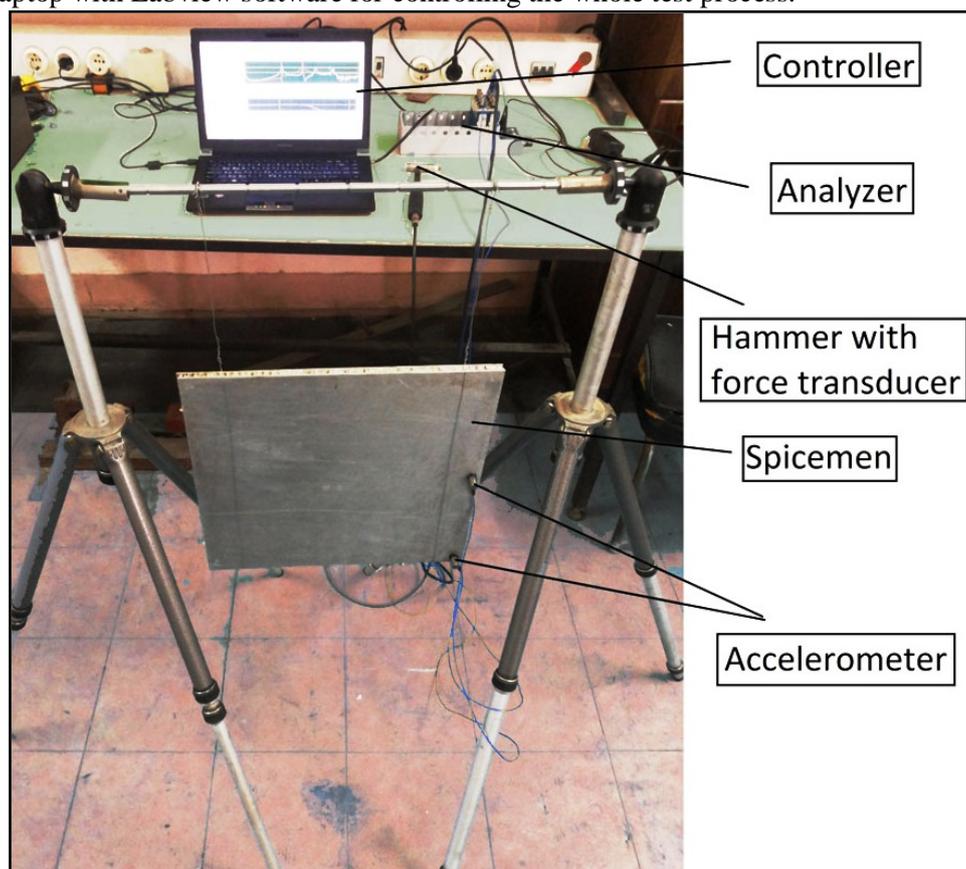
$E_x = E_y$	0.1616 MPa	$G_{xz}$	155.89 MPa
$G_{xy}$	0.097 MPa	$G_{yz}$	242.9 MPa
$u_{xy}$	1	$u_{xz} = u_{yz}$	0

#### 4. Experimental modal testing

Modal testing is carried out so as to validate the computational results of both detailed and equivalent modelling. The Free-Free boundary conditions are simulated by hanging the sandwich plate using stainless steel wires. The test configuration is shown in figure 5.

The test includes the following devices:

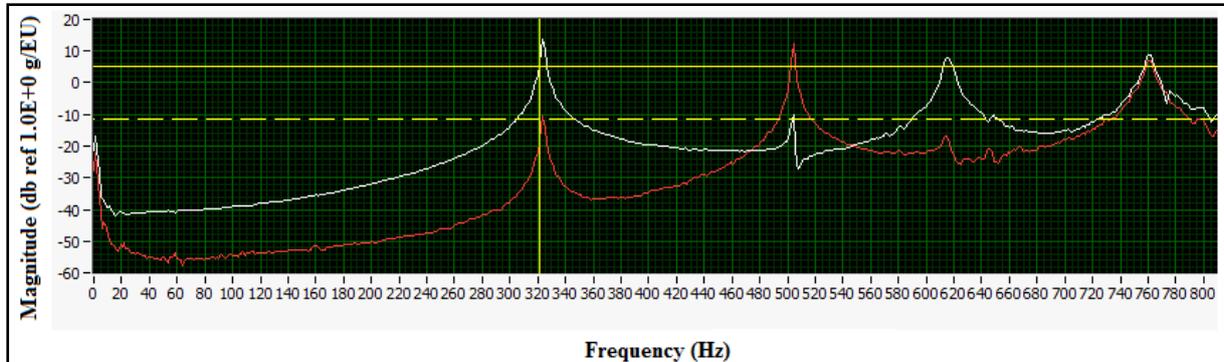
- Structure excitation using a hammer that comprises a force transducer.
- Response sensing elements using two accelerometers attached to the plate using special kind of wax. The location of such accelerometers is determined using numerical modal analysis results in the way that helps to extract the four mode shapes. This location is selected at the points of maximum deformations (corners and sides mid-distance).
- Analyzer for interpreting hammer force and accelerometers response.
- Laptop with Labview software for controlling the whole test process.



**Figure 5.** Modal testing configuration.

Eight excitation points are decided at the four corners, and the four mid points of each side. The test procedure implies performing five consecutive hammer impacts at each excitation point in order to

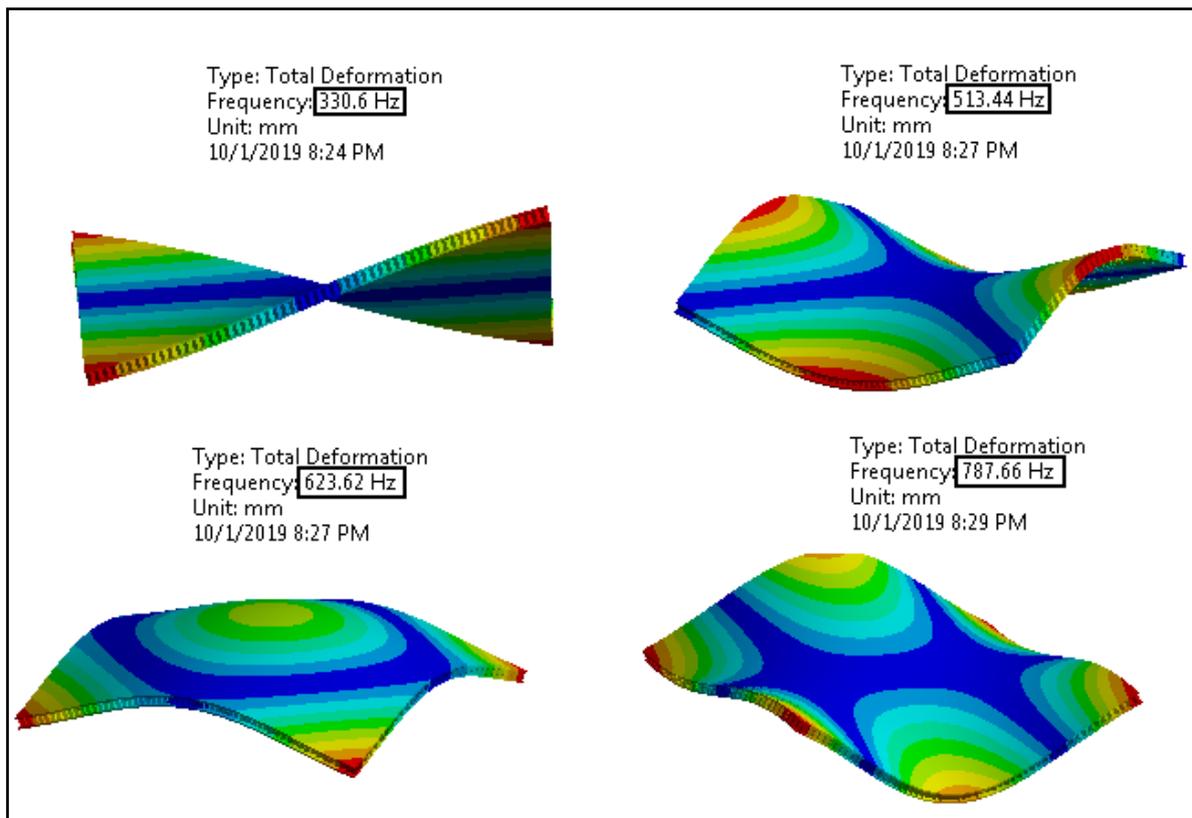
take the mean readings. The frequency response function (FRF) is recorded and the four natural frequencies are measured as shown in figure 6.



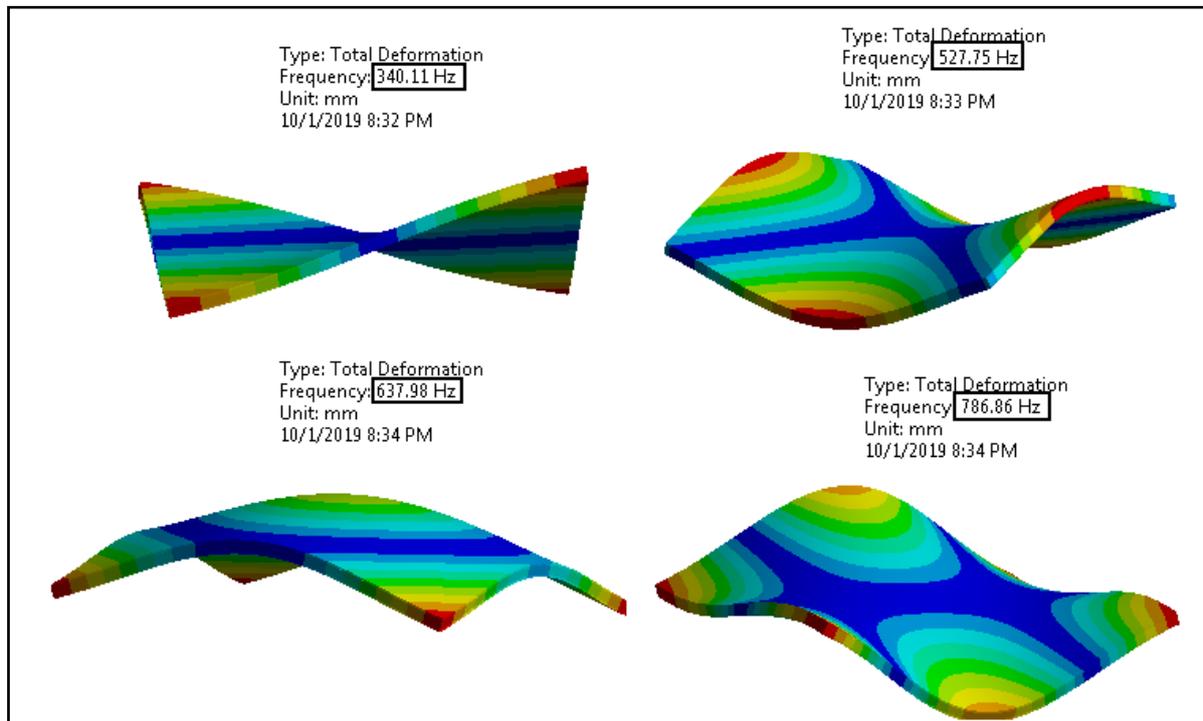
**Figure 6.**Modal testing FRF.

**5. Results comparison and discussion**

Figures 7 and 8 presents the numerically calculated natural frequencies and mode shapes using the detailed and equivalent modelling.



**Figure 7.**Detailed model results.



**Figure 8.**Equivalent model results.

The comparison of experimental and numerical results concerning the four natural frequencies is listed in table 7.

**Table 7.** Comparison of experimental and numerical modal frequencies.

Mode order	Mode Type	Experimental, Hz	Numerical, Hz	
			Detailed modelling	Equivalent modelling
First mode	Torsion	322	330.6	340.11
Second mode	Bending	504	513.44	527.75
Third mode	Bending	614	623.62	637.98
Fourth mode	Torsion	761	787.66	786.86
Mean error, %			2.403	4.41
Computational time, min.			210	1

The error of natural frequency value is calculated as follows:

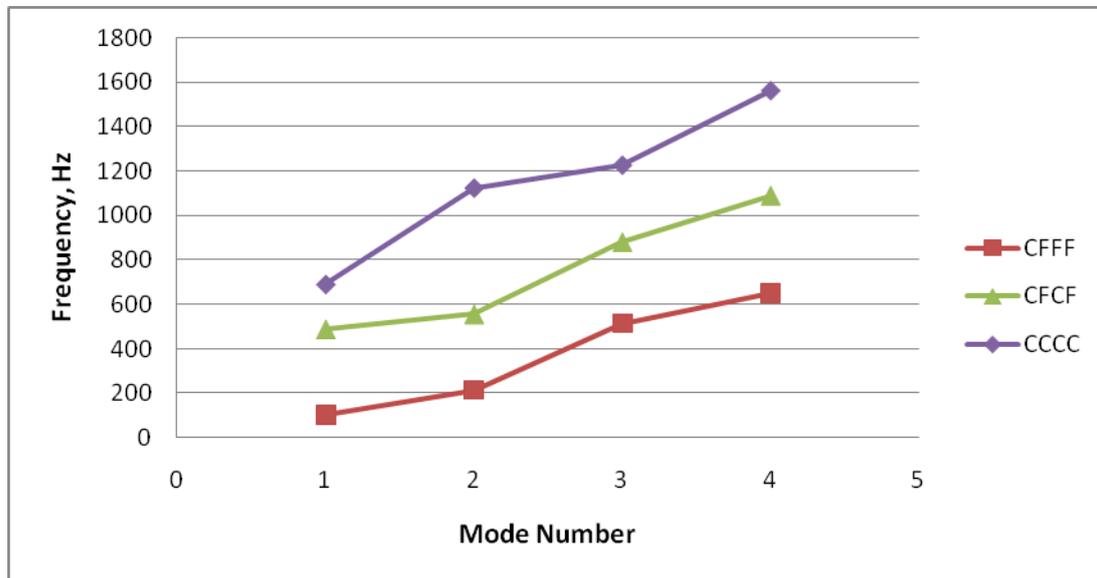
$$error = \frac{|Numerical\ frequency - Experimental\ frequency|}{Experimental\ frequency} \times 100\% \quad (10)$$

The previous results indicate clearly the good agreement between the experimental modal frequencies and the numerical ones using both types of modeling. Nevertheless, detailed modeling exhibit an extreme computational time and resources. Consequently, the use of equivalent modeling is mandatory for its acceptable accuracy and reasonable computational expense.

## 6. Boundary conditions parametric study

The main target of this study is to relate the natural frequencies of the validated honeycomb sandwich plate with different boundary conditions cases including four sides clamped (CCCC), clamped-free-

clamped-free (CFCF), and clamped-free-free-free (CFFF) cases. Equivalent model using SVS approach will be used during this study. Figure 9 shows the parametric study results.



**Figure 9.** Parametric study results.

## Conclusions

Detailed and equivalent FEM of honeycomb sandwich structures are thoroughly discussed in this article. Although detailed modelling is more precise, it undergoes a high computational time and computing resources. Hence, the utilizing of equivalent modelling in representing honeycomb sandwich structures is inescapable. The sandwich theory and its corresponding shell-volume-shell (SVS) approach achieve such modelling accurately with a mean error below 5% when compared with the experimental modal testing results. Moreover, a parametric study is carried out in order to relate the modal analysis results of the validated honeycomb plate with different boundary conditions. The results show that the proposed FEM can be a reliable basis for satellite honeycomb sandwich structures design.

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