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LETTER

Compression properties of z-pinned sandwich composites

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Sandwich composites are ultra-light weight structural materials consisting of thin face skins covering a low-density core. The skins are made of metal alloy sheet or fibre-reinforced polymer laminate, and provide the sandwich composite with high in-plane mechanical properties. A variety of low-density materials are used in the core, with the most common being metallic honeycomb, polymer foam, syntactic foam, Nomex® and balsa. Sandwich composites are used in a large number of structural applications because of their high in-plane properties and light-weight, including in aircraft, ships, rail carriages and buildings.

A major limitation of sandwich composites is their low through-thickness compression properties, which are determined by the compliant and weak core material. The compression modulus and strength in the through-thickness direction is less than 10% of the in-plane properties for most types of sandwich composites, and this has limited their use in structures that must support high through-thickness compression loads. A method to improve the through-thickness compression properties is z-pinning, which involves inserting high modulus, high strength pins through the sandwich material. The mechanical performance of z-pinned sandwich composites have not been thoroughly characterised, and there are few micro-mechanical models to predict their structural properties. Previous research has revealed that z-pinned sandwich composites possess improved damage tolerance [1, 2], and Cartiѐ and Fleck [3] recently showed that the through-thickness compression strength of foam core sandwich materials is increased with fibrous composite or metal pins. However, the effects of the volume content and diameter of the pins on the compression properties has not been determined. This paper presents a study to determine the effect of z-pinning on the through-thickness compression properties of sandwich composites. Improvements to the through-thickness compression modulus and strength with increasing volume content and size of z-pins is determined by experimental testing, and a model for predicting the compression properties of z-pinned sandwich composites is presented.

A sandwich composite consisting of fibreglass skins and a poly(vinyl chloride) foam core was reinforced with fibrous composite pins. The skins were a woven glass/epoxy laminate and the core was a closed cell PVC foam with a density of 90 kg/m^3. The sandwich material was reinforced with thin (0.28 mm diameter) T300 carbon/bismaleimide pins to volume contents of 0.5%, 2% and 4%. The material was also pinned using thick (0.51 mm diameter) T650 carbon/bismaleimide pins to the volume content of 2%. Aztex Inc. (Waltham, MA) produced the pins using a pultrusion process that aligned the carbon fibres in the lengthwise direction. The mechanical properties of the pins are given in Table 1. The z-pins were inserted through the sandwich composite using a hand-held ultrasonically actuated horn in a process described by Partridge et al. [4]. The process used is the standard z-pinning technique for reinforcing composite laminates and sandwich materials. A problem with this process is the difficulty in accurately inserting the z-pins in the orthogonal orientation, and the pins are usually offset at a shallow angle. This is a problem often encountered with the z-pinning process, and is difficult to avoid when the pins are inserted manually. Figure 1 presents a histogram showing the percentage of pins offset at different angles from the orthogonal direction in the sandwich composite. The pins are

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Table 1 Mechanical properties of z-pins

	Thin Pins (T300 carbon/bismaleimide)	Thick Pins (T650 carbon/bismaleimide)
Axial compression modulus (E_x)	135 GPa	150 GPa
Transverse compression modulus (E_y)	8.3 GPa	8.3 GPa
Shear modulus (G_{xy})	125 MPa	125 MPa
Axial compression strength (σ_x)	1.59 GPa	1.77 GPa
Transverse compression strength (σ_y)	60 MPa	60 MPa
Shear strength (τ_{xy})	70 MPa	70 MPa
Poisson's ratio (υ_{xy})	0.24	0.24

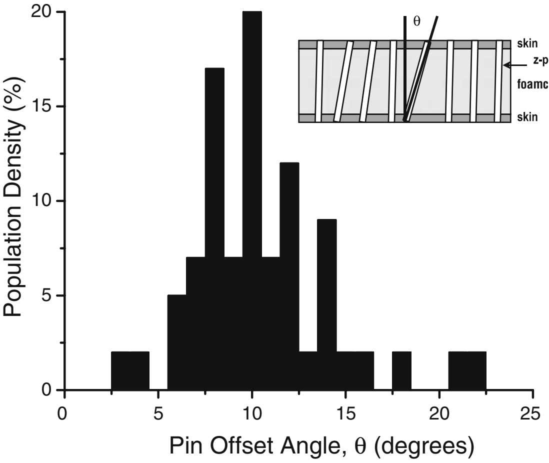

Fig. 1 Histogram plot of pin offset angle against percentage of pins. The schematic shows offset of z-pins in the sandwich composite

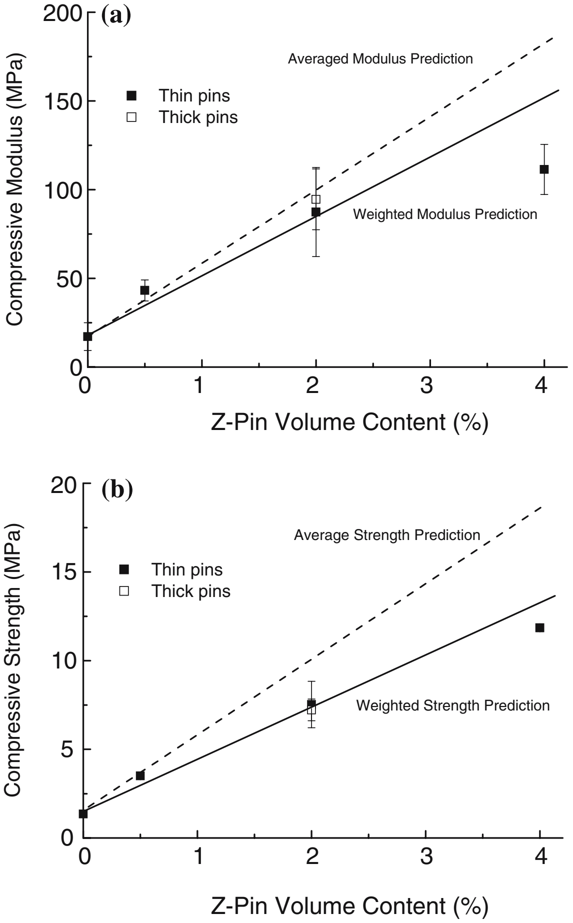

Fig. 2 Effect of z-pin content on the through-thickness (**a**) compression modulus and (**b**) compression yield strength of the sandwich composite

offset over a range of angles (θ) between 4° and 22°, with the average angle being 10°.

Figure 2 shows the effect of the volume content of z-pins on the compression modulus and yield strength of the sandwich composite measured in the through-thickness direction. The composites were tested using 40 mm × 40 mm specimens in flat-wise compression according to ASTM C393 at a loading rate of 1 mm/min. The compression strength is the stress value at which the core experiences irreversible (plastic) deformation. Figure 2 shows the pins are extremely effective at improving the compression properties. The modulus and strength increased at a linear rate with the pin content, with these properties more than doubling with every 1% of z-pins. The compression properties for the sandwich composite reinforced with the thin or thick z-pins to a volume content of 2% are the same, revealing that the pin diameter does not have a significant influence over this size range.

The through-thickness compression modulus of a z-pinned sandwich composite can be calculated using the rule-of-mixtures equation:

$$E = E_c V_c + E_p V_p \tag{1}$$

where V_c and V_p are the volume fractions of the core and z-pins, and E_c and E_p are the compression modulus of the core and pins. The through-thickness strength can be determined using the expression:

$$\sigma = \sigma_c V_c + \sigma_p V_p \tag{2}$$

where σ_c and σ_p are the compression strengths of the core and pin. This equation is valid when the compression yield strain of the core is greater than for the pins, which it is for the material system studied here.

Table 2 compares the measured and calculated compression properties of the sandwich composite. The properties were calculated using the above equations, and it is assumed the z-pins are perfectly aligned in the orthogonal direction (ie. $\theta = 0°$). The measured properties are much lower than the calculated values, particularly the modulus values. The disagreement arises because the compression properties of the pins are greatly reduced when offset from the orthogonal direction, even at a shallow angle. As mentioned, it is difficult to insert all the pins in the orthogonal direction using the manual z-pinning process, and this reduces the potential of the pins to improve the through-thickness compression properties. Table 2 shows that extremely large improvements to the compression properties are predicted when the pins are perfectly aligned in the orthogonal direction.

The compression property values of the pins (E_p, σ_p) are highly sensitive to their orientation in the foam core. It is well known that the compression modulus and strength of unidirectional fibrous composites decrease rapidly with increasing offset angle from the load direction e.g. [5]. The effect of offset angle on the modulus and strength of the unidirectional z-pins can be calculated using the Halpin-Tsai equations:

$$E_p(\theta) = \left[\frac{\cos^4\theta}{E_x} + \frac{\sin^4\theta}{E_y} + \left(\frac{1}{G_{xy}} - \frac{2\upsilon_{xy}}{E_x}\right)\sin^2\theta\cos^2\theta\right]^{-1} \tag{3}$$

and

$$\sigma_p(\theta) = \left[\frac{\cos^2\theta(\cos^2\theta - \sin^2\theta)}{\sigma_x^2} + \frac{\sin^4\theta}{\sigma_y^2} + \frac{\cos^2\theta\sin^2\theta}{\tau_{xy}^2}\right]^{-1/2} \tag{4}$$

The subscripts x and y refer to the directions parallel and normal to the pin axis. G_{xy}, τ_{xy} υ_{xy} are the shear modulus, shear strength and Poisson's ratio values of the z-pins, respectively, and these are given in Table 1.

Because the pins are offset at a range of angles, Eqs. (3 and 4) must be modified using sum-weighted analysis to account for variability in the pin orientation. Using this analysis, the pin modulus and strength can be calculated using:

$$E_p\left(\sum\theta\right) = \sum_{\theta=0}^{\theta=90} V_p(\theta).E_p(\theta) \tag{5}$$

and

$$\sigma_p\left(\sum\theta\right) = \sum_{\theta=0}^{\theta=90} V_p(\theta).\sigma_p(\theta) \tag{6}$$

where $V_p(\theta)$, $E_p(\theta)$ and $\sigma_p(\theta)$ are the volume fraction, compression modulus and compression strength of the pins at a given angle, θ.

The predicted increase in the through-thickness compression modulus and strength of the sandwich composite using the rule-of-mixtures model is plotted in Fig. 2. The curves labelled 'average modulus prediction' and 'average strength prediction' were calculated using Eqs. (3, 4). These calculations were performed assuming the average pin offset angle was 10°. Equations 5 and 6 were used to calculate the curves 'weighted modulus prediction' and 'weighted strength prediction', and the variation in pin angle shown in Fig. 1 was used in the analysis. The curves for the thin and thick pins are superimposed into a single curve because their mechanical properties are virtually identical. It is seen in Fig. 2 that the weighted predictions give a more accurate estimation than the average predictions in the increase to the through-thickness compression properties with z-pin content. This demonstrates the weighted modelling approach can be used to predict the through-thickness compression modulus and strength properties of z-pinned composites.

The model can be used in the design of z-pinned sandwich composites to determine the optimum type and amount of pins. Figure 3 presents design maps showing the calculated improvement to the through-thickness compression properties of sandwich materials reinforced with different z-pin materials up to a volume content of 10%. It is assumed that the pins are aligned in the orthogonal direction, although it is possible to generate maps for pins offset at various angles using the modelling approach outlined above. It is seen in Fig. 3 that large improvements to the compression modulus and strength of sandwich composites are predicted using small amounts of z-pins made of fibrous composite, metals or carbon nanotubes. However, experimental data supporting these predicted improvements to the compressive properties is not available. Furthermore, z-pins made from carbon nanotubes

Table 2 Measured and calculated compression properties of the z-pinned sandwich composite It is assumed the z-pins are in the orthogonal direction

	Compression modulus (MPa)	Compression strength (MPa)	Measured	Calculated
	Measured	Calculated		
0.5% thin z-pins	43 ± 6	692	3.5 ± 0.2	9.3
2.0% thin z-pins	87 ± 25	2710	7.5 ± 1.3	33.1
2.0% thick z-pins	95 ± 17	3017	7.2 ± 0.6	36.7
4.0% thin z-pins	111 ± 14	5416	12.0 ± 0.2	64.7

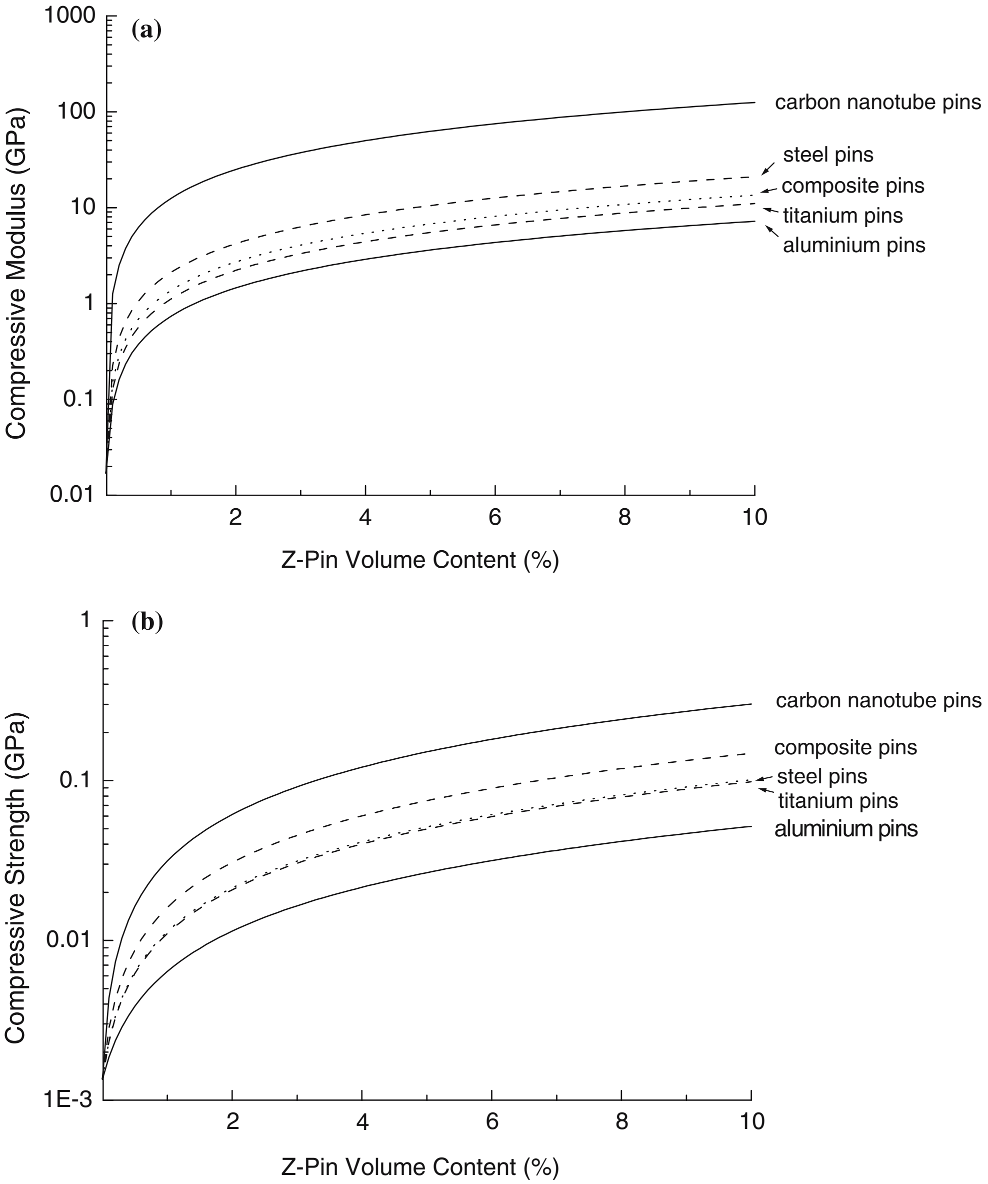

Fig. 3 Design maps showing the calculated improvement to the through-thickness (**a**) compression modulus and (**b**) compression yield strength of sandwich composites having a low modulus, low strength core. The steel is taken to be a high strength low alloy steel, the titanium alloy is Ti–6Al–4V, the aluminium alloy is 7075 Al–T651, the fibrous composite is T300 carbon/bismaleimide, and the carbon nanotubes are single-walled tubes

cannot yet be manufactured, and methods for inserting nano-pins have not been determined.

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