Finite element analysis of plastic hollow core sandwich composites

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Abstract. Applications of sandwich composites are increasing as they continue to develop. The reason for the growth in development and the rising demand for sandwich composites in numerous industries is due to its ability to achieve high stiffness and strength, while simultaneously being lightweight in comparison to traditional materials. 3D printed plastic hollow core sandwich composites were focused on in this study where a bioplastic, Polylactic Acid (PLA), was compared to a conventional plastic, Polypropylene (PP). The study investigated the effects of varying core and face sheet parameters on the mechanical properties of 3D printed plastic core sandwich composites to obtain the optimum sandwich composite structure. A finite element model was developed in ANSYS Workbench to conduct the study. Numerical results were compared with experimental results, and both results revealed that the mechanical properties of sandwich composite structures are certainly influenced by the core and face sheet parameters. An optimum sandwich composite structure cannot be defined for a general case, as it depends on the application for which it is being designed. Hence, different optimum structures were determined for different desired mechanical properties.

1. Introduction
As composites continue to evolve, many industries nowadays are utilising the advantages of composite materials for different applications which traditional materials such as metals and concrete are not able to offer. The main advantage of composite materials is the ability to achieve high strength and stiffness, while simultaneously being lightweight, and this is the reason for the growth in development and the rising demand of composite materials in several markets globally [1]. Composites materials are being used in different high-performance applications, such as aerospace (aircraft wings), automotive, marine, healthcare (medical exterior prosthetics), building structures and many other applications. This study focused on investigating the effects of varying core and face sheet parameters on the mechanical properties of 3D printed plastic core sandwich composites to obtain the optimum sandwich composite structure.

A typical sandwich composite consists of two relatively thin but stiff face sheets, which are separated by a relatively thick lightweight core. A layer of adhesive bonds the face sheets and the core together. The purpose of a sandwich composite structure is to achieve a strong, stiff and simultaneously light component [2]. There are three types of cores that are usually used in sandwich composites, which are honeycomb, balsa and foam cores [3]. The core material usually is low in strength, however, it provides a high bending stiffness to the overall sandwich composite due to its thickness, while keeping the overall density low. The material of the core is decided based on what application it is being used for [4]. Honeycomb cores, inspired by honeycombs built by bees, are widely used due to its high strength to weight ratio and high compressive strength [5]. This study focused on 3D printed plastic honeycomb
cores with varying parameters, including cell shape, cell size, core orientation, core material and core thickness. The face sheets can be constructed of various materials and can be a composite itself. Glass, carbon and natural fibre reinforced polymers (FRP), and metals such as aluminium are commonly used face sheet materials [6,7]. In this study, glass and coir fibre reinforced epoxy resin was used.

Many studies in regards to sandwich composites have been done previously, however, majority of them have been done using metallic materials for the core and face sheets. Therefore, there is very limited information available when it comes to plastic sandwich composites, which can be expanded by exploring knowledge gaps. This study investigated the mechanical properties of sandwich composites made with 3D printed plastic cores, with primary focus on a bioplastic core material. The results were utilised to define optimum sandwich composite structure characteristics, which can be applied to different applications. The principal objective of this study is to investigate the effects of varying core and face sheet parameters on the mechanical properties of plastic hollow core sandwich composites by developing a finite element (FE) model to analyse and obtain characteristics of an optimum sandwich composite structure.

2. Materials and methods

Along with analytical and experimental methods, finite element analysis has also become a common method for modelling and analysing the behaviour of different materials and geometries, including composite materials and structures. As this paper aims to study the effects of varying core and face sheet parameters on the mechanical properties of the sandwich composite, finite element models were developed in ANSYS Workbench and the parameters that were varied during the simulations include: cell shape, cell size, core orientation, core thickness, face sheet thickness, and core material. While an individual parameter was being varied for analysis, all other parameters were kept constant. Hence, a default geometry was decided in which each parameter was varied sequentially. Table 1 provides details of the parameters that were chosen for the default geometry. A total of eighteen different FEA simulations were run for the variations in the core and face sheet parameters. Table 2 shows the different parameter variations used in the study. All PLA parts were printed at 220°C printing temperature and printing speed of 35mm/s.

| Table 1. Default geometry parameters. |
|--------------------------------------|
| **Default Geometry**                 |
| Cell Shape                           | Hexagonal                       |
| Cell Size                            | 8mm                              |
| Core Orientation (θ)                 | 30° (regular hexagon)           |
| Core Thickness                       | 10mm                             |
| Face Sheet Thickness                 | 4mm                              |
| Core Material                        | PLA                              |

This study only focuses on simulating a three-point bending scenario. A three-point bending test consists of a rectangular or flat cross-section specimen with two supporting pins and one loading pin. The supporting pins are mounted underneath the specimen at a distance, which is called the span length, while the loading pin is positioned above and in the middle of the specimen for a force to be applied. The complete FE model can be seen in Figure 1. The way that the three pins are mounted allows free rotation about the axis parallel to the pin axis, as well as the axis parallel to the specimen axis. A bending or flexure test produces tensile stress on the convex side of the specimen and compressive stress on the concave side. An area of shear is formed along the mid-line. This shear stress must be minimised by controlling the specimen’s span to depth ratio (span length divided by height) to ensure that the primary failure occurs due to the tensile or compressive stress. The force required to bend the specimen under three-point loading conditions can be determined from this test. It also provides values for the flexural
modulus, flexural stress and flexural strain of the material. A bending stress-strain curve can be plotted using the data obtained from the test.

Table 2. Parametric study variations (all dimensions are in mm).

| Parameter        | Cell Shape | Cell Size | Cell Orientation | Core Thickness | Face Sheet Thickness | Core Material |
|------------------|------------|-----------|-------------------|----------------|----------------------|--------------|
|                  | Hexagonal  | 4         | 30°               | 10             | 4                    | PLA          |
|                  |            | 8         | 30°               | 10             | 4                    | PLA          |
|                  |            | 10        | 30°               | 10             | 4                    | PLA          |
|                  |            | 12        | 30°               | 10             | 4                    | PLA          |
|                  | Circular   | 4         | 30°               | 10             | 4                    | PLA          |
|                  |            | 8         | 30°               | 10             | 4                    | PLA          |
|                  |            | 12        | 30°               | 10             | 4                    | PLA          |
| Core Orientation | Hexagonal  | 8         | 10°               | 10             | 4                    | PLA          |
|                  | Hexagonal  | 8         | 20°               | 10             | 4                    | PLA          |
|                  | Hexagonal  | 8         | 30°               | 10             | 4                    | PLA          |
|                  | Hexagonal  | 8         | 40°               | 10             | 4                    | PLA          |
|                  | Hexagonal  | 8         | 50°               | 10             | 4                    | PLA          |
| Core Thickness   | Hexagonal  | 8         | 30°               | 10             | 4                    | PLA          |
|                  | Hexagonal  | 8         | 30°               | 15             | 4                    | PLA          |
|                  | Hexagonal  | 8         | 30°               | 20             | 4                    | PLA          |
| Face Sheet Thickness | Hexagonal  | 8         | 30°               | 10             | 2                    | PLA          |
|                  | Hexagonal  | 8         | 30°               | 10             | 3                    | PLA          |
|                  | Hexagonal  | 8         | 30°               | 10             | 4                    | PLA          |
|                  | Hexagonal  | 8         | 30°               | 10             | 5                    | PLA          |
| Core Material    | Hexagonal  | 8         | 30°               | 10             | 4                    | PLA          |
|                  | Hexagonal  | 8         | 30°               | 10             | 4                    | PP           |

Figure 1. Finite element model of 3 point bending of sandwich panel.
The sandwich composite geometries were created in SolidWorks, however, all models were imported to and simulated under three-point bending in ANSYS Workbench. To be able to import the geometries into ANSYS Workbench, the SolidWorks files were converted to STEP file format. Each sandwich composite model created in Solidworks consisted of three main parts: honeycomb core, top face sheet, and bottom face sheet. The interfaces of the face sheets and the core are modeled as rigid contact with no slip or friction. Modelling and analysis of the sandwich composite were performed using an elastic model, i.e. the materials were defined with an elastic definition by inputting the density, modulus of elasticity and Poisson’s ratio values for each material. The material properties are listed in Table 3. Material properties of the printed core and face sheets are obtained by three-point bending and tensile testing.

### Table 3. Material properties used in the FE model.

| Part        | Material            | Density (kg/m³) | Modulus of Elasticity (GPa) | Poisson’s Ratio | Bulk Modulus (GPa) | Shear Modulus (GPa) |
|-------------|---------------------|-----------------|----------------------------|-----------------|-------------------|---------------------|
| Core        | Polylactic Acid     | 1240            | 6.10                       | 0.390           | 9.24              | 2.19                |
|             | Polypropylene       | 900             | 1.22                       | 0.416           | 2.42              | 4.31                |
| Face Sheets | Glass and Coir FRP | 1860            | 1.50                       | 0.315           | 1.35              | 5.70                |
| Rollers    | Structural Steel    | 7850            | 200.00                     | 0.300           | 1.67              | 7.69                |

3. **Results and discussions**

To be able to conduct the parametric study, it was first necessary to validate the FE model using experimental results. For the sandwich composite samples used in experimental testing, the core was fabricated from PLA using 3D printing, and the face sheets were fabricated from epoxy reinforced with randomly oriented glass and coir fibre using hand lay-up technique. Load vs. deflection graphs have been plotted for both experiments and finite element simulations and selected results presented in Figure 2 show good agreements between experiments and FE simulations. The differences between experimental and numerical results are mainly due to variation of properties of 3D printed materials as well as assumptions and simplifications in the FE model.

Parametric studies were then conducted after FE model validation. Based on FE results presented in Figure 3, for all cell sizes, the circular cell core requires a higher bending load in comparison to the hexagonal cell cores for the same amount of deformation. The bending load decreases with increasing cell size for both cell shapes, except for the 12mm cell cores, which have almost the same bending loads as the 10mm cell cores (when comparing within their respective cell shapes).
Figure 2. Load vs deflection for 10mm circular cell core (left), and hexagonal cell core (right).

Figure 3. Bending load (left), and equivalent stress (right) for different cell shapes and sizes.

From the FEA stress contour plots, the maximum stress is acting on the core edges. This means that failure is likely to occur in the core first. Figures 4 and 5 show a close up of the stress contours for the 8mm hexagonal cell core and 8mm circular cell core, respectively. The 4mm hexagonal cell core experiences the lowest stress, with a value of 68.31 MPa. Maximum stress of 113.96 MPa was observed in the 4mm circular cell core sandwich composite.
As can be seen in Figure 6, the lowest equivalent elastic strain was observed in the 4mm circular cell core, while the highest strain was observed in 12mm circular cell core. A higher elastic modulus indicates better resistance to elastic deformation, i.e. higher stiffness. Within the circular cores, the 4mm cell core exhibited the highest elastic modulus (4208 MPa), while the 12mm cell core exhibited the lowest elastic modulus (3807.9 MPa). Within the hexagonal cores, the 8mm cell core exhibited the highest elastic modulus (2541.2 MPa), while the 4mm cell core had the lowest elastic modulus (2348.1 MPa). A higher modulus of elasticity is not necessarily the optimum case, as some applications may require low stiffness. Hence, the cell shape and size corresponding to both the highest and the lowest modulus of elasticity can be optimal depending on the application.

The parametric study results for variation of core angle are presented in Table 4 and show that the core with a 10° cell angle requires the highest bending load out of all the cell angles analysed for a 10mm deformation. The bending load decreases with increasing cell angle. Once again, the FEA stress contour plots for all core orientations display maximum stress concentrated on the core edges, especially at the top and bottom tips of the hexagonal cells. The sandwich composite with the 40° cell angle core experiences the lowest stress of 56.19 MPa, and the 20° cell angle core experiences the highest stress of 111.26 MPa. The lowest equivalent elastic strain was observed in the 10° cell angle core, while the highest strain was observed in 30° cell angle core. The highest elastic modulus (4059.1 MPa) was
observed in 20° cell angle core, and the lowest elastic modulus (1904.9 MPa) was observed in the 50° cell angle core. It is also observed that the elastic modulus of the 10° and 20° cell angle core, and the 40° and 50° cell angle core are similar to each other, while the elastic modulus value of the 30° cell angle core is in between.

Also, by changing the core material, as can be seen in Figure 7, a higher bending load is required by the PLA core sandwich composite compared to the PP core sandwich composite. The bending load of the PLA core is 25.5% higher than that of PP core. Equivalent stress of 77.88 MPa is observed in the PLA core, which is 89.7% higher than the stress of 41.05 MPa in the PP core. Unlike the PLA core sandwich composite, the maximum stress in the PP core sandwich composite was observed in the face sheets rather than the core. This means that failure is likely to occur in the face sheet first.

As listed in Table 5, the bending load increased by 77.3% and 53.6% as the core thickness was increased from 10mm to 15mm and 15mm to 20mm, respectively. The 20mm core thickness sandwich composite experienced the maximum equivalent stress of 149.32 MPa while the 10mm core thickness sandwich composite experienced the lowest stress of 77.88 MPa. The lowest equivalent elastic strain was observed in the 10mm thick core, while the highest strain was observed in 20mm thick core. The 20mm thick core exhibited the highest elastic modulus (2862.5 MPa), while the 10mm thick core exhibited the lowest elastic modulus (2541.2 MPa).

Table 4. Results from variation of core orientation.

| Core Orientation (cell angle) | Maximum Bending Load (N) | Maximum Equivalent (von Mises) Stress (MPa) | Maximum Equivalent Strain | Modulus of Elasticity (MPa) |
|------------------------------|--------------------------|------------------------------------------|--------------------------|----------------------------|
| 10°                          | 1296.7                   | 109.08                                   | 0.0283                   | 3989.1                     |
| 20°                          | 1267.4                   | 111.26                                   | 0.0283                   | 4059.1                     |
| 30°                          | 1203.6                   | 77.88                                    | 0.0291                   | 2541.2                     |
| 40°                          | 1180.8                   | 56.19                                    | 0.0289                   | 1934.0                     |
| 50°                          | 1125.0                   | 56.76                                    | 0.0288                   | 1904.9                     |

Figure 7. Load vs deflection (left), and equivalent stress vs strain (right) for different core materials.
Table 5. Results from variation of core thickness.

| Core Thickness (mm) | Maximum Bending Load (N) | Maximum Equivalent (von Mises) Stress (MPa) | Maximum Equivalent Strain | Modulus of Elasticity (MPa) |
|---------------------|--------------------------|---------------------------------------------|---------------------------|-----------------------------|
| 10                  | 1203.6                   | 77.88                                       | 0.0291                    | 2541.2                      |
| 15                  | 2134.4                   | 113.81                                      | 0.0391                    | 2774.1                      |
| 20                  | 3278.5                   | 149.32                                      | 0.0498                    | 2862.5                      |

Table 6 shows the effect of variation of face sheet thickness on the results. Similar to the pattern observed with the variation of core thickness, the bending load increases as the face sheet thickness is increased. The maximum equivalent stress of 81.68 MPa was observed in the 5mm thick face sheet, while the lowest stress of 74.68 MPa was observed in the 2mm thick face sheet. The lowest equivalent elastic strain was observed in the 2mm thick face sheet, while the highest strain was observed in 5mm thick face sheet. Unlike the results from varying core thickness, the thinner face sheet (2mm) exhibited the highest elastic modulus (2562.4 MPa), while the thickest face sheet (5mm) exhibited the lowest elastic modulus (2413.3 MPa). However, there is no pattern in the elastic modulus values that can be obtained by these results.

Table 6. Results from variation of face sheet thickness.

| Face Sheet Thickness (mm) | Maximum Bending Load (N) | Maximum Equivalent (von Mises) Stress (MPa) | Maximum Equivalent Strain | Modulus of Elasticity (MPa) |
|--------------------------|--------------------------|---------------------------------------------|---------------------------|-----------------------------|
| 2                        | 463.5                    | 74.68                                       | 0.0278                    | 2562.4                      |
| 3                        | 796.3                    | 74.96                                       | 0.0298                    | 2436.8                      |
| 4                        | 1203.6                   | 77.88                                       | 0.0291                    | 2541.2                      |
| 5                        | 1713.1                   | 81.68                                       | 0.0325                    | 2413.3                      |

4. Conclusions

The results obtained from FEA can be utilised to determine the characteristics of an optimum sandwich composite structure that would provide optimum mechanical properties. However, an optimum sandwich composite structure cannot be defined for a general case, as it depends on the application for which it is being designed. For example, some applications may require the stiffness to be maximised for minimal deformation, whereas some applications may require minimising the stiffness if large deformation is desired. The results presented in this paper present the optimum combination of core and face sheet parameters for different desired mechanical properties.

References

[1] Nandaragi S R, Reddy B & Badari Narayana K 2018 Fabrication, testing and evaluation of mechanical properties of woven glass fibre composite material. Materials Today: Proceedings, 5(1), 2429-2434. https://doi.org/10.1016/j.matpr.2017.11.022

[2] Arora S P S & James N R 2016 Study the Effect of Core Design on Mechanical Behaviour of Honeycomb Sandwich Structures under Three Point Bending. International Journal of Innovative Research in Science, Engineering and Technology, 5(6), 9444-9449. https://doi.org/10.15680/IJIRSET.2016.0506121
[3] Lu C, Zhao M, Jie L, Wang J, Gao Y, Cui X & Chen P 2015 Stress Distribution on Composite Honeycomb Sandwich Structure Suffered from Bending Load. *Procedia Engineering*, **99**, 405-412. https://doi.org/10.1016/j.proeng.2014.12.554

[4] Sadeghian P, Hristov D & Wroblewski L 2016 Experimental and analytical behavior of sandwich composite beams: Comparison of natural and synthetic materials. *Journal of Sandwich Structures & Materials*, **20**(3), 287-307. https://doi.org/10.1177/1099636216649891

[5] Arbaoui J, Moustabchir H, Pruncu C I & Schmitt Y 2016 Modeling and experimental analysis of polypropylene honeycomb multi-layer sandwich composites under four-point bending. *Journal of Sandwich Structures & Materials*, **20**(4), 493-511. https://doi.org/10.1177/1099636216659779

[6] Mohammed D A F, Ameen H A & Mashloosh K M 2015 Experimental and Numerical Analysis of AA3003 Honeycomb Sandwich Panel with Different Configurations. *American Journal of Scientific and Industrial Research*. https://doi.org/10.5251/ajsir.2015.6.2.25.32

[7] Shi Y, Dileep P K, Heidenreich B & Koch D 2018 Determination and modeling of bending properties for continuous fiber reinforced C/C-SiC sandwich structure with grid core. *Composite Structures*, **204**, 198-206. https://doi.org/10.1016/j.compstruct.2018.07.086