

# OPTIMIZATION OF ELASTIC PROPERTIES OF COMPOSITE HONEYCOMB CORE BY FINITE ELEMENT METHOD

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**ABSTRACT:** Fiber Reinforced Polymers (FRP) have important role in the construction of the sandwich structures due to their advanced mechanical properties and excellent compatibility. Therefore, these structures are used in many industrial fields, such as automotive, aerospace and civil engineering. In this study, a Finite Element model for a Representative Volume Element (RVE) of the FRP honeycomb core is developed using Abaqus CAE software. Then, the developed model is optimized using a Multi-Island Genetic Algorithm through non-GUI interference with Isight software. The optimization process includes the out-of-plane elastic properties of the core as a function of the orientation angle and the number of composite layers that comprise the cells' wall of the honeycomb core. The optimization results confirmed that the FRP honeycomb core has good out-of-plane elastic properties for a certain number of layers and orientations.

**KEYWORDS:** FRP honeycomb core, multi-objective optimization, Finite Element modelling, out-of-plane elastic properties.

## 1 INTRODUCTION

Microstructural architecture significantly influences the mechanical performance of multifunctional cellular materials. The optimal microstructure is characterized by reducing weight while maintaining fundamental load-bearing capacity. Honeycomb materials are a two-dimensional arrangement of polygons that act as a periodic topological organization in a planar area. These structures are inspired by nature and are found in nature, for example, in beehives, microstructures of woods and bones (Wang & Wang, 2020; Schaedler & Carter, 2016; Zhang et al., 2015).

The honeycomb sandwich structures consist of a lightweight core and two stiff face sheets, as shown in Figure 1. Due to their potential, sandwich structures are used in numerous applications such as aerospace, automotive, marine and architecture (Al Fatlawi et al. 2020; Sutherland, 2018; Todor et al. 2017). Therefore, more studies are focused on the mechanical properties of honeycomb and its use as a core in sandwich structures. Honeycomb cores are made of Aluminum alloys or Nomex paper due to their lightweight, high strength, and good energy absorption capacity (Al Antali et al., 2017; Kundrák et al. 2019; Rodriguez-Ramirez et al., 2018).

Recently, due to its lightweight and good mechanical performances, fiber reinforced polymers composite materials have drawn remarkable atten-

tion in replacing traditional Aluminum and Nomex honeycombs. As a result, different manufacturing techniques have been used to produce FRP composite honeycomb cores (Anguita et al., 2020; Kun-Bodnár et al. 2018; Mohanty et al., 2018). Although the concept of FRP composites cores is not new, there is still a need for contemporary design and optimization methods for these kinds of structures.

Considering this, Stocchi et al. are manufactured and investigated the elastic properties of composite honeycomb cores experimentally under out-plan compression load (Stocchi et al., 2014). Also, they studied mechanical properties and failure modes of synthetic and natural fibers reinforced composite sandwich panels under three-point bending.

Vitale et al. investigated analytically and experimentally the mechanical properties and failure modes of sandwich panels made of natural and synthetic fiber reinforced polymer under three-point bending (Vitale et al., 2017). They used the vacuum assist resin transfer molding (VARTM) process with a honeycomb mold to fabricate fiber reinforced honeycomb cores. Fan et al. produced two-dimensional (2D) hierarchical cellular materials with cell walls consisting of two faces separated by a softcore (Fan et al., 2008). The study compared the mechanical properties of this structure with those of cellular materials with solid walls. They concluded that hierarchical cell walls significantly improve the mechanical properties of cellular cores. FEM is an often used technique during the optimization

(Szirbik & Virág, 2021; Hazim & Jármai, 2020; Sztankovics, 2019; Kundrák et al. 2018). Wang et al. investigated a novel honeycomb with composite laminate cell walls using Finite Element analysis (FE) and an analytical model to improve the specific stiffness. Their results showed that the analytical model has good accuracy in predicting the elastic properties of composite cores (Wang & Wang 2018).

Florence et al. used hybrid FRP to fabricate sandwich panels with a honeycomb core filled with energy absorbing materials (Florence et al., 2020). Experimental and Finite Element studies were conducted to investigate the failure mechanisms of the sandwich under in-plane compression, in-plane compression and Charpy impact tests. They concluded that the proposed sandwich structure had improved strength, specific stiffness, critical load and shear moduli. Li et al. developed a mixed numerical-experimental method for inverse solution of the equivalent material parameters of the sandwich panel using a Genetic Algorithm (Li et al., 2019). They used sandwich panel theory to extract the equivalent properties of the honeycomb core using FE analysis.

This paper introduces a practical method to evaluate and optimize the out-of-plane homogenized elastic properties of a hexagonal honeycomb core with Fiber Reinforced Polymer cells.

The structure of the study including 7 Sections: Section 2 describes a Finite Element model for a hexagonal FRP unit cell, which is a Representative Volume Element (RVE) of the honeycomb core structure. ABAQUS CAE software is used to derive the Finite Element model in this study. In Section 3, analytical solutions for the homogenized out-of-plane elastic properties of the FRP core are presented with the key equations. Then, in Section 4, the Finite Element model verification is performed by comparing the obtained results with the analytical solutions to emphasize the reliability of the proposed model. In Section 5, the optimization problem is solved using the Multi-Island Genetic Algorithm under Isight software to determine the composite layers' optimal angles that provide the best elastic properties. The optimization results are presented in Section 6. Furthermore, the obtained results were compared with the properties of Aluminum honeycomb cores (Al-3003) for the same densities. The conclusions are presented in Section 7.

## 2 FINITE ELEMENT MODELLING

### 2.1 Modelling of a unit cell

Modeling the entire core using finite elements could be a difficult or impractical approach due to the complexity and high computational cost. Therefore, a hexagonal unit cell of the honeycomb core structure with periodic boundary conditions is used to represent the behavior of the core with a reasonable computational cost. The micromechanics tool in the ABAQUS software environment is employed to evaluate the homogenized mechanical properties of the honeycomb unit cell (Duval et al., 2014). This tool assigns the appropriate loads and boundary conditions to the periodic unit cell through pre-scripting code and sequential processes to finally obtain the homogenized elastic properties. Figure (2-A) shows the entire core and the selected unit cell in 3D with the global coordinate system of the core (1, 2, 3).

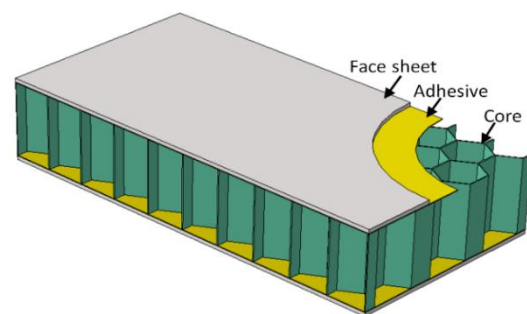


Fig.1 Honeycomb sandwich structure

The micromechanics tool specifies the fixing point for the unit cell and the reference point for applying the required load in the proper directions (i.e., normal and shear loads), as shown in Figure (2-A). S4R shell elements are utilized to build the FRP unit cell as they are accurate and efficient in solving this problem. The cell size ( $d$ ), cell angle ( $\theta$ ), wall thickness ( $t$ ), core thickness ( $b$ ), and cell side lengths ( $l$ ) and ( $h$ ) are completely defined in Figures (2-A) and (2-B). For this study, the cell has a size of  $d = 6.06$  mm and core thickness  $b = 18$  mm. The unit cell's deformed shapes and displacement responses under the three combinations of loading cases assigned by the micromechanics tool to determine the out-of-plane elastic properties ( $G_{13}$ ,  $G_{23}$  and  $E_{33}$ ) are shown in Figure 3.

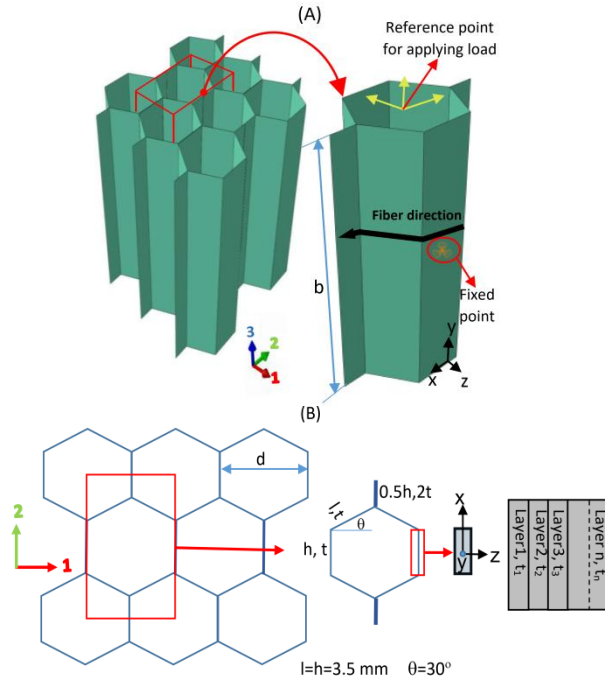


Fig. 2 3D and 2D geometry of honeycomb structure and unit cell

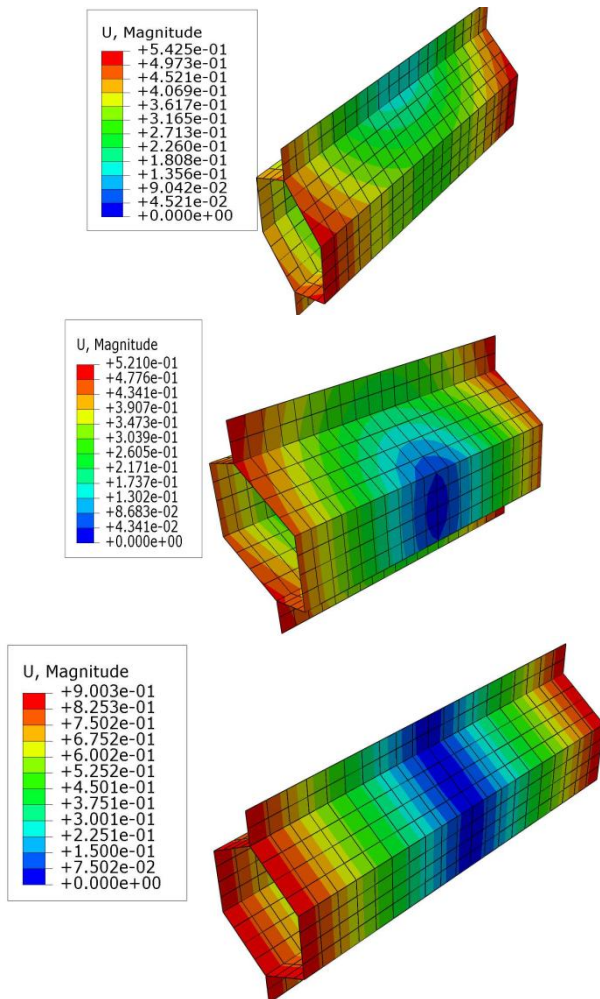


Fig. 3 Deformed shapes for three loadings cases

## 2.2 Material properties of the FRP cell

The core geometry consisting of a hexagonal honeycomb with FRP cells is considered in this study. Figure (2-B) shows the details of the layered FRP cell walls and the composite layers' local coordinates  $(x,y,z)$ . The material used is T300 carbon fiber / N5208 epoxy resin (T300/N5208), which is widely used in industrial applications. The standard properties of a lamina are listed in Table 1 (Da- babneh et al., 2018).

Table1. T300/N5208 composite properties

Material Properties	Value
Longitudinal modulus - $E_x$ [MPa]	181000
Transverse modulus - $E_y$ [MPa]	10300
In-plane shear modulus - $G_{xy}$ [MPa]	7170
Major Poisson's ratio - $\nu_{xy}$ [-]	0.28
Density - $\rho$ [kg/m <sup>3</sup> ]	1600

## 3 ANALYTICAL MODELLING

Gibson and Ashby's model can be considered a fundamental model for the analytical estimation of the homogenization properties of honeycomb cores (Lakes, 1989). Analytical expressions have been developed to deal with the effective properties of the laminated honeycomb cell wall (Florence et al., 2020; Wei et al., 2019).

In this study, the effective out-of-plane moduli are calculated by the following equation:

$$E_{33} = E_y \cdot \bar{\rho} \quad (1)$$

where:  $\bar{\rho}$  is the relative density of the core.

$\bar{\rho}$  can be calculated for the hexagonal cells by the following formula:

$$\bar{\rho} = \frac{2}{\cos\theta(1 + \sin\theta)} \left( \frac{t}{l} \right) \quad (2)$$

The shear moduli  $G_{13}$  can be calculated by the following equation:

$$G_{13} = 3.27 \cdot \frac{E_x}{(1 - \nu_{xy}\nu_{yx})} \left( \frac{t}{b} \right)^2 \left( \frac{t}{l} \right) + 0.577 \cdot G_{xy} \left( \frac{t}{l} \right) \quad (3)$$

For  $G_{23}$ , the analytical model provided two solutions as upper and lower bounds. However, these two limits coincide when the unit cell consists of regular hexagons.

The general solution for  $G_{23}$  applied in this study is the following:

$$G_{23,upper} = G_{23,lower} = \frac{(h + l \sin^2 \theta)}{(h + l \sin \theta) l \cos \theta} G_{xy} \cdot t \quad (4)$$

#### 4 VALIDATION OF THE FINITE ELEMENT MODEL

To verify the proposed Finite Element (FE) model and emphasize its predictive accuracy, the estimated homogenized effective properties for the

FRP unit cell from the simulations of FE model are compared with the effective elastic properties of the core calculated analytically using the introduced equations in Section 3.

These results are presented in Table 2 for core walls made of single, double and triple FRP composite layers. As summarized in Table 2, the percentage difference shows how accurately the FE model predicts the effective properties of the FRP honeycomb core.

Table. 2 Comparison of FEM results with analytical solutions

Layer number of the cell's wall	$G_{13}$ [MPa]		Difference [%]	$G_{23}$ [MPa]		Difference [%]	$E_{33}$ [MPa]		Difference [%]
	FEM	Analytical		FEM	Analytical		FEM	Analytical	
1 layer	198.09	198.1	0.01	339.3	330.2	2.76	966.36	910.8	6.1
2 layers	777.77	773.6	0.54	1369	1288	6.3	2319.7	2225	4.24
3 layers	1904.8	1920	0.81	2921	3175	8.01	10465	10645	1.69

#### 5 OPTIMIZATION PROCEDURE

The sandwich structure consists of two faces separated by a soft core. The thin faces carry most of the normal stresses. The role of the core is to support the faces, resist the shear stresses resulting from out-of-plane loading, and absorb energy against compressive loads. For this reason, improving the out-of-plane mechanical properties of honeycomb cores is an important objective. In this study, the mechanical properties of FRP cores are optimized, including the out-of-plane shear moduli and elastic modulus (i.e.  $G_{13}$ ,  $G_{23}$ , and  $E_{33}$ ). Since one solution can be found for each FE model, it is time consuming to determine the optimal layers' orientations that improve the core properties individually. Therefore, Isight software is used to organize the design variables (layer orientations) generated by the optimization algorithm.

In this paper, the optimization problem is solved using the Multi-Island Genetic Algorithm (MIGA). The MIGA algorithm outperforms the traditional genetic algorithm in terms of global solution capability and convergence speed. It

divides the population into multiple islands, performs the traditional genetic operations on each island separately, and then migrates individuals between islands. This allows for a more thorough search of the design space compared to a single genetic algorithm (Velden, 2010).

The modeling steps of FEM are recorded to generate the Python file with parameterized codes. The python file can be called by Isight and executed in non-GUI mode. This process increases the efficiency of the computation. The FRP wall cell was considered as one, two and three layers with different orientation angles. Since the proposed optimization for the core is a flat loading condition, the out-of-plane mechanical properties ( $G_{13}$ ,  $G_{23}$  and  $E_{33}$ ) are considered as objectives in the optimization process. The optimization problem was solved according to the flowchart shown in Figure 4.

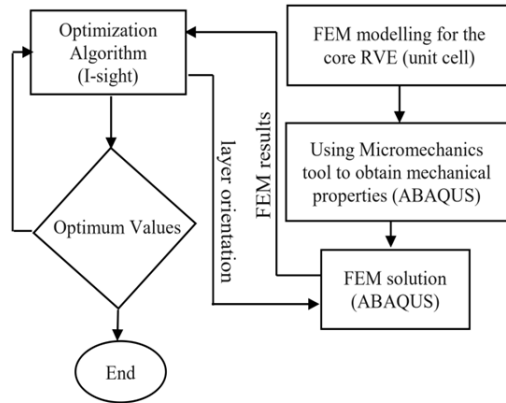


Figure 4 Flow chart of the optimization process

## 6 OPTIMIZATION RESULTS

The orientation angles and effective properties of the one, two, and three layers' cell wall FRP core are plotted in Figures 5-7. The figures show a variation of the effective properties with the values of layers angles for the FRP core.

In general, the highest out-of-plane elastic modulus ( $E_{33}$ ) is found at orientation angles close to  $[89.5^\circ]$ ,  $[87.5^\circ/-89.5^\circ]$  and  $[82^\circ/-87.5^\circ/88.5^\circ]$  for the 1-layer, 2-layers, and 3-layers cell wall, respectively. This is due to the orientation of the fibers near the out-of-plane direction of the core.

In contrast, the shear moduli ( $G_{13}$  and  $G_{23}$ ) have their lowest values for the same arrangement of layers. The transverse shear moduli record peak values at layer orientations  $[44.5^\circ]$ ,  $[45^\circ/-45^\circ]$  and  $[-42.5^\circ/44^\circ/-44.5^\circ]$  in terms of one, two and three cell wall layers, respectively. This implies that the maximum effective shear resistance for the composite cell wall can be achieved when the layers have captioned orientations.

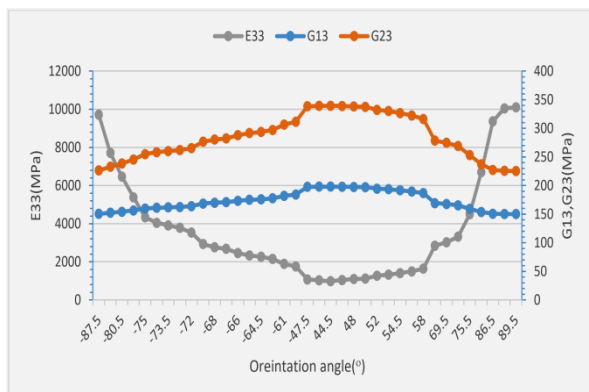


Figure 5. Mechanical properties of 1-layer FRP honeycomb core

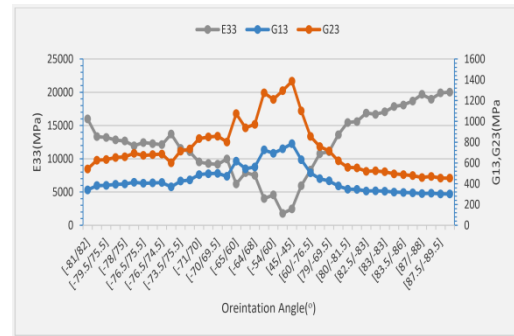


Figure 6. Mechanical properties of 2-layers FRP honeycomb core

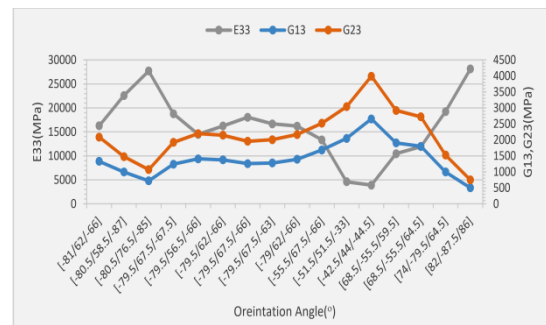


Figure 7. Mechanical properties of 3-layers FRP honeycomb core

Figures 8-10. compare the mechanical properties of the Aluminum core (Al-3003) with the maximum values of the corresponding properties of the FRP composite core at the same densities for both. The properties of the Al-3003 core were obtained using Digimat-H.C. software.

Figure 8. shows the comparison between a 1-layer FRP core and an Aluminum core, which have the same densities with a value around  $89.0 \text{ kg/m}^3$ . The shear moduli ( $G_{13}$  and  $G_{23}$ ) of the FRP core reach their maximum values at a layer orientation angle ( $44.5^\circ$ ). However, these values are only about 0.62 and 0.68 times with respect to the shear moduli of the Aluminum core. Therefore, a significant reduction in  $G_{13}$  and  $G_{23}$  was observed for the single-layer FRP cell wall compared to the Aluminum wall. In contrast, the maximum  $E_{33}$  value is increased by 4.47 times compared to the  $E_{33}$  value of the Al-3003 core.

Figure 9. shows a comparison between a 2-layers FRP core and Al-3003 with a density of  $178.9 \text{ kg/m}^3$ . Compared to the Aluminum core, the out-of-plane elastic properties show a concrete improvement, with the maximum values of  $G_{13}$ ,  $G_{23}$ , and  $E_{33}$  reaching 1.23, 1.40, and 4.43 times of the corresponding properties of the Al-3003 core.

The same scenario was performed with a 3-layers FRP honeycomb core and Al-3003 with a density of about  $268.0 \text{ kg/m}^3$ . As it can be seen, the FRP core has better effective properties than the Al-



3003 core, with  $G_{13}$ ,  $G_{23}$ , and  $E_{33}$  achieving 2.78, 2.70, and 4.19 times, respectively.

As can be seen in Figures 5-7, the stiffness moduli ( $G_{13}$  and  $G_{23}$ ) of the FRP core are inversely proportional to  $E_{33}$ . This means that the improvement of one property ( $E_{33}$ ) is at the expense of the others ( $G_{13}$  and  $G_{23}$ ). Therefore, the selection of the efficient design (layers angles) from the pool of feasible design points obtained through the optimization process should meet the requirements of the final sandwich structure and the predefined loading conditions.

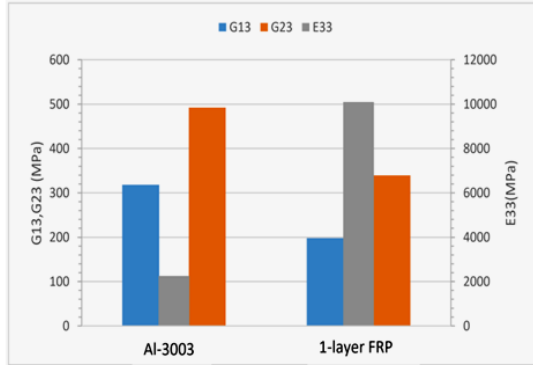


Figure 8. Mechanical properties of 1-layer FRP and Al-3003 honeycomb core

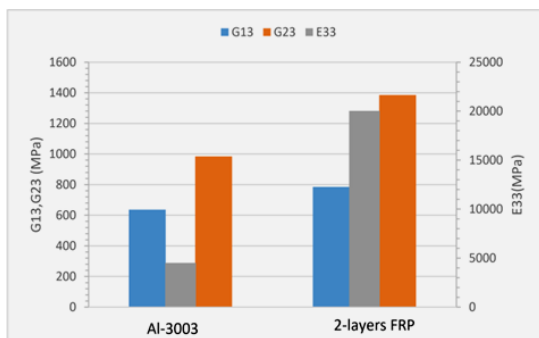


Figure 9. Mechanical properties of 2-layers FRP and Al-3003 honeycomb core

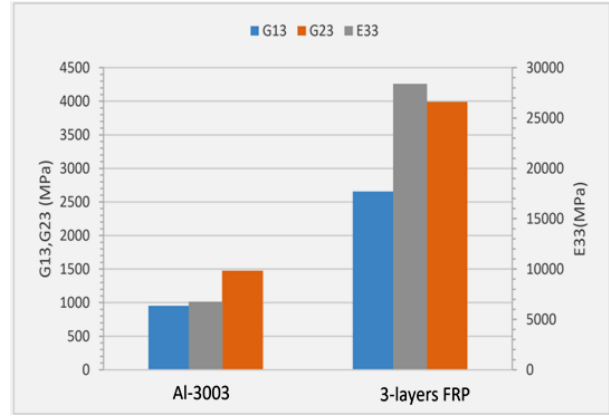


Figure 10. Mechanical properties of 3-layers FRP and Al-3003 honeycomb core

Table 3 represents an attempt to find a compromise between the properties and obtain the best mechanical properties for the FRP cores with the same density of the corresponding Al-3003 cores. The FRP-Al ratios reflect the improvement or deterioration of the properties of the FRP honeycomb cores compared to the Al-3003 ones at the same densities. We can find that for a 1-layer, only  $E_{33}$  can be improved; however,  $G_{13}$  and  $G_{23}$  are about half of the corresponding values for Al-3003. In comparison, the wall cell with 2-layers increases  $G_{23}$  and  $E_{33}$  compared to the Al-3003 core when the orientation angles are  $[60^\circ/-63.5^\circ]$ , while  $G_{13}$  is close to that of Al-3003. The 3-layer FRP core with the structure  $[68.5^\circ/-55.5^\circ/59.5^\circ]$  significantly improves the properties compared to a counterpart of Al-3001.

Table. 3 Comparison mechanical properties of Aluminum and FRP composite cores of equal densities

Property	Al-3003	FRP 1-layer/ [87.5°]	Ratio FRP/Al	Al-3003	FRP 2-layers/ [60°/-63.5°]	Ratio FRP/Al	Al-3003	FRP 3-layers/ [68.5°/-55.5°/59.5°]	Ratio FRP/Al
Wall thickness [mm]	0.0745	0.127	-	0.149	0.254	-	0.223	0.381	-
Core density $\rho$ [kg/m <sup>3</sup> ]	89.38	89.47	1	178.93	178.77	1	268.39	268.15	1
$G_{13}$ [MPa]	318.32	150.472	0.47	636.64	630.902	0.99	954.96	1904.84	1.99
$G_{23}$ [MPa]	492.1	225.839	0.46	984.19	1100.77	1.12	1476.28	2920.64	1.98
$E_{33}$ [MPa]	2258	9695.68	4.29	4515.9	5943.89	1.32	6773.87	10465.3	1.54

## 7 CONCLUDING REMARKS

The paper presented a comprehensive study of the out-of-plane elastic properties of FRP honeycomb cores. In the first part, the newly developed Finite Element model for composite honeycomb unit cell was introduced. The micromechanics tool in the Abaqus CAE environment was used to obtain the homogenized properties of the investigated core.

In the second part of the article, analytical solutions were carried out to determine the homogenized properties of the core.

Then, the analytical results were compared with the results of the numerical simulation in order to validate the correctness of the Finite Element model. The results show that the Finite Element model has good agreement in predicting the out-of-plane elastic moduli of the FRP honeycomb core.

In the third part, an optimization process was carried out using the numerical model and Isight software to achieve an optimal orientation of the layers that gives the best elastic properties of the FRP core. The optimization results show that the transverse shear moduli ( $G_{13}$ ,  $G_{23}$ ) and the elastic modulus ( $E_{33}$ ) are in conflict, where an increase on one side (i.e.  $G_{13}$ ,  $G_{23}$ ) leads to a decrease on the other one (i.e.  $E_{33}$ ) and vice versa.

The main conclusions and contributions of the study are the following:

- (1) The use of FRP materials in the fabrication of honeycomb cores provides the flexibility to enhance certain properties by changing the angles of the layers, which is not possible with isotropic materials such as Aluminum. This offers an exceptional opportunity to develop customized honeycomb cores for a specific industrial application, such as construction structures.
- (2) A wide range of constituent materials (i.e. fibers and matrices) can be used during the construction of sandwich structures. The optimization process can be performed at the micro-level of the honeycomb core, resulting in sandwich structures being designed with less computational and experimental effort.
- (3) Compared the FRP honeycomb cores to metal cores, the lower density, higher stiffness, lower thermal deformation, and compatibility with composite face sheets are the main advantages of FRP honeycomb cores.
- (4) The three elastic properties ( $G_{13}$ ,  $G_{23}$  and  $E_{33}$ ) are significantly improved as the number of composite layers increased due to the increasing wall cell thickness and thus the relative density of the core.

## 8 ACKNOWLEDGEMENTS

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## 10 NOTATION

The following symbols are used in this paper:

- $b$  = core thickness;
- $d$  = cell size;
- $E_x$  = longitudinal modulus of composite layer;
- $E_y$  = transverse modulus of composite layer;
- $E_{33}$  = core modulus of elasticity in out-of-plane;
- $G_{xy}$  = in-plane shear modulus of composite layer;
- $G_{13}$  = out-of-plane shear modulus in 1,3 plane;
- $G_{23}$  = out-of-plane shear modulus in 2,3 plane;
- $l, h$  = cell side lengths;
- $t$  = cell wall thickness;
- $\theta$  = cell angle;
- $\rho$  = density  $\text{kg/m}^3$  of composite layer;
- $\bar{\rho}$  = relative density of the honeycomb core;
- $\nu_{xy}, \nu_{yx}$  = Poisson ratios of the composite layer.