

THE MANUFACTURE OF HONEYCOMB CORES USING FUSED DEPOSITION MODELLING

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Keywords: Additive, Manufacture, Honeycomb, Core, Layup

Abstract

Sandwich panels are used in many industries, for the advantageous properties of high stiffness, good strength to weight ratio, and impact resistance. Modern manufacturing methods are dominated by manual layup; secondary structure panels often contain multiple core components, complex geometries, and tight placement tolerances. This paper compares cores manufactured using Fused Deposition Modelling (FDM) with conventional Nomex core. FDM is a process of creating complex components from extruded layers of plastic. To analyse the inter-layer bond strength of thin-walled FDM components, tensile behaviour was evaluated for variations in wall thickness. Honeycomb cores were manufactured using different build patterns, and tested in compression.

It was shown through tensile tests thick-walled FDM components exhibit a more ductile failure with a lower yield point compared to thinner walls. The ultimate tensile stress remained constant across samples. Honeycomb cores produced using FDM were found to have a higher compressive failure force than Nomex, but a lower specific strength. The force-displacement curves of the core failure show a higher energy absorbance of the thicker walled FDM core due to the ductile response.

1. Introduction

In many industries, sandwich structures are commonly used to achieve a stiff and lightweight product that fulfils geometric requirements. In advanced composite applications, core materials are used between two face sheets of high-strength material, such as cured carbon fibre laminates; providing advantageous properties of high stiffness, good strength to weight ratio, and impact resistance [1]. Within the aerospace industry, honeycomb core is a dominant choice in secondary structure applications. Due to the high component complexity, manual layup is the primary manufacturing method. With tight geometric and placement tolerances, combined with the honeycomb lateral stiffness being a very small proportion of the vertical stiffness, there is a narrow margin of error between the achievable quality and the required tolerances [2, 3]. Honeycomb cores are also manufactured in large sheets requiring machining to size and are susceptible to damage and moisture absorbance, resulting in significant waste [4].

One potential method for a reduction in production waste and improvement in lateral stiffness is employment of Rapid Prototyping (RP) for core manufacture. RP has been used in a range of industries for its ability to create net-shape parts with geometries unsuitable for conventional manufacturing techniques; an example is the ability to create internal geometries unreachable through typical milling methods [6]. Fused Deposition Modelling (FDM), a type of RP, is a technology pioneered by Stratasys Inc (now

Stratasys Ltd) in 1991 [7]. A typical FDM system involves extrusion of molten plastic from a nozzle, with actuation provided to move the nozzle in a Cartesian coordinate system. The RepRap project began in 2008, providing open source designs for FDM machines [8]. With the proliferation of different designs, the cost of FDM systems has decreased, widening use within industry [5, 7].

One factor limiting adoption of FDM in industrial manufacturing is the reduction in mechanical strength of components. Agarwala et al [9] investigated defects in FDM components due to the deposition method, such as internal voids, the staircase effect, and start/stop errors. The anisotropic properties of FDM components in compression was explored by Lee et al. [10]; finding an 11.6% change in compressive strength dependent on part orientation. Tymrak et al. [11] found the FDM components manufactured on open-source RepRap machines have comparable mechanical properties to those produced on a commercial machine. Many methods for improving the mechanical properties of the components have been suggested, such as the use of curved layers [12], design optimisation [13], and process parameter optimisation [14].

To date, there has been little research of RP technology applications in sandwich panel manufacture. In a patent filed in 2002, Boeing describes the use of RP thermoplastic honeycomb structures for use in radar cross sections [15]. The described advantages are increased manufacturing efficiency and improved design space over conventional cores. This concept has been explored by the University of Bristol [16, 17, 19], investigating the mechanical properties of thermoplastic cores, the potential for use in repairing sandwich panels, and the potential for use on curved surfaces. An application to composite sandwich structures has been explored by Riss et al. [18], optimising honeycomb wall thickness for expected loads. Whilst previous work has provided an insight into the flexibility afforded to FDM cores, there has been little characterisation of properties and comparison to existing core materials.

If sandwich panels are to remain competitive in future applications, improved manufacturing methods will be required to achieve the “Bigger, Faster, Cheaper” mantra [20]. This paper evaluates thin-walled honeycomb cores produced through FDM to provide a comparison to Nomex. Section 2 investigates the effect of different wall thicknesses and print speeds on the inter-layer bond strength of acrylonitrile butadiene styrene (ABS), a commonly used material in FDM, manufactured with a RapMan 3.2 printer¹. Following these results, Section 3 presents a method of manufacturing and testing of FDM cores, evaluating the effect of different build patterns. The results are discussed, presenting a theory regarding the causes of variability, succeeded by conclusions and further work.

2. Tensile testing of bond strength

To investigate build patterns for a low density core, a thin wall structure was considered; with each wall layer composed of a single extruded filament of ABS. A dominating factor of FDM part mechanical properties is the bond strength between layers [14, 21]. Tensile testing was performed to characterise the bond strength between different thickness walls, based on ASTM D638 [22]. The test performed is similar to that conducted by Yan et al. [23], where an analytical prediction of bonding potential was investigated.

2.1. Manufacture of tensile specimens

A number of thin vertical walls were manufactured, with each layer consisting of a single line of extruded ABS filament. Wall thickness variations were introduced through variation of the nozzle speed and the material flow rate. Three extruder flow rates were considered (4.08, 5.44, 6.8 mm³s⁻¹), each with three

¹Manufactured by BFB, now part of 3D Systems

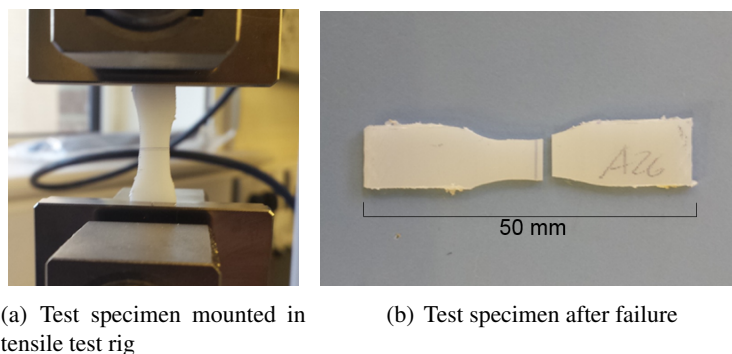


Figure 1. Thin-walled test specimens used for tensile testing. (a) shows a specimen mounted in the test rig, (b) shows the fracture during failure along the inter-layer bond

wall thicknesses (1.5, 2, 2.5 mm).

The walls were then machined into hourglass-shaped test specimens, shown in Figure 1. Each specimen was 50mm long, with a gauge length of $9\text{mm} \pm 1\text{mm}$, and a width of $7\text{mm} \pm 0.5\text{mm}$. Figure 1(a) shows a test specimen mounted in a tensile testing rig, and Figure 1(b) depicts a typical failure observed during testing. Any failure outside of the gauge length was discounted from results.

2.2. Tensile testing results

Testing was conducted at a rate of 2mm/min, observed with a 10kN load cell sampled at 100Hz. From the peak force before failure, the ultimate tensile stress for each wall thickness was calculated using measurements for sample width and thickness. The results are shown in Table 1. The results show little variation in ultimate tensile stress for variations in extruder flow rate and wall thickness, with the exception of the thicker-walled specimens. 6 samples were manufactured for each set of test parameters, with at least 4 samples failing within the gauge length.

Table 1. Ultimate tensile stress for variations in wall thickness and flow rate (MPa). Limits of ± 1 standard deviation are included.

		Wall thickness (mm)		
		1.5	2.0	2.5
Flow rate (mm^3s^{-1})	4.08	24.2 \pm 1.3	26.1 \pm 2.4	24.1 \pm 2.4
	5.44	25.2 \pm 3.8	26.3 \pm 4.1	22.1 \pm 2.1
	6.80	24.7 \pm 3.9	25.9 \pm 4.1	22.9 \pm 1.8

Figure 2 shows the force-displacement results for a range of flow rates and the corresponding wall thicknesses. The yield points for each test are marked; it can be seen the thinner-walled structures behave in a more brittle way than the thicker walled samples. It can be hypothesised that with a higher amount of plastic deformation, the specimen behaves closer to that expected for a conventionally manufactured plastic specimen; implying a higher level of inter-layer bonding than exhibited in the thinner-walled structures.

Due to increased contact area between filaments in thicker walls, a heat gradient during the bond-forming process would form across the inter-layer bond. As the inter-layer entanglement is related to the temperature [21], a higher level of entanglement is exhibited in the centre of the bond relative to the edge.

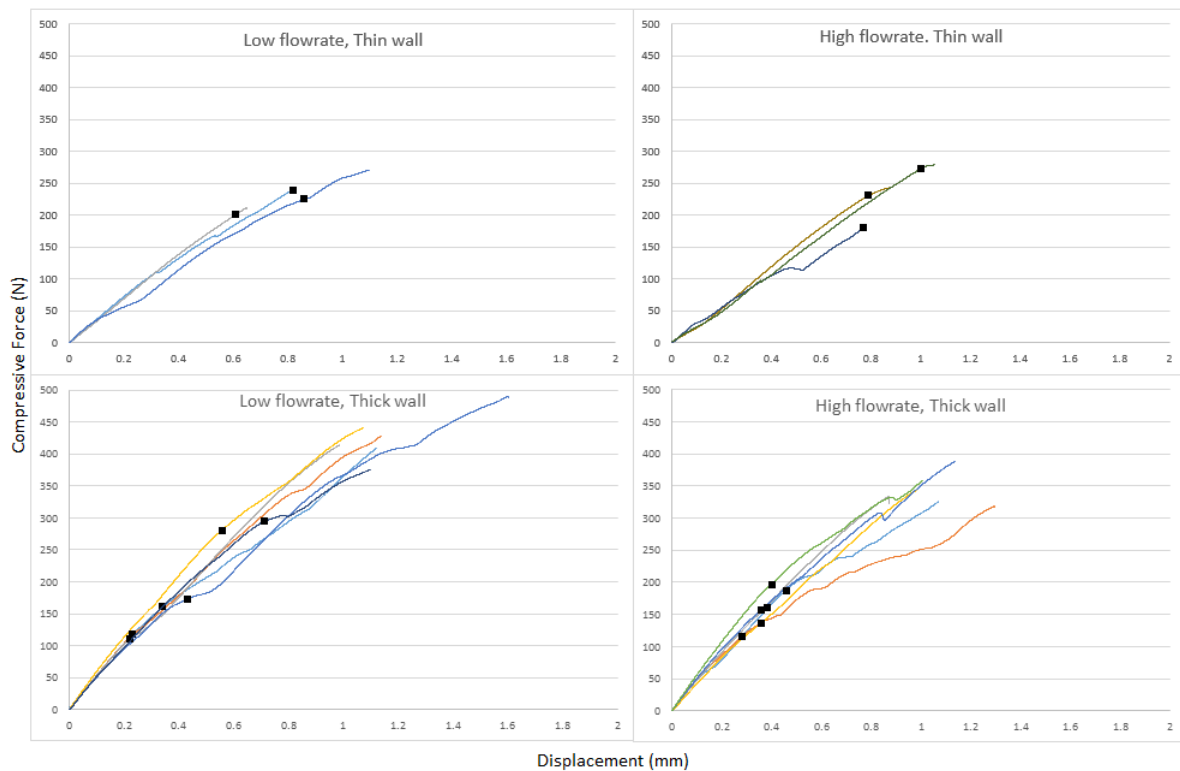


Figure 2. Force-Displacement curves for tensile samples. The yield points for each specimen are highlighted. All axes have the same units.

With the lower level of bonding at the edge, a peeling action may occur, causing the earlier yield point observed. As the thinner walls would have a more uniform temperature along the filament bond, the yield point is reached closer to failure with minimal peeling between layers.

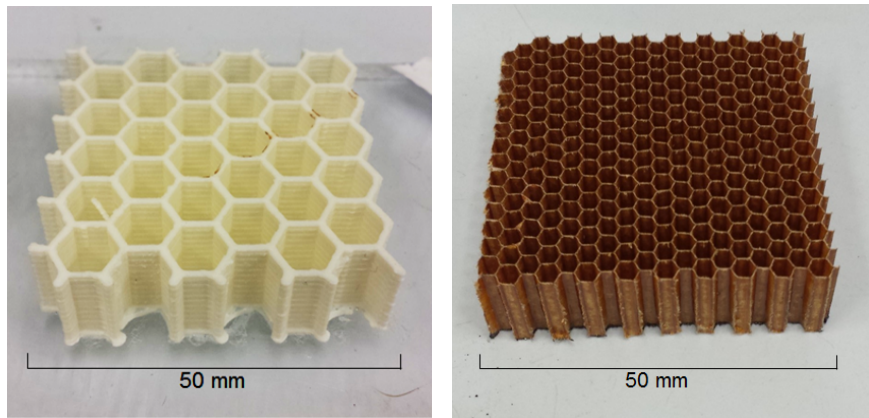
3. Compressive testing of cores

Cores were tested under compression, investigating the effect of different build patterns. A honeycomb build pattern was selected, due to the efficiency of honeycomb as a filling pattern and the resemblance to Nomex. The test design is based on ASTM D7336 [24], with specimens centrally mounted on level compression plates. ABS plastic was used to evaluate the effect from wall thickness variations, and a core manufactured in the same style from polylactic acid (PLA) provides a comparison for material variation.

3.1. Manufacture of FDM cores

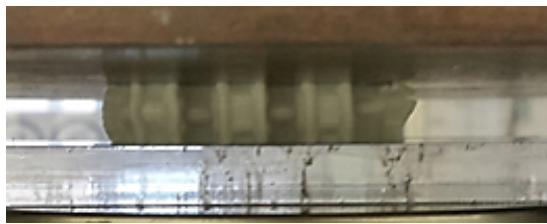
Custom code was created using MATLAB to output a GCode file directly to the 3D printer, enabling full control over the print parameters, allowing full control over different deposition patterns for thin-walled objects.

Three different build profiles were investigated, as described in Table 2, with the wall thicknesses, normalised and expected normalised thicknesses stated. The expected normalised thickness values were estimated based on the number of walls a hexagon are traced by the deposition path. Cores manufactured from PLA were produced using wall type 2. The type 3 toolpath is identical to that output by the slicing software.



(a) Core manufactured using FDM

(b) Nomex core machined to specimen dimensions



(c) FDM core at failure point under compressive loading



(d) Nomex core at failure point under compressive loading

Figure 3. Cores used during testing. (a) and (b) show the ABS and Nomex cores respectively, with (c) and (d) showing the core failure under compressive loading.

FDM and Nomex cores are shown in Figures 3(a,b). A 5mm cell radius was used for the FDM core, and a 1.5mm cell radius for Nomex. FDM specimens were printed to a size of $50 \times 50 \times 14 \pm 1$ mm, and the Nomex core cut with a bandsaw from a 14mm depth sheet to $50 \times 50 \pm 2$ mm.

Table 2. Specimen wall thickness and deposition pattern description

Wall type	Thickness (mm)	Normalised thickness	Expected normalised thickness	Description
1	0.56	1	1	All hexagon edges individually deposited
2	0.79	1.42	1.33	Hexagon rows deposited continuously, columns deposited continuously
3	1.11	1.98	2	Deposition pattern traces hexagon outline
PLA	0.85	–	1.33	
Nomex	0.08	–	1.33	

3.2. Compressive testing results

Testing was conducted at a rate of 2mm/min, with compressive force observed using a 50kN load cell sampled at 10Hz. Table 3 presents the yield force, yield and crush stress, and specific crush stress for each build pattern. In a similar result to that found in Section 2, the thinner walled core behaves in a more brittle manner than the thicker wall counterparts, as little plastic deformation occurred between yield and crush stresses.

Table 3. Force and stress obtained during crush testing of different deposition patterns for FDM and Nomex cores

Wall type	Yield Force (kN)	Yield stress (MPa)	Crush Stress (MPa)	Specific Yield Stress (MPa/g)
1	9.1	18.9	21.6	4.0
2	20.1	29.6	35.2	4.8
3	33.2	34.5	40.0	3.7
PLA	32.8	42.9	51.1	5.0
Nomex	5.4	36.6	41.2	19.1

Figure 4 shows the Force-Displacement curves of the different core materials tested. Whilst the Nomex follows the anticipated crushing behaviour with a constant crush force, the FDM cores follow a more typical buckling behaviour for plastic structures. The FDM-manufactured cores were shown to withstand a significantly higher force than Nomex, with similar crush stresses; but due to the increased mass of the FDM core the specific crush stress is much lower. The higher compressive strength of the PLA specimen corresponds the findings of Tymrak et al. of improved mechanical properties of PLA over ABS [11].

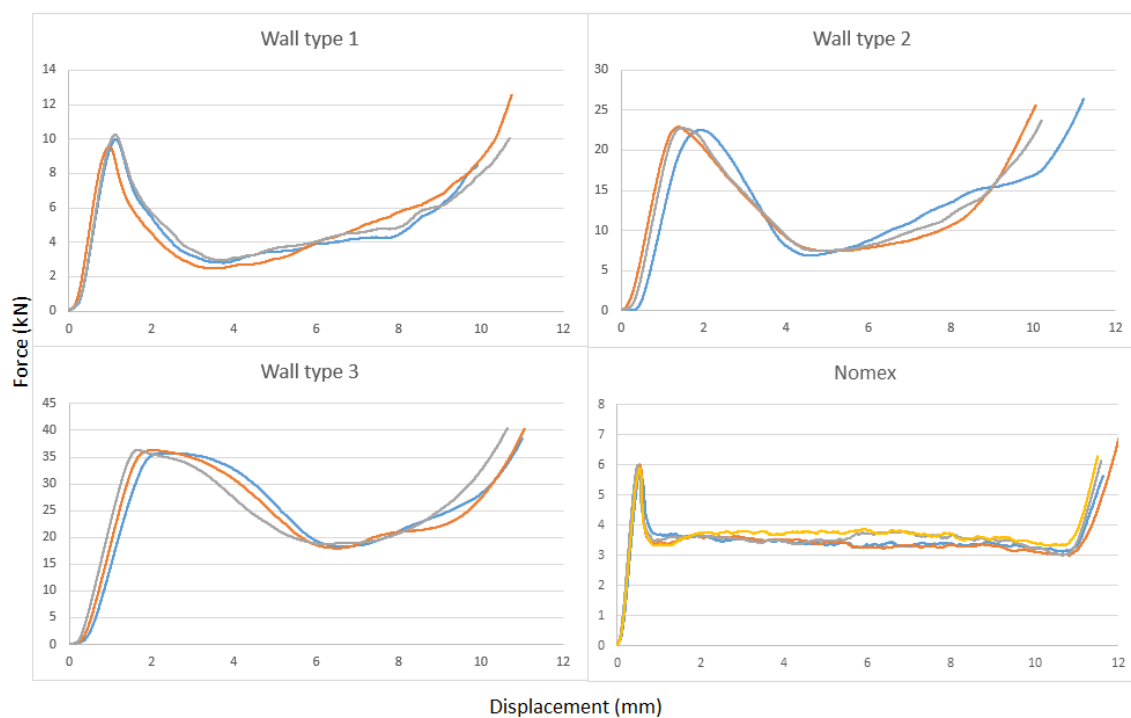


Figure 4. Force-Displacement curves for tensile test samples for variations in flow rate and wall thickness. Yield points are highlighted by black squares.

Relating the force-displacement compression graphs with the ductility variation exhibited in the tensile tests, the behaviour following the peak load was as expected. With a more brittle thin-walled structure, there is little deformation before the buckling caused by layer separation. The thicker-walled specimens exhibited a ductile response in tensile testing, reflected in the compressive core testing as the layer bond yields. This effect caused the larger force required for further deformation after peak force.

The deposition pattern also introduces anisotropic properties to the core. As discussed in [1, 4], traditional Nomex honeycomb exhibits anisotropic properties due to the lamination construction method,

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with the T and W directions. As discussed in [14], FDM exhibits anisotropic properties in the vertical direction due to the layers, but due to the higher stiffness of the ABS compared to the paper-based Nomex, there is no noticeable difference when handling different orientations.

4. Discussion

Section 2 presents the different inter-layer bond failure mechanisms for different wall thicknesses; thicker walls behaved in a more ductile manner. In Section 3, it can be seen the FDM cores exhibit a higher compressive force, and a lower specific strength than Nomex. With the increased crush force after failure of the plastic cores, there is potential for improved impact resistance; the properties of which are determined by wall thickness. Through correlation between the two sections, it can be concluded that inter-layer bond strength is key in determining the failure properties of the final core.

There are advantages to using FDM cores in secondary structures, where low cost and ease of manufacturing are a priority; especially when complex geometries are common. Here, the core strength could be optimised for areas with high localised loads (e.g. inserts) through modifying the deposition pattern and wall thickness. In addition to the ability to support localised loads, a more complex structure can be made than is possible to do with conventional sandwich panels. Using multiple Nomex sheets to form complex geometry requires careful machining and splicing [1]. With FDM, extra complexity in manufacturing is available at virtually no extra cost[6].

5. Conclusion and further work

This paper presented the results of testing filament bond strength and compressive strength of thin-walled honeycomb cores produced using FDM. Tests have shown thicker walls are more susceptible to plastic deformation with a lower yield point than the thinner walls. Fused Deposition Modelling (FDM) was used to produce cores with wall thickness variations from ABS and PLA plastic, with compressive failures showing the maximum crush force is significantly greater than Nomex. A second key advantage is the improved design envelope, reducing manufacturing limitations imposed by conventional machining. While the specific compressive strength remains roughly constant with wall thickness variations, it is lower than Nomex, a barrier to use in weight-critical applications.

Future work will involve further testing of FDM cores in impact and torsion, two areas where there is a possibility for significant advantages over Nomex. A second aspect is ensuring quality control during core fabrication, with in-process monitoring reducing the requirement for further inspection.

Acknowledgments

This work was supported by the EPSRC Centre for Doctoral Training in Future Autonomous Robotic Systems (FARSCOPE) at the Bristol Robotics Laboratory, (grant: EP/L015293/1).

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