THE EFFECT OF CORE ARCHITECTURE ON THE BEHAVIOUR OF SANDWICH COLUMNS UNDER EDGEWISE COMPRESSION LOADING

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ABSTRACT

Sandwich structures are a form of construction that offers high performance and low-weight. This type of construction became popular by the mid of the twenty century where different metallic faces and core materials were used for the construction of aircrafts and marine vessels. The development of high-strength, high-modulus, light-weight fibres and new forms of core materials has opened a new horizon for sandwich structures.

Using sandwich structures for columns was investigated by different researchers. However, none of the located literature reported using strong-weak core (mixed-core) materials in sandwich columns. To investigate the effect of using mixed-core on the column behaviour was investigated by testing five sets of prototype columns under edgewise compression. The column cores were made of PVC low-density foam, end-grain balsa wood or a combination of both materials. The column skins were laminated by using glass/epoxy composites. The test results showed that the mixed-core can lead to having a failure mode that has not been reported previously.

This paper presents the experimental work conducted in testing these columns. It highlights the effect of core structure on the failure mode and capacity of the sandwich columns.

KEYWORDS

FRP, sandwich, column, core.

INTRODUCTION

The sandwich form of construction is a relatively new system. The Second-World-War "Mosquito" aircraft is often referred to as the first major structure that incorporated sandwich panels. However, some records refer to Fairbairn (1849) and even as early as Leonardo da Vinci (Allen, 1969). Sandwich structures started to gain popularity by the middle of the 20th century when different metallic faces and core materials were used for the construction of aircrafts and marine vessels. This popularity is attributed to its characteristics of light-weight, high stiffness, and excellent absorption of mechanical and sound energy. The development of high-strength, high-modulus, light-weight fibres and new forms of core materials has opened a new horizon for sandwich structures where the structural properties can be fully adapted to the design requirements. In addition, the orthotropic nature of the composite materials, along with the flexibility in selecting the fibre types and architecture, can significantly increase the buckling capacity of the sandwich structure (Librescu and Hause, 2000).

The first published paper, which dealt with in-plane compression loads, was by Marguerre (1944). As metallic skins and cores were the original materials used for sandwich structures, first investigations had focused on the behaviour of this form of sandwich structure. During the 1950s, the US Forest Products Laboratory (USFPL) was the primary group in developing analysis and design methods for sandwich structures. Their effort led to publishing the military design handbook MIL-HDBK-23 (Anon, 1955) that was continuously updated until being cancelled in 1988. For many years, Allen (1969) and Plantema (1966) were the most popular references that provided simplified and practical approaches to the analysis and design of sandwich structures.

Four failure modes for sandwich columns (two global and two local) are presented in the MIL-HDBK-23 (Anon, 1955) and found in many references such as Vinson (1999), and Fleck and Sridhar (2002). In addition to the overall buckling of the column (Figure 1a), shear crimping failure (Figure 1b) is another form of general overall buckling in which the wavelength of the buckles is very small, because of the low core-shear modulus. The

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crimping of the sandwich occurs suddenly and usually causes the core to fail in shear at the crimp; it may also cause shear failure in the bond between the facing and the core. It is important to note that the critical skin stress, where core shear instability can occur, is independent of the column dimensions. However, it is related to the core and skin properties and the boundary conditions (Vinson, 1999). If the core is of cellular structure, honeycomb, it is possible for the facings to buckle or dimple into the spaces between core walls or corrugations as shown in Figure 1c. Wrinkling is the fourth form of failure (Figure 1d). It can occur if the skin buckles inward or outward, depending on the flat-wise compressive strength of the core relative to the flat-wise tensile strength of the bond between the facing and the core. If the bond between the facing and the core is strong, facings can wrinkle and cause tension failure in the core. This simulates plate-on-elastic foundation. The wrinkling load depends upon the elasticity and strength of the foundation system, namely, the core and the bond between the facing and the core. Since the facing is never perfectly flat, the wrinkling load will also depend upon the initial eccentricity of the facing or original waviness (Allen, 1969).

Face plastic micro-buckling failure is a shear buckling instability of the face fibres due to large shear strains in the face matrix (Fleck, 1997). The shear yield strength of the composite and the initial fibre misalignment angle are the main factors controlling the micro-buckling compressive strength, Argon (1972) and Budiansky (1983). The compression strength is sensitive to the degree of imperfection (fibre waviness) and the fibre mis-alignment with the loading direction. For sandwich columns, plastic micro-buckling of the skins is the most probable failure mode (Fleck and Sridhar, 2002). It occurs when the axial compressive stresses in the skins attains the plastic micro-buckling strength. Progressive end-crushing (Figure 2) was another failure mode that was reported by Mamalis et al (2005). The end-crushing mode of failure can occur in short columns with high-density core material of non-brittle behaviour (typically used in crushing application).

In all the reviewed literature, the concept of using mixed-core for sandwich columns could not be located. However, this concept was used in manufacturing the fuselage of the Vultee BT-15 aircraft (Rheinfrank and Norman, 1944). Using mixed-core materials in sandwich columns can influence their capacity and failure mode. A testing program was conducted in the Centre of Excellence in Engineered Fibre Composites – University of Southern Queensland to highlight the effect of using mixed-core on the failure mode and capacity of sandwich columns. This paper presents the experimental work conducted in testing five column sets, where the ratios of the mixed-cores changed from the weak core to the strong core.
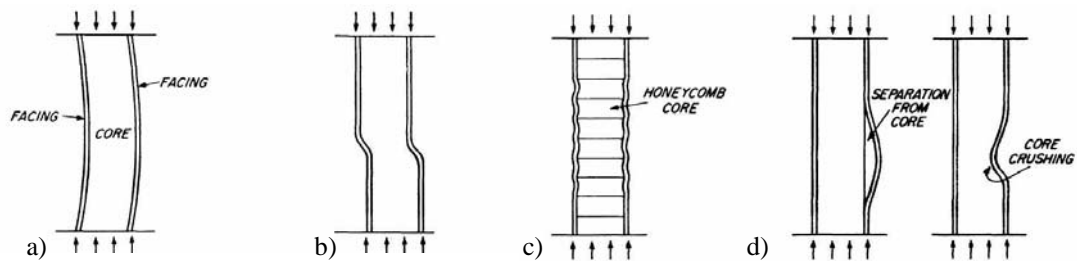

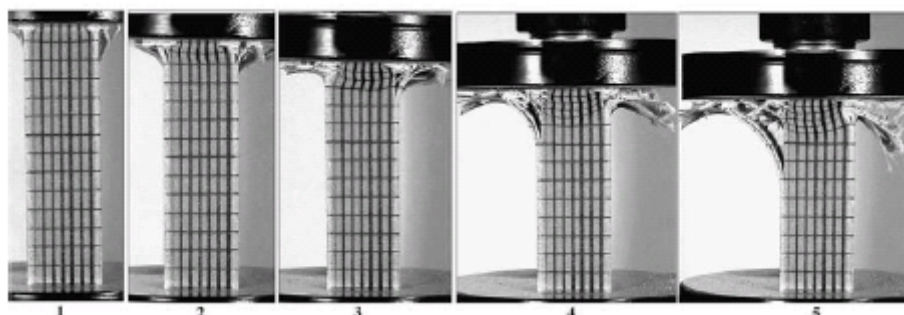Figure 1. Modes of failure in sandwich panels under edge load - MIL-HDBK-23 (Anon, 1955)

Figure 2. Progressive end-crushing failure mode for sandwich columns (Mamalis et al, 2005)

Test Specimens and Material Properties

Prototype columns of 550mmL (460mm clear height) x 120mmW were manufactured, with the cross-section layout as shown in Figure 3. Column skins were manufactured from Hyrez 202 Bisphenol-A epoxy resin system with polyamine-based hardener (Rogers, 2004) and three layers of uni-glass fibres (450gsm). The skin properties

were characterised by testing coupon specimens in tension (ISO527-4-1993) and compression (ISO14126-1999). These testing were conducted on both of the two principal directions of the laminate (1-1 & 2-2). The glass content of the laminated skins was 41.4% (ISO1172-1999). Summary of the skin properties are shown in Table 1.

SB100 end-grain balsa (core1, Figure 3) and Klegecell-R45 PVC closed-cell foam (core2, Figure 3) were used for the column cores with the widths and shear modulus shown in Table 2. The column cores were of 20mm thickness. Two methods were used to assess the shear modulus of the core materials. The first method was the flexure method (ASTM C393-00) while the second was the developed rocket test method (Figure 4). The rocket test method was developed after difficulties in determining the SB100 shear modulus by using the ASTM method. The Rocket test specimens were manufactured from loading members of 250mmL (made of pultrusion section SHS50x50x5), core material specimens (two pieces cut to dimensions of 200mmL x 50mmW x 20mmThk), and HPR26 thixotropic-toughened epoxy adhesive system. After assembling each specimen on a special jig, specimens were left to cure for 24 hours at ambient temperature. The test specimens were then post-cured at 60°C for 2 hours with 1 hour ramp to ensure obtaining sufficient stiffness of the adhesive layers. Excess glue was then removed by sanding and the specimens were squared to ensure loads applied parallel to the core plane. After conditioning the specimens for 24 hours in 23°C temperature and 50% relative humidity, they were tested as shown in Figure 4b. The applied loads was recorded by the MTS Alliance RT/10 testing machine with the relative movement between the middle and outer pultrusions recorded by laser extensometer at acquisition rate of 200Hz. The shear modulus was calculated by using Equation 1 with typical load-deflection curves shown in Figure 5. More clearly shown in Table 2, the estimated shear modulus of the SB100 core (using ASTM C393-00) was much less than that obtained from the Rocket test and the product data sheets. However, for R45 foam, all the figures were close. This can suggest that for more rigid cores, Rocket testing can be good testing procedures to assess the shear modulus of the core.
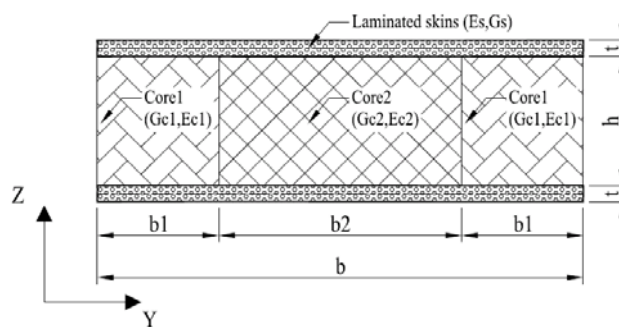

Figure 3. Cross-section of the mixed-core column

Table 1. Skin laminates material properties

Thk/ply	ISO1172-1996	ISO527-4-1993 Tensile Properties (MPa) in				ISO14126-1999 Compression Prosperities (MPa) in			
	Glass	1-1 direction		2-2 direction		1-1 direction		2-2 direction	
(mm)	Content %	E	σ	E	σ	E	σ	E	σ
0.697	41.40%	18607	363.2	5707	24.3	24519	360.7	7939	96.65

Table 2. Mixed-core column geometries

Column	Core Width (mm)		Core Shear Modulus (MPa)		
	b1(SB100)	b2(R45)	ASTM C393-00	Rocket	Data sheets
T01	0	120	16.58	14.99	14.00
T02	15	90	25.45		
T03	20	80	25.09		
T04	30	60	29.88		
T05	60	0	33.73	159.00	159.00

$$G = \frac{St}{2Lb} \qquad (1)$$

Where,

        G: Core material shear modulus

        S: Initial linear slope of the load deflection curve

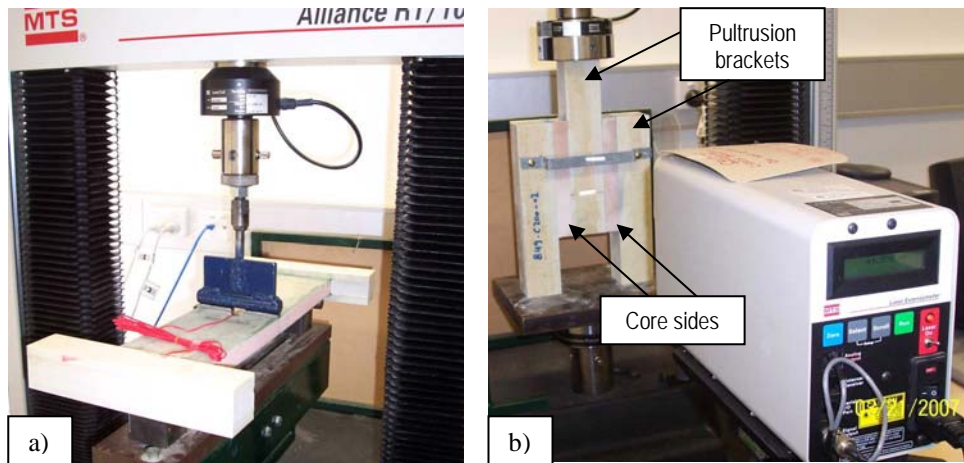   t, L & b: Average core thickness, length & width (of both sides)

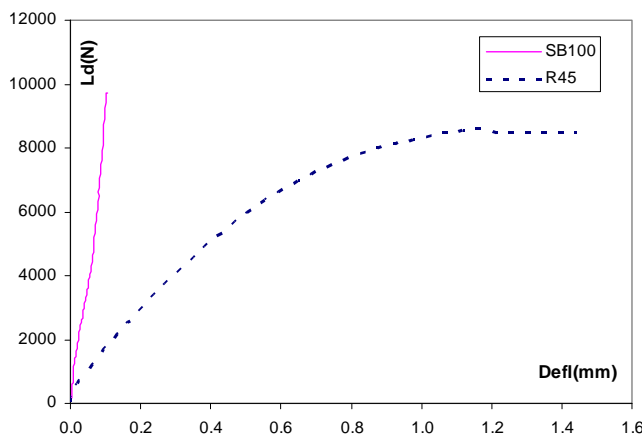Figure 4. Characterising core materials a) ASTM C393-00 3-point test, b) Rocket test

Figure 5. load-deflection curves for the core materials

Figure 6. Columns test set-up

Test Set-up

Column tests were conducted on Shimadzu CSP-300 machine. Clamped-end restraints were implemented using a special fixture attached to the machine ram (Figure 6) with applied loads recorded by 222kN loading cell, vertical displacement recorded using string pot, and horizontal displacement recorded using LVDT while strain gauges were attached at the mid-height of the column at both faces. All data were collected by System 5000 data-acquisition system and recorded on a standard PC at 10Hz. Displacement-controlled loads were applied at a rate of 0.5mm/min.

Test Results and Discussions

Generally, the test results were consistent for each set of columns. Increasing the SB100 core percentage continuously increased the column capacity with slight increase in the column weight. Figure 7 show the relative capacity and stiffness of the tested columns to column T01 with the X-axis representing the percentage of the SB100 in the core. As expected for sandwich columns, the core material had minor effect on the column stiffness. It was observed that the load-deflection and the strain-load curves were linear until failure with complete loss of strength once reached the ultimate capacity. At failure, the ratio of the minimum strain to the maximum strain recorded at the two skins ranged from 70%-80% for the different columns.

A few failure modes were observed. For single core columns, T01 column failed in global buckling mode (Figure 8a) while T05 column failed in two modes, skin micro-buckling (Figure 8b) and shear crimping (Figure 8c). In spite of having two modes of failure, T05 specimens failed at close margin of load, within 7% of the average capacity. For mixed-core columns, two failure mode combinations were observed. For columns with high percentage of SB100 (T04), shear crimping dominated the failure mode (Figure 9a), while for T02 and T03, face wrinkling dominated the failure mode (Figure 9b). In addition to the dominant failure, shear failure was observed in the column skins along the lines separating the components of the core materials. The shear

crimping failure was accompanied by debonding of the skins from the core material, while the face wrinkling was accompanied by skin micro-buckling at the SB100 cores and shear failure in the R45 cores (Figure 9).

The behaviour of T01 was very well predicted. However, the failure of T05 in shear crimp mode was surprising due to the high shear modulus of the SB100 (Table 2). The estimated micro-buckling failure stress of T05 was 259MPa, which was significantly less than the predicted value obtained during the characterisation program (Table 1). The combined failure modes were found unique for mixed-core columns.
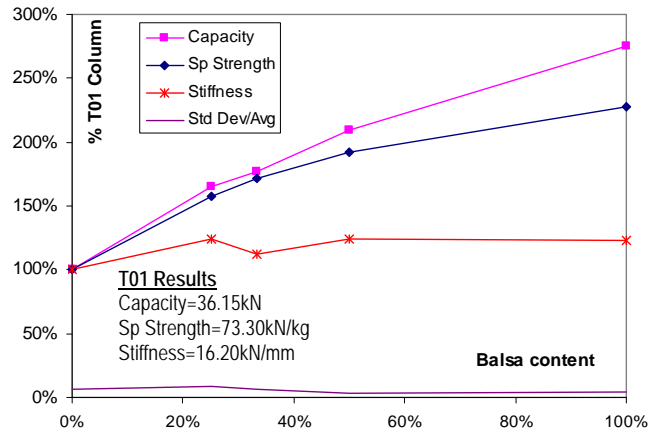

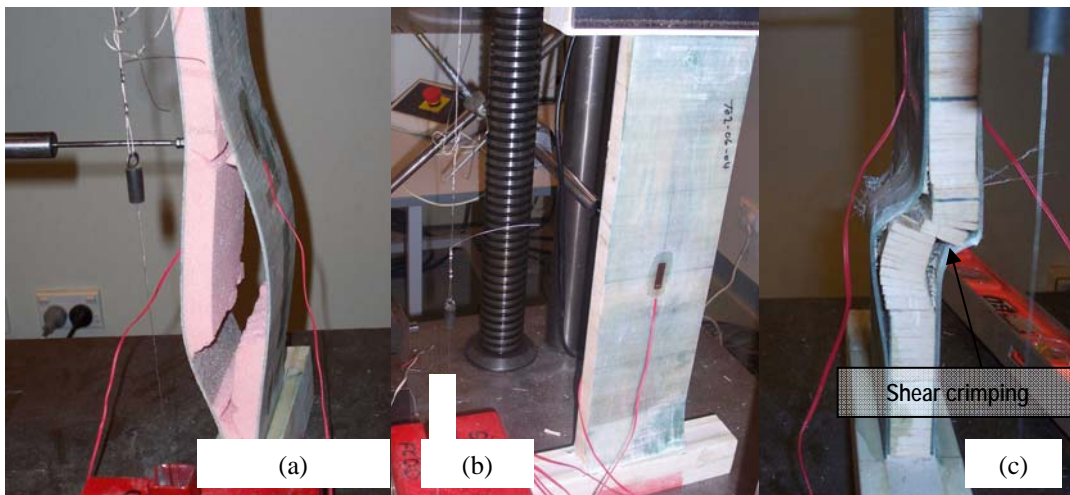
Figure 7. Column capacities and stiffness

Figure 8. Single-core columns failure modes (a) T01 buckling, (b) T05-skin micro-buckling, (c) T05-shear crimping
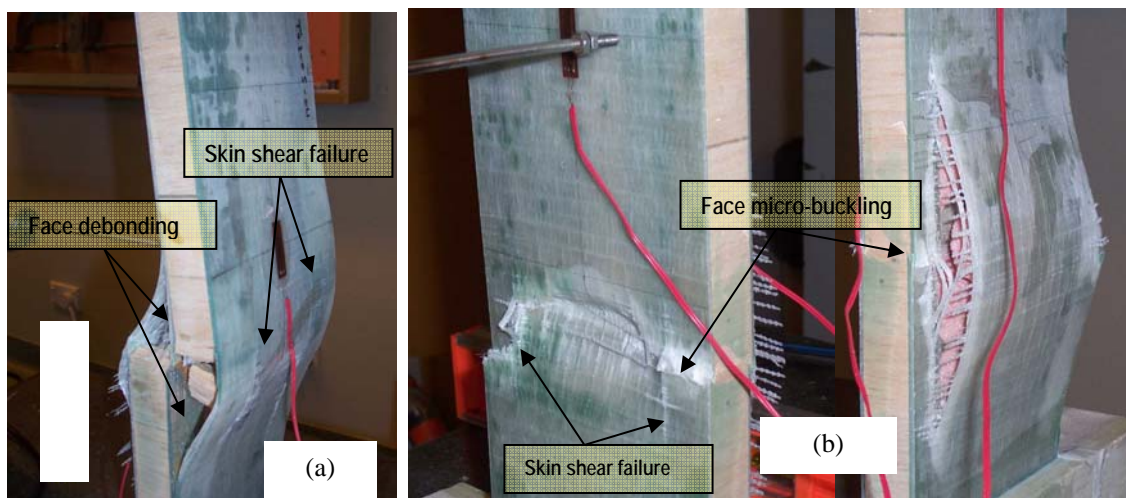

Figure 9. Mixed-core columns failure modes (a) shear crimping, (b) Face wrinkling and skin micro-buckling

Currently, further investigations are undertaken to explain having the different modes of failure in balsa-core columns. In addition, the concept of using mixed-core needs further research. This concept can provide load redundancy, by controlling the failure mode, to avoid the sudden failure observed in sandwich columns. Furthermore, it can provide tools to optimise the column behaviour.

CONCLUSIONS

Experimental data for the tested sandwich columns were presented in this paper. The tested columns had similar skin architecture and testing layout with different core contents. The column cores were made of PVC low-density foam, end-grain balsa wood or a combination of both materials. Increasing the core shear modulus shifted the single-core column failure modes from global buckling (PVC foam core). Single-core balsa columns failed in two different modes, at close ultimate capacity. The first failure mode was due to shear crimping. The second failure mode was due to face micro-buckling at the bottom end of the column. There was no clear explanation why this column set had these two modes of failure and why it failed at lower load than expected.

The usage of mixed-core concept complicated the column failure by introducing a combination of failure modes for these columns. For columns with high content of balsa, shear crimping dominated the column failure. However, face wrinkling dominated the columns with high percentage of low-density PVC core. In both cases, shear failure in the skins along the interface between the two core materials was observed.

For rigid core materials, some difficulties were observed in assessing the core shear modulus, by using existing standard. The proposed Rocket test procedures showed potential of overcoming these difficulties.

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