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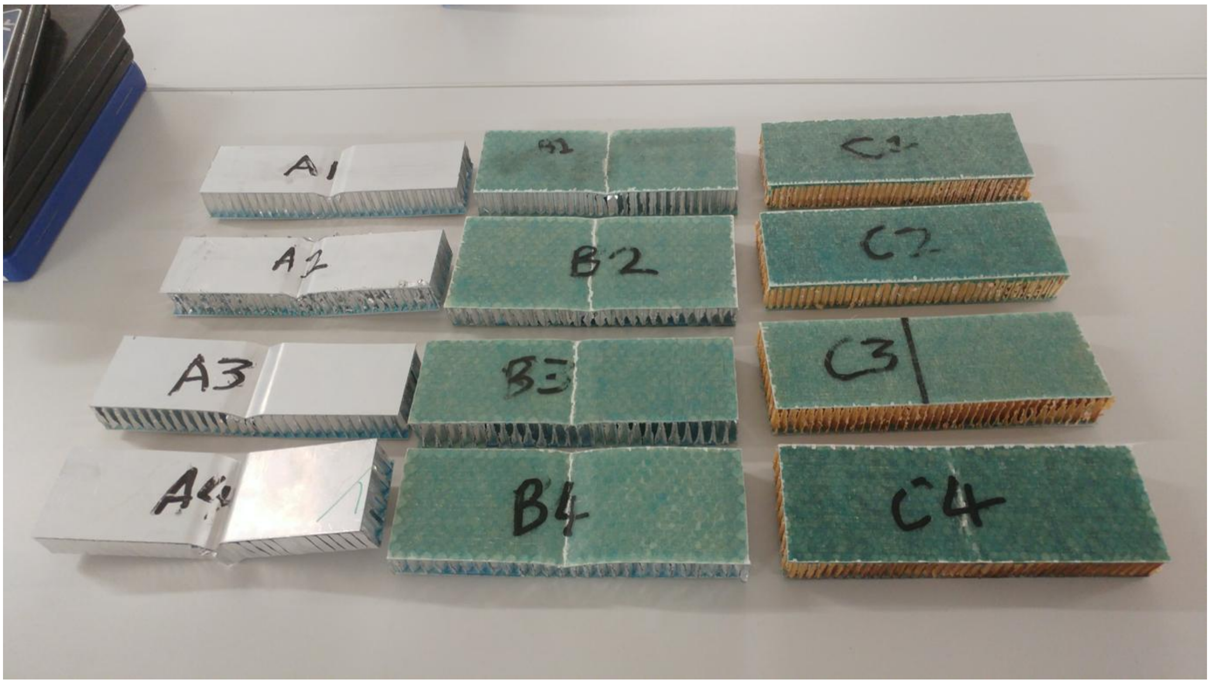
Design and Structural Optimisation of an Aluminium Honeycomb Sandwich Panel under three-point bending using Finite Element Analysis (FEA) software ANSYS



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Abstract

This study describes a Finite Element Analysis (FEA) of a honeycomb core composite sandwich panel simulated through ANSYS with the aim to minimise the ratio of average density to flexural rigidity. Throughout the study, the honeycomb sandwich panel was modelled and tested under three-point bending conditions with the model constraints kept constant. The three most influential parameters are analysed and varied independently, namely the honeycomb core thickness, honeycomb ribbon thickness and honeycomb cell size. The remaining parameters are kept constant. The effects of the varying parameters on the average density to flexural rigidity ratio are discussed, finalised with a suggested set of optimum parameters.

1. Introduction

Nomenclature

Symbol	Description	SI Unit
F	Force	N
L	Distance between pins	mm
δ	Displacement	mm
$(EI)_{eq}$	Flexural rigidity	Nm^2
b	Core thickness	mm
t	Skin thickness	mm
T	Ribbon thickness	mm
α	Cell size	mm
ϕ	Honeycomb angle	Degrees
E_C	Elastic Modulus: Core	MPa
E_S	Elastic Modulus: Skin	MPa
ν_C	Poisson's Ratio: Core	
ν_S	Poisson's Ratio: Skin	
ρ_c	Ribbon material density	kg/m^3
ρ_h	Honeycomb density	kg/m^3
σ_y	Yield Stress	MPa
σ_c	Yield strength: Core	MPa

Table 1.1 Variables used throughout the Structural Optimisation

Honeycomb sandwich panels are being increasingly implemented for applications where weight must be kept to a minimum whilst a high strength and flexural rigidity is necessary. Examples of such applications include structural supports in airplanes and rockets where the overall mass must be kept to a minimum to maximise fuel efficiency.

This report aims to find the optimum parameters of a panelled honeycomb structure which minimises the average density to flexural rigidity ratio. The analysis will be executed using the Finite Element Analysis (FEA) software ANSYS by independently varying three of the most influential parameters whilst keeping the remaining parameters constant. The parameters under scrutiny are the core thickness, ribbon thickness and cells size. These were evident to be the most influential parameters by using a excel data sheet that calculated the percentage change in the average density to flexural rigidity ratio seen in the appendix.

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2. Model Configuration

A quarter model of a honeycomb sandwich panel was designed in SpaceClaim with the script parameters being shown in figure 2.1. The core thickness is varied using this script with the other dimensions kept constant. A quarter model was used to reduce the computational cost without reducing the integrity of the analysis.

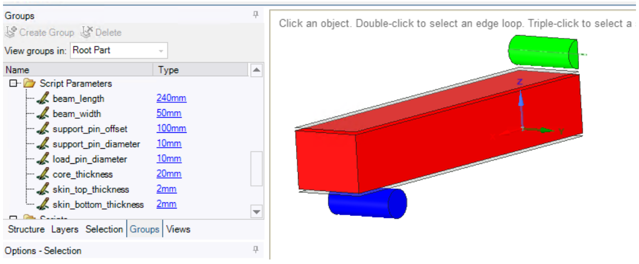

Figure 2.1 Python Script used to Vary Dimensions of Honeycomb Sandwich Panel

The cell size and ribbon thickness of the aluminium honeycomb core was altered through an excel data sheet seen in the appendix. This data sheet calculated the effective X, Y and Z Youngs Modulus, XY, YZ and XZ Poissons ratio and the XY, YZ and XZ Shear Modulus using numerical theory outlined in several scientific literatures (1). These engineering property values were manually transferred to ANSYS by editing the honeycomb core material properties, allowing different of values of cell size and ribbon thickness to be implemented in the FEA simulation.

Properties of Outline Row 4: Honeycomb

	A	B	C	D	E
1	Property	Value	Unit		
2	Density	52	kg m^-3		
3	Orthotropic Elasticity				
4	Young's Modulus X direction	1.636	MPa		
5	Young's Modulus Y direction	1.636	MPa		
6	Young's Modulus Z direction	1347.2	MPa		
7	Poisson's Ratio XY	0.998			
8	Poisson's Ratio YZ	0.0004			
9	Poisson's Ratio XZ	0.0004			
10	Shear Modulus XY	0.41	MPa		
11	Shear Modulus YZ	326.5	MPa		
12	Shear Modulus XZ	494.7	MPa		
13	Orthotropic Stress Limits				
23	Ply Type				

Figure 2.1 Manual Input of Honeycomb Core Properties

The structural constraints used on the model in ANSYS are shown in figure 2.2 to ensure an accurate and representitive simulation was constructed. A constant displacement of 2mm was applied to the load pin in the negative Z direction over one second (yellow arrow). The equal and opposite reactionary force acting in the positive Z direction was calculated in the solutions to find the resultant force excerted by the sample specimen (or conversely the force required to displace the specimen by 2 mm). This force was quadroupled before it was processed in calculations to become representitive of a full beam specimen.

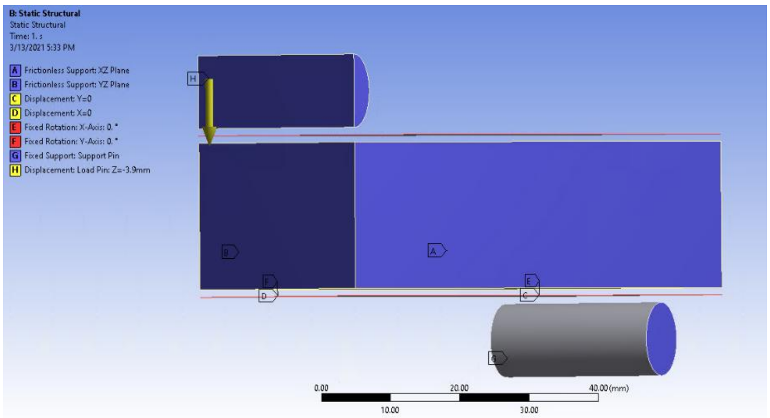

Figure 2.2 Constraints in Ansys of Specimen Model

Table 2.2 outlines the materials allocated to each piece of geomentry. The materials were kept constant throughout the analysis with only the honeycomb properties changing.

Geometry	Material
Honeycomb Core	Aluminium
Top/Bottom Skin	
Support/Load Pin	Stainless Steel

Table 2.2 Materials of Components of Specimen

The table below shows the constant meshing configuration used throughout analysis. The mesh size was carefully selected so the results were of sufficient accuracy whilst computationally low budget.

Geometry	Mesh Size (mm)
Honeycomb Core	2.00
Top/Bottom Skin	1.00
Support/Load Pin	1.00

Table 2.3 Mesh Sizing of Components of Specimen

Figure 2.3 shows the stress and deformation solutions needed for a comprehensive analysis. Values from each solution are necessary for determining the yield stress in each geometry, the reactionary force from the loading pins displacement and ultimately the average density to flexural rigidity ratio.

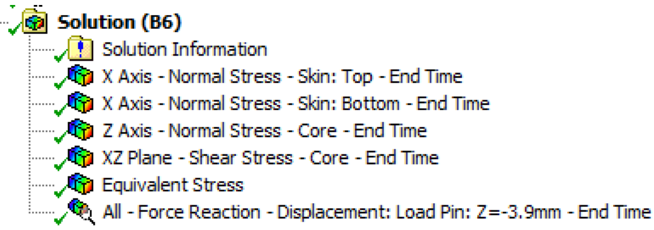

Figure 2.3 Solutions to Ansys Simulation

3. Methodology

Description	Equation	No.
Density-to-rigidity-ratio	$Ratio = \frac{average\ density\ of\ the\ panel}{flexural\ rigidity\ of\ the\ panel}$	(1)
Deflection	$\delta = \frac{FL^3}{48EI}$	(2)
Constant	$C_1 = \frac{F}{\delta}$	(3)
Constant	$C_2 = \frac{skin\ axial\ maximum}{F}$	(4)
Constant	$C_3 = \frac{skin\ axial\ minimum}{F}$	(5)
Constant	$C_4 = \frac{core\ through\ minimum}{F}$	(6)
Constant	$C_5 = \frac{core\ shear\ maximum}{F}$	(7)
Buckling	$\sigma = \lvert C_3F \rvert < \frac{2E_s}{1-\upsilon_s^2}\left(\frac{2t}{\alpha}\right)^2$	(8)
Wrinkling	$\sigma = \lvert C_3F \rvert < E_s^{1/3}\left(\frac{3(\rho_h/\rho_c)E_c}{2(3-\nu_c)(1+\nu_c)}\right)^{2/3}$	(9)
Core collapse	$\sigma = \lvert C_4F \rvert < \sigma_c(\rho_h/\rho_c)^{5/3}$	(10)
Shear failure	$\tau = C_5F < 2E_c(\rho_h/\rho_c)^3$	(11)
Yield C (skin)	$\sigma = \lvert C_3F \rvert < \sigma_Y$	(12)
Yield T (skin)	$\sigma = C_2F < \sigma_Y$	(13)
Area Fraction	$\% = 2\frac{T/\alpha}{cos\phi(1+sin\phi)}$	(14)

Table 3.1 Equations used throughout study to structurally optimise specimen

Below outlines the constant values for the parameters unless their value is stated elsewhere.

Symbol	Parameter	Value	Units	Constant	Varied
t	Skin thickness Top & Bottom	0.50	mm	✓	
δ	Displacement	4.00	Mm	✓	
ρ_c	Ribbon material density	2700	Kg//m^3	✓	
E_c	Elastic modulus: Core	70.0	GPa	✓	
ν_s	Poisson's ratio: Core	0.350	-	✓	
b	Core thickness	20.0	mm		✓
T	Ribbon thickness	0.050	mm		✓
α	Cell Size	2.00	mm		✓
ϕ	Honeycomb angle	30.0	Degrees	✓	
D	Pin diameter Load & Support	10.0	mm	✓	
σ_y	Yield Stress	240	MPa[4]	✓	

Table 3.2 Fixed and Varied Parameter Valued Used Throughout Study

The analysis of this report focusses on the core with changes to the core thickness (b), ribbon thickness (T) and cell size (α) being independently tested.

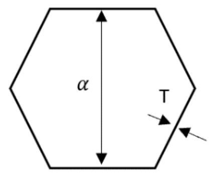

Figure 3.1 Honeycomb Cell Size and Ribbon Thickness

The average density to flexural rigidity ratio (equation 1) is a measure of how structurally supportive the specimen is in relation to its overall mass. This ratio can be scaled and applied for panelled honeycomb specimens of all sizes. The main aim of this report is to minimise this ratio by designing the strongest specimen with the lowest mass.

To determine whether the specimen deforms plastically or elastically, we assume the specimen deforms linearly with force by introducing constants (equations 3 - 7). Once these constants are found the maximum force which can be applied before plastic deformation occurs is calculated. This force will be considered as the failure force and is calculated for each failure mode, with the failure mode being that of which has the lowest failure force (equations 8 – 13).

Geometry	Failure Mechanism	Stress Analysed	Equation Number
Top/Bottom Skin	Wrinkling	Normal Stress in X-Axis	9
	Buckling	Normal Stress in X-Axis	8
	Tension Yield	Normal Stress in X-Axis	13
Honeycomb Core	Core Collapse	Normal Stress in Z-Axis	10
	Shear Failure	Shear Stress in XZ Plane	11

Table 3.3 Failure Criteria for Components of Specimen

4. Results

4.1. Core thickness

Several three-point bending tests of a honeycomb sandwich panel quarter model was simulated in ANSYS and the failure force and criteria was analysed. The only parameter that was varied in this simulation was the core thickness (b) with the aim to maximise the average density to flexural rigidity ratio.

Core thickness (b) (mm)	Force (N)	Average ρ (kg/m^3)	Flexural Rigidity (N/m^2)	Ave. Density/Flexural Rigidity ratio (kg/Nm)	First Failure Force (N)	Failure Criteria
10	19200	2460	892	1.98	183	Core Collapse
20	26400	2030	1210	1.69	209	Core Collapse
30	41800	1430	1910	0.93	202	Core Collapse
40	61200	1210	2350	0.51	232	Core Collapse
50	79100	1010	3280	0.32	285	Core Collapse
60	81000	911	3520	0.23	305	Core Collapse

Table 4.1 Results Displaying Effect of Core Thickness to Critical Ratio

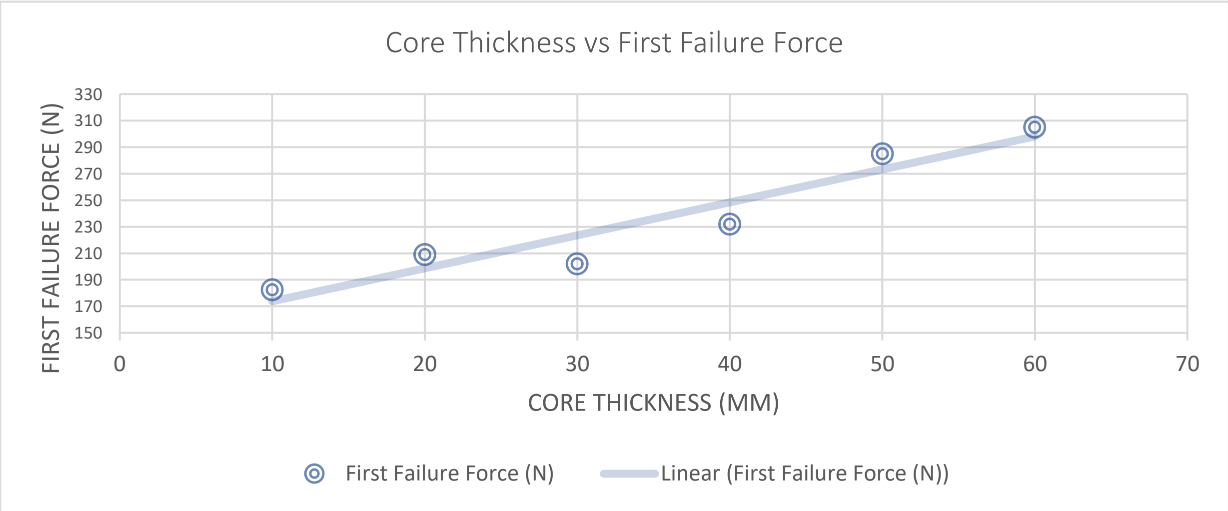

Figure 4.1.1 Relationship Between Core Thickness and First Failure Force

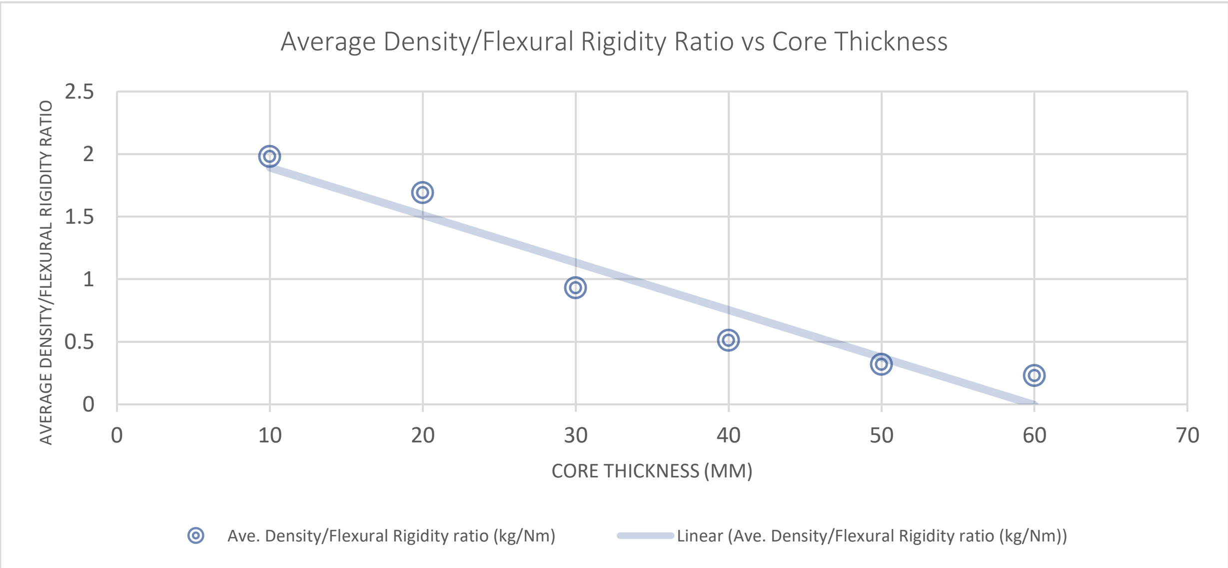

Figure 4.1.2 Relationship Between Core Thickness and Critical Ratio

4.2. Ribbon thickness

An identical test to that of the previous was carried out on ANSYS however the only variable that was independently changed in this simulation was the ribbon thickness. The results are displayed in the table below and their relationship with the key quantities are graphically represented.

Ribbon Thickness (t) (mm)	Force (N)	Average ρ (kg/m^3)	Flexural Rigidity (N/m^2)	Ave. Density/Flexural Rigidity ratio (kg/Nm)	First Failure Force (N)	Failure Criteria
0.03	22300	1947	972	2.14	112	Core Collapse
0.04	24300	1960	1040	1.84	158	Core Collapse
0.05	27400	2030	1210	1.67	201	Core Collapse
0.06	31200	2050	1310	1.51	239	Core Collapse
0.07	33700	2100	1450	1.44	301	Core Collapse
0.08	35200	2130	1570	1.33	352	Core Collapse

Table 4.2 Results Displaying Effect of Ribbon Thickness to Critical Ratio

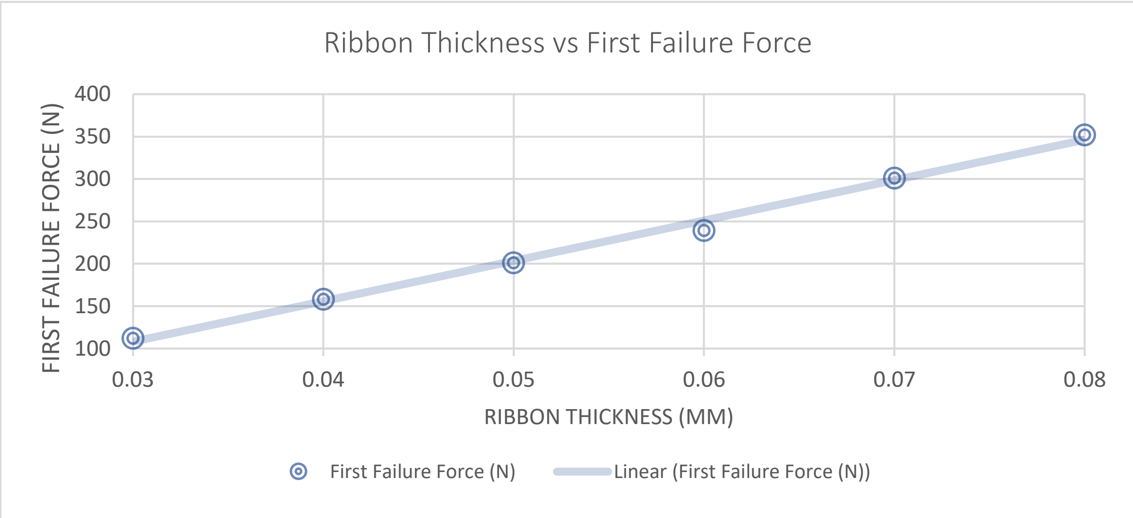

Figure 4.2.1 Relationship Between Ribbon Thickness and First Failure

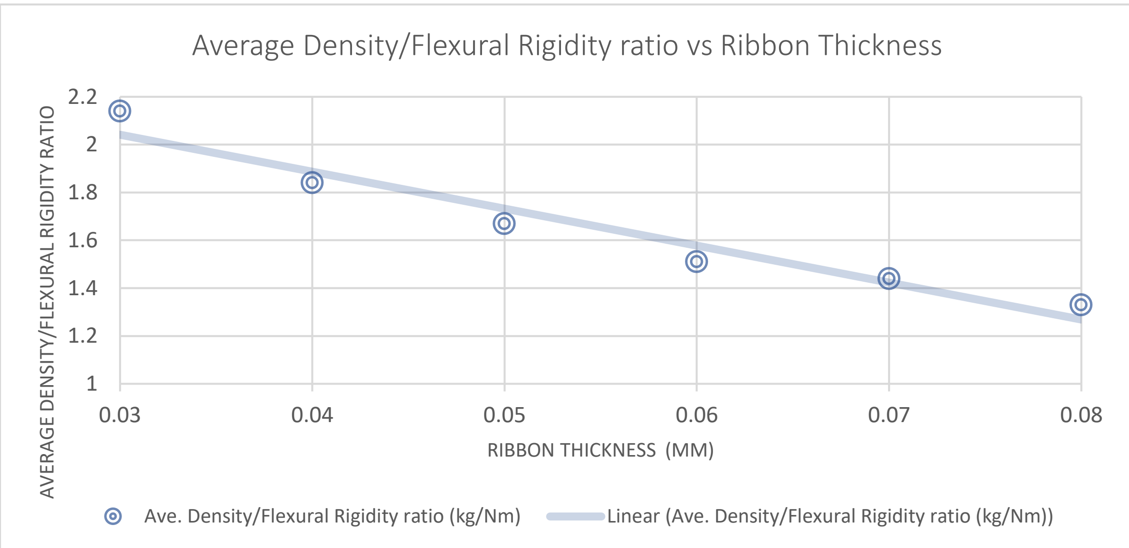

Figure 4.2.2 Relationship Between Core Thickness and Critical Ratio

4.3. Cell Size

An identical test to that of the previous was carried out on ANSYS however the only variable that was independently changed in this simulation was the honeycomb core cell size. The results are displayed in the table below and their relationship with the key quantities are graphically represented.

Cell Size (α) (mm)	Force (N)	Average ρ (kg/m^3)	Flexural Rigidity (N/m^2)	Ave. Density/Flexural Rigidity ratio (kg/Nm)	First Failure Force (N)	Failure Criteria
1.00	44300	2510	2010	1.13	572	Core Collapse
2.00	38200	2190	1650	1.27	439	Core Collapse
3.00	32400	2070	1410	1.44	271	Core Collapse
4.00	27100	2010	1170	1.71	202	Core Collapse
5.00	24200	1970	1090	1.83	148	Core Collapse
6.00	21900	1930	910	2.11	120	Core Collapse

Table 4.3 Results Displaying Effect of Cell Size to Critical Ratio

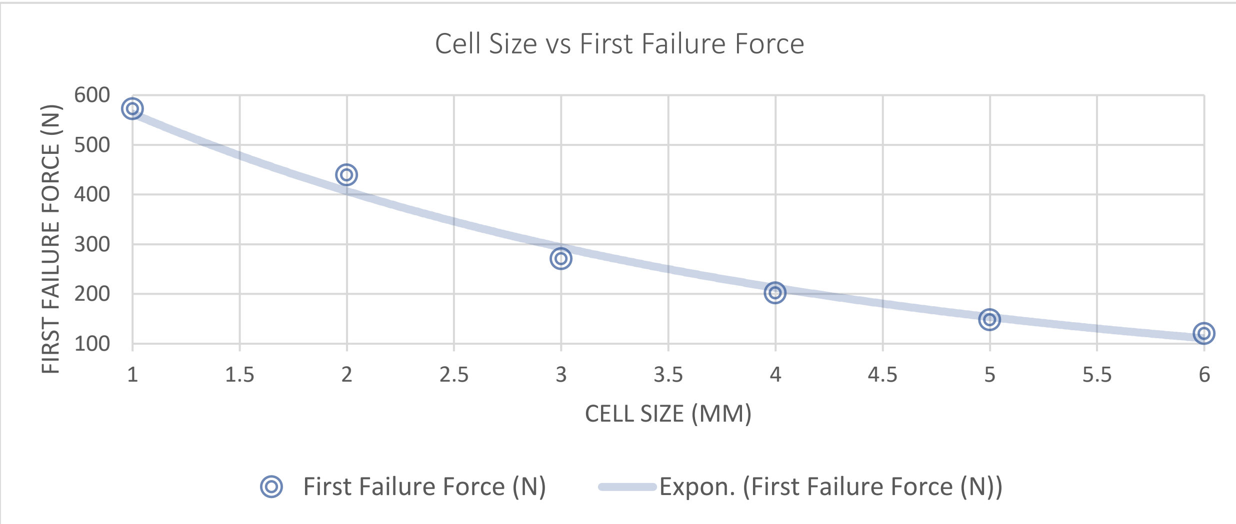

Figure 4.3.1 Relationship Between Ribbon Thickness and First Failure Force

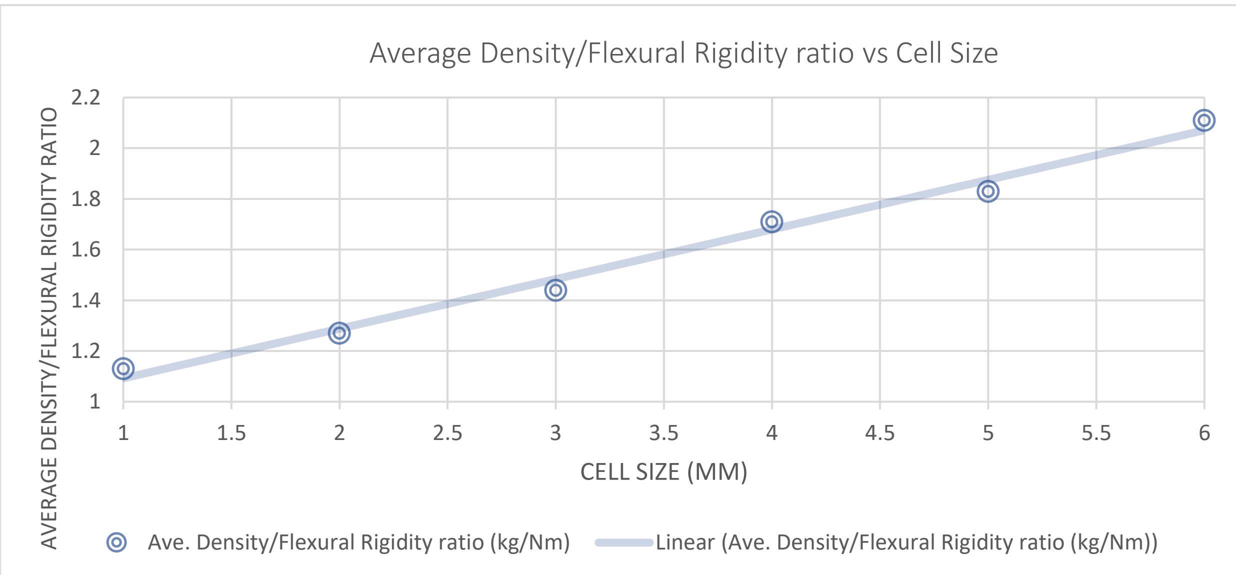

Figure 4.3.2 Relationship Between Ribbon Thickness and First Failure Force

4.4. Optimum Parameters

Several final simulations were executed in ANSYS using the parameters from tables 4.4.1 – 4.4.3 which provided the lowest average density to flexural rigidity. The best four simulations that produced the lowest ratio are displayed in the table below.

Cell Size (mm)	Core Thickness (mm)	Ribbon Thickness (mm)	Force (N)	Average ρ (kg/m^3)	Flexural Rigidity (N/m^2)	Ave. Density/Flexural Rigidity ratio (kg/Nm)	First Failure Force (N)
2.00	50.0	0.07	179000	1360	2110	0.174	984
2.00	40.0	0.07	122000	152	1630	0.289	801
2.00	50.0	0.08	203000	1440	1390	0.171	1120
3.00	50.0	0.07	135000	1210	1200	0.204	613

Table 4.4 Results from Final Simulations that gave Minimum Critical Ratio

5. Discussion

5.1. Core Thickness

Table 4.1 shows the results of five different realistic values for the core thickness ranging from 10 mm to 60 mm. Ultimately, the application on the composite sandwich panel will depend on the thickness of the core but for this study the thickness was constrained to these values for time limitations. It is evident from figure 4.1.1 that as the core thickness increases, the force required to yield the panel increases in a linear fashion suggesting the thicker the core, the stronger the specimen is. Infinite thickness would provide the strongest specimen, but this is unpractical for any application. Figure 4.1.2 suggests that the critical ratio decreases (becomes optimised) as the core thickness increases but the same constraints must apply as an infinitely thick core is unpractical/impossible. To compromise between structural benefit and cost effectiveness, a core thickness of 50 mm has been chosen as the optimum value in this study.

5.2. Ribbon thickness

Table 4.2 shows the effect of the ribbon thickness of the honeycomb cores' cells on the first failure force and the critical ratio. The ribbon thickness values were constrained between 0.03 mm to 0.08 mm due to manufacturing constraints and time limitations. It is evident from figure 4.2.1 that as the ribbon thickness increased, the force required to yield the specimen increased linearly suggesting the overall yield strength of the specimen increased. Increasing the ribbon thickness indefinitely would result in a solid aluminium core defeating the purpose of the honeycomb structure. The table shows that ribbon thickness has a very small effect on overall average density assuming the cell size is sufficiently large. Figure 4.2.2 shows the relationship the ribbon thickness has on the critical ratio. As the ribbon thickness increased, the critical ratio becomes optimised, suggesting the flexural rigidity of the specimen increases at a faster rate to that of the average density. For practical purposes, a ribbon thickness of 0.08 mm was suggested to be the optimum value to provide the structurally strongest specimen per unit mass.

5.3. Cell Size

Table 4.3 shows the effects of five manufacturable honeycomb cores consisting of cell sizes ranging between 1 mm in diameter up to 6 mms on the failure force, density and overall critical ratio. Increasing the cell size within the honeycomb core decreases the average density of the specimen and similarly decreases the flexural rigidity, but at a slower rate. Figure 4.3.1 shows the force required to yield the specimen increases the smaller the cell size is suggesting the strongest specimen would consist of infinitely small cell diameters. This would result in a nearly solid aluminium block which is very hard to manufacture due to tolerances and would give it a very high density. Figure 4.3.2 shows a linear relationship of negative gradient between the critical ratio and the cell size. This suggests that the ratio becomes optimised with very small cell sizes which would be very costly and unpractical to manufacture. The optimum cell size suggested in this study after farther analysis with the remaining optimised parameters was seen to be 0.2 mm seen from table 4.4. This provided a cost effective yet structurally rigid honeycomb core.

5.4. Optimum Parameters

The results in 4.1. to 4.3. gives a representation of the relationship between the core thickness, ribbon thickness and the cell size to the average density to flexural rigidity respectfully. Understanding these relationships allowed for table 4.4 to be produced where several final simulations were carried out. These simulations involved implementing changes to all three varying parameters simultaneously allowing for an overall optimisation of the three parameters under investigation.

5.4.1. Core Thickness Optimisation

Increasing the core thickness provided the greatest contribution to lowering the critical ratio and increasing the failure force but limitations must be implemented to compromise between manufacturing costs (3). A core thickness of 50 mm was observed in this study.

5.4.2. Ribbon Thickness Optimisation

Researching honeycomb composite sandwich panel suppliers, the average ribbon thickness offered for manufacture was around 0.7 mm (4). Ribbon thickness proved to have a lesser impact on the critical ratio than the remaining two parameters, so a value of 0.7 mm is presented as the optimum value.

5.4.3. Cell Size Optimisation

The minimum cell size offered by manufacturers on the open market online is roughly 3.2 mm (3). Assuming manufacturers can provide smaller cell sizes upon request - and from this study – the optimum cell size of 2 mm was derived.

6. Conclusion

This study executes a comprehensive structural optimisation of an aluminium skinned, aluminium honeycomb cored composite sandwich panel through the FEA software ANSYS. The specimen is constrained and modelled under three-point bending conditions with varying core thickness, core ribbon thicknesses and core cell size diameters. Optimum values for the latter three parameters to minimise the average density to flexural rigidity are provided with evidence and consideration to application and manufacturing constraints.

Core Thickness (mm)	Ribbon Thickness(mm)	Cell Size (mm)	Ave. Density/Flex. Rig Ratio
50.0	0.0700	2.00	0.162

Table 6.6 Optimum values of Parameters Investigated in this Study.

7. Appendix

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V
1	Honeycomb																					
2		Directions	1	ribbon direction, i.e., following the sheets						Geometry	b	20	mm	core thickness (between skins)				Average Density	519.282			
3			2	transverse							phi	30	degrees	honeycomb angle (internal angle is 90 + phi)								
4			3	out-of-plane, i.e., looking through the hexagons							cosphi	0.8660254		cos(phi)				Mass			Volume	0.00024
5											sinphi	0.5		sin(phi)				rho_s	2700			
6		Material	Ec	70000.0	MPa	core material: elastic modulus					t	0.1	mm	ribbon thickness				rho_c	83.14			
7			Gc	25925.9	MPa	core material: shear modulus					alpha	5	mm	cell size				length_s/c	0.2			
8			vs	0.35		core material: Poisson's ratio					hex	2.89	mm	hexagon side		Note: these calculations assume all sides same		width_s/c	0.05			
9										=>		3.08%		area fraction				height_c	0.02			
10			E3	2155.44	MPa	out-of-plane modulus												height_s	0.002			
11			v31	0.35		v13	0.001084															
12			v32	0.35		v23	0.001084							Summary		For ANSYS, assuming X=1, Y=2, Z=3		Average Mass	0.12463			
13																						
14						Gibson et al.								6.67434746	MPa	Young's Modulus X direction						
15			Kf	58.2	N/mm	Flexure force constant								6.67434746	MPa	Young's Modulus Y direction						
16			E1	6.7	MPa									2155.441	MPa	Young's Modulus Z direction						
17			E2	6.7	MPa									0.99523261		Poisson's Ratio XY						
18			v12	1.00										0.00108378		Poisson's Ratio YZ						
19			v21	1.00										0.00108378		Poisson's Ratio XZ						
20			G12	1.68	MPa									1.676178	MPa	Shear Modulus XY						
21														518.518519	MPa	Shear Modulus YZ						
22						Masters & Evans								787.594514	MPa	Shear Modulus XZ						
23			Ks	48497.4	N/mm	Stretching force constant																
24			Kh	17962.0	N/mm	Hinging force constant								2700	kg/m3	ribbon Material Density (rho_c)						
25			E1	6.67435	MPa	in-plane elastic properties								83.14	kg/m3	Honeycomb desnity (rho_h)						
26			E2	6.67435	MPa																	
27			v12	0.9952																		
28			v21	0.9952				Note: sign error corrected; unchecked														
29			G12	1.676178	MPa			Note: equation error corrected; unchecked								ANYTHING YELLOW CAN BE CHANGED						
30																						
31						Grediac								Flexual Rigidity	1694							
32			G_R1	0.03										Average Density	519.282032							
33			G_R2	1.00																		
34			G_R3	6.93										GOLDEN RATIO	0.30654193	MINIMISE QUANTITY						
35			G_R4	2.00				Note: assumes ribbon manufacture														
36			G13_l	777.78	MPa	lower limit																
37			G13_u	864.20	MPa	upper limit								Parameters		Units						
38			G13	787.595	MPa	out-of-plane elastic properties								width (b)	0.05	m						
39			G23	518.519	MPa									skin thickness	0.002	m						
40														E_s	7E+10							
41														core thickness	0.02	m						
42			Failure Mechanism	Max Values			Parameters		Units					core + skin (d)	0.022	m						
43		1	Buckling Stress	1.02E+11	Pa		E_s	7E+10	Pa													
44		2	Wrinkling Stress	3.85E+09	Pa		E_c	7E+10	Pa													
45		3	Core Collapse Stress	7.26E+05	Pa		v_s	0.35														
46		4	Shear Failure Stress	4.09E+06	Pa		v_c	0.35														
47		5	Skin Yield (Compression) Stre	2.40E+08	MPa		Alpha	0.005	m													
48		6	Skin Yield (Tension) Stress	2.40E+08	MPa		thickness (skin)	0.002	m													
49							rho_h	83.14	kg/m3													
50			Constants				rho_c	2700	kg/m3													
51			C_1				Aluminium Yield :	240000000	Pa													
52			C_2																			
53			C_3																			
54			C_4																			
55			C_5																			
56			C_6																			
57																						
58			Force (N)	200																		
59		c_1	Deflection (m)																			
60		c_2	skin axial maximum (normal in x direction)																			
61		c_3	skin axial minimum (normal in x direction)																			
62		c_4	core compression maximum (normal z direction)																			
63		c_5	abs(core shear stress) maximum																			

Figure 7.1 Excel Data Sheet Used to Calculate Honeycomb Core Density, Average Panel Density and Maximum Appliable Stresses

	A	B	C	D	E	F	G	H	I
1	F	134324	N						
2	DELTA	3.9	mm	c1	34442.05128	n/mm			
3	EI	5740.34188	N/m2	c2	0.008693904	Mpa/N			
4	SKIN AXIAL MAX	1167.8	Mpa	c3	-0.019123909	Mpa/N			
5	SKIN AXIAL MIN	-2568.8	Mpa	c4	-0.001584974	Mpa/N			
6	CORE THROUGH MIN	-212.9	Mpa	c5	0.000235848	Mpa/N			
7	CORE SHEAR MAX	31.68	Mpa						
8	L	200	mm	bucking (f)	283295.3029	Mpa	f1	14813671	N
9	ES	71000	Mpa	wrinkling(f)	4351.796294	Mpa	f2	227557.88	N
10	EC	71000	Mpa	core collapse (f)	0.977803537	Mpa	f3	616.92101	N
11	VS	0.33		shear failure (f)	6.583384428	Mpa	f4	27913.716	N
12	VC	0.33		Compressive yield			f5	13072.641	N
13	t	2	mm	Tensile Yield			f6	28755.78	N
14	ph	99.51	kg/m3						
15	pc	2770	kg/m3						
16	sigma c	250	Mpa						
17	sigma y	250	Mpa						
18	cell size	3	mm						
19	Average density	1189.30864	kg/m3						
20	ratio	0.20718429							
21									
22	Mass Core	0.014927							
23	Mass Skin	0.01662							
24	Volume Core	0.00015							
25	Volume Skin	0.000006							
26	Force 1/4	33581							
27									
28									

Figure 7.2 Excel Data Sheet Used to Calculate Minimum Failure Force and Constants of Linearity.

8. References

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