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CHARACTERISTIC VALUES OF PULTRUDED FIBRE COMPOSITE SECTIONS FOR STRUCTURAL DESIGN

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ABSTRACT

Characteristic values of structural products are fundamental pieces of information for design engineers. Such properties are to be established considering variables between products and deviations of selected samples as representative of all products. The correspondence with design principles and applications are also to be ensured accordingly. For conventional structural products, national and international test standards provide guidelines to evaluate a variety of material properties. Design standards or guidelines then provide the procedure for implementing the tested properties for structural design.

This paper presents a procedure for evaluating characteristic values of pultruded fibre composite square hollow sections (SHS). Detailed material tests and estimated characteristic values are summarised in accordance with a selected design guideline and test standards. Furthermore, analysis of the tests and detailed observations are presented that particularly focus on non-linear behaviour under various types of loadings.

KEYWORDS

Design, FRP, fibre composites, non-linear behaviour, pultrusion

INTRODUCTION

Evaluating material properties for structural design can be a simple procedure beginning with a set of material tests followed by analysis of the results and evaluation in accordance with relevant test standards. The evaluated values can be then used for structural design after being adjusted by factors specified by relevant design standards or guidelines. Such a simple procedure can become complicated and may produce variable results if each of the test methods and design guides do not follow the same design principle (e.g. for material tests, adapting member tests rather than coupon tests may result in considerably different values, ASCE 2010)

A procedure is proposed herein for evaluating the characteristic values of a 100x100 Square Hollow Section (SHS) produced by Wagners CFT. The procedure included a series of material tests followed by the implementation of an evaluation procedure. As a design reference, pre-standard ASCE (2010) has been selected and relevant national and international test standards are also referred to for the material tests. The pre-standard follows the ultimate states design principle (i.e. ultimate limit states and serviceability limit states) and adapts a specific design format of Load and Resistance Factor Design (LRFD). A schematic diagram of the proposed procedure is shown in Figure 1, while detailed information and comments are presented in the following sections.

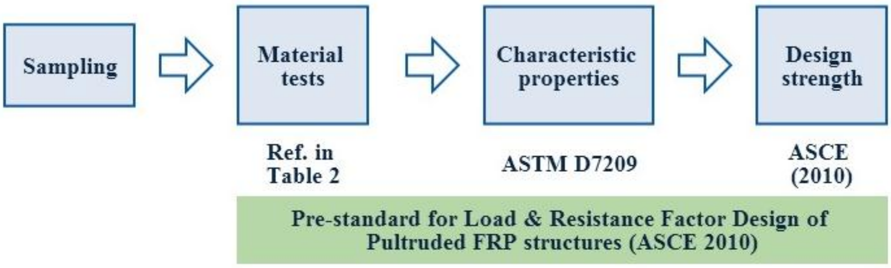
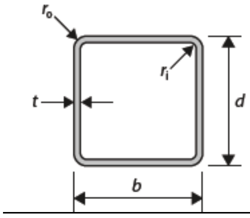


Figure 1. Analysis procedure

MATERIALS AND SAMPLING

The 100x100 SHS under consideration is a fibre composite structural section manufactured by a pultrusion process using glass fibre and vinyl ester resin. Continuous fibre is laid in the longitudinal direction of the pultruded section in addition to fibres wound at ±50 ° to the longitudinal axis. The nominal percentage of each longitudinal and wound fibre is 48% and 10% by volume, respectively. General information of the section is given in Table 1.

Table 1. 100x 100 SHS

	**Dimensions**					**Section properties**	
	b	d	t	r_0	r_i	Mass	Sectional area
			(mm)			(kg/m)	(mm^2)
	100	100	5.2	10.0	4.75	3.87	1910

The test specimens were randomly selected from a certain period of product manufacture. Ten pieces in total of 1.2 m long 100x100 SHS were selected from a total of 4432 linear meters of product that was manufactured over a 5 day period in December 2013.

MATERIAL TESTS

According to the design standard, a total six sets of tests were undertaken in order to consider variable fibre directions as well as tensile, compressive and shear actions. A detailed breakdown is provided in Table 2. A minimum of ten test specimens was prepared for each material property for the purpose of calculating characteristic values in accordance with ASTM D7290 as specified by the design standard. All tests adhered to the test standards indicated in Table 2 while some modification was adapted for selected tests due to geometry. For example, the maximum flat length of test specimen perpendicular to the fibre direction (i.e. 90 °tests) was limited to 80 mm (refer to dimensions in Table 1). A universal test machine was utilised for all material tests.

Table 2. Test details and specimen numbers

Property	Tests	No. specimen	Standard
Tension	Tension - 0 °	14	AS 1145 (ISO 527)
	Tension - 90 °	10	
Compression	Compression - 0 °	11	ISO 14126
	Compression - 90 °	14	
Shear	In-Plane Shear	10	ASTM D7078
	Interlaminar Shear	10	ASTM D 2344

TEST RESULTS

A summary of the material property tests is provided in Table 3. Due to space limitations, average (AV), standard deviation (SD) and Coefficient of Variation (CoV) results are provided. In addition, stress-strain responses of test specimens are provided in Figures 2 and 3. Tests were instrumented with extensometers and strain gauges, and the test results arising from strain gauges are only provided.

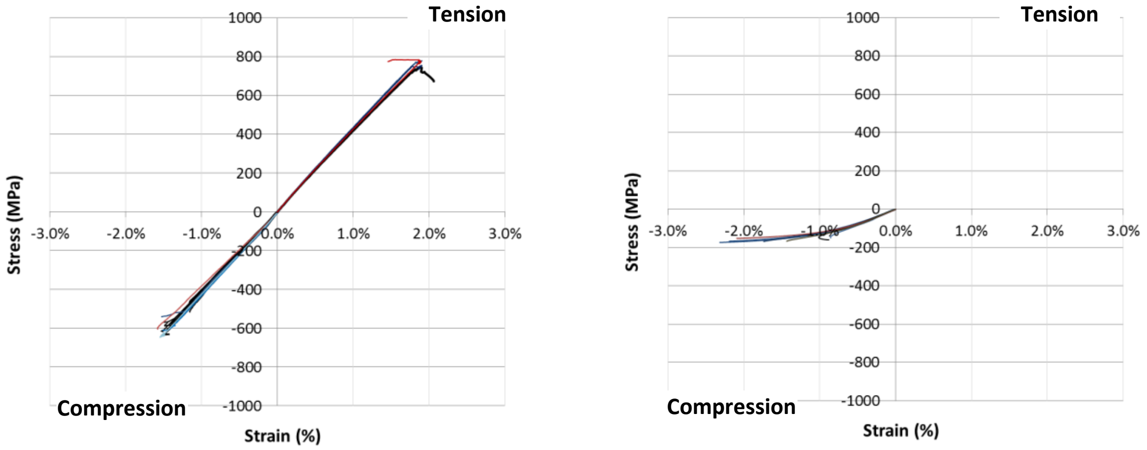
Table 3. Summary – Material property tests

Tests		Maximum Stress (MPa)	Modulus (MPa)
Tension - 0 °	AV	720.68	41,916
	SD	36.30	1,537
	CoV	5.04%	3.67%
Tension - 90 °	AV	67.50	12,340
	SD	4.03	572
	CoV	5.97%	4.64%
Compression - 0 °	AV	591.03	39,616
	SD	39.84	1,653
	CoV	6.74%	4.17%
Compression - 90 °	AV	153.97	15,116
	SD	12.37	1,380
	CoV	8.04%	9.13%
In-Plane Shear	AV	107.17	5,416
	SD	4.13	333
	CoV	3.85%	6.15%
Interlaminar Shear	AV	50.06	N/A
	SD	1.87	N/A
	CoV	3.73%	N/A

AV= average, SD = Standard Deviation, CoV = Coefficient of Variation

Tension and compression

Overall, the tension and compression test results are quite consistent in both maximum stress and elastic modulus (i.e. not more than 10 % variation). Comparing the tension and compression modulii, the tension modulus is approximately 6 % higher than that of compression in the longitudinal direction (i.e. main fibre direction denoted by ‘0°’ in Table 3). The transverse direction test results, however, show that the compression modulus is higher than the tension modulus by approximately 22 %. Also, the same trend can be found in the stress test results.



(a) Longitudinal direction (0 °)

(b) Transverse direction (90 °)

Figure 2. Stress-strain responses: Tension and compression (0 °, 90 °)

According to the stress-strain responses provided in Figure 2a, longitudinal direction tests show expected linear-elastic behaviour. Failure then occurs without a significant change in the slope (i.e. stiffness) of the response.

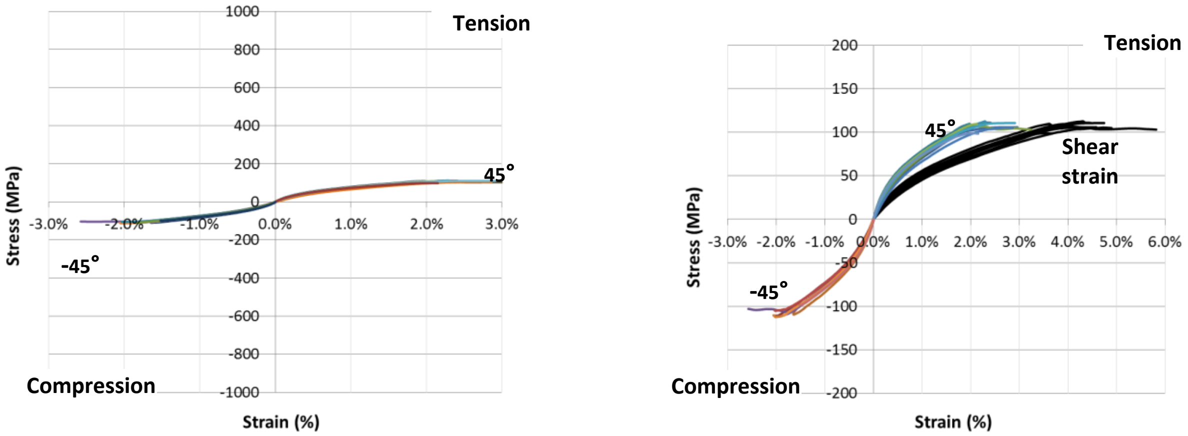
The behaviour of the composite in transverse compression (Figure 2b) shows typical non-linear elastic-plastic behaviour which is dependent on the characteristics of the resin. The specimens show linear behaviour at lower loading although elongation increases at a more rapid rate as the load is increased. The results were quite scattered at failure.

As all transverse tension tests were undertaken with an extensometer which measured elongation in lower stress range just for the modulus estimation, the full tress-strain curve response could not be provided in the tensile range. According to the recorded cross-head movements (although it would not be precise elongation information), there was a sudden change in the rate of elongation and fluctuation of the applied load observed at higher stress (i.e. approximately 70-80 % of the peak load). Further investigation is planned to more accurately determine such transverse tensile behaviour.

Shear

Two types of shear tests showed consistent results in both strength and modulus as given in Table 3. In accordance with the test standard (i.e. ASTM D2344), only the maximum interlaminar shear stresses were recorded. The stress-strain responses of in-plane shear specimens showed typical non-linear elastic-plastic behaviour as previously reported by other researchers (e.g. Bank 1990). The tests followed the standard v-notched rail shear method (ASTM D7078) and measured the force and strains accordingly.

Two directional elongations (i.e. ±45 ° strains with respect to longitudinal fibre direction) are plotted with the estimated shear stress Figure 3a. The estimated shear strain (i.e. denoted by 'Shear strain' in Figure 3b) of the tested specimen is calculated from the sum of the plotted two directional strains (i.e. add absolute values of both ±45 ° strain results) in accordance with test standard. The presented ±45 ° stress-strain responses, however, represent tension and compression behaviours of the tested specimen in each direction. Similar to the transverse compression behaviour, both direction test results show linear behaviour at lower loading followed by plastic deformation at higher level loading.



(a) Each ±45 ° only (b) All

Figure 3. Stress-strain responses: Shear (±45 °)

CHARACTERISTIC VALUES

The characteristic value of each material property was estimated based on tested maximum strength and initial chord moduli in accordance with ASTM D7290. The estimated values are statistically determined material properties representing the 80 % lower confidence bound on a 5th percentile value of a specific population. The estimated values can be used as reference strengths for design purposes and a summary is provided in Table 4. It should be noted that additional adjustment (e.g. environmental and load shearing factors) should be undertaken in accordance with design guidelines before being used for design.

Table 4. Characteristic material properties: Summary

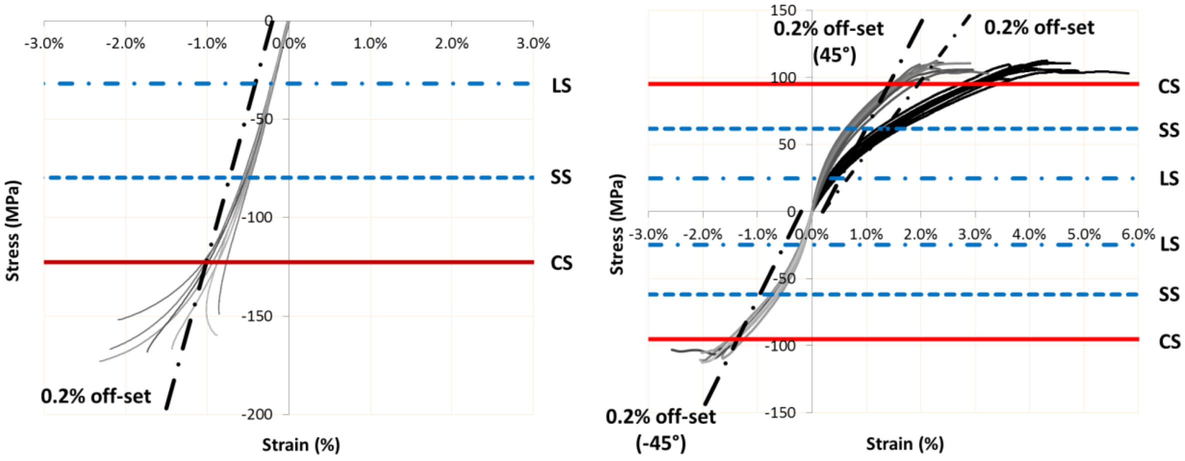
Test	**Tension**		**Compression**		**In-Plane Shear**	**Interlaminar Shear**
	0 °	**90 °**	**0 °**	**90 °**		
Characteristic Strength (MPa)	611.93	54.79	485.70	122.65	95.08	43.90
Characteristic Modulus (MPa)	37,401	10,820	34,684	11,604	4,414	-

DISCUSSION

According to the test results, the material properties can be classified into two categories, namely (i) fibre dominant property, and (ii) resin dominant property. Such classification mainly originates from the nature of orthotropic materials while and the characteristic of the dominant material governs the behaviour. For example, the tested longitudinal tension and compression behaviour (Figure 2a) shows linear-elastic behaviour and it is typical behaviour of fibre material.

The typical behaviour of a resin matrix can be found from the transverse compression and shear test results provided in Figures 2b and 3. Such non-linear elastic-plastic behaviour can be commonly found from conventional construction materials (e.g. cold-formed steel and stainless steel). For materials that do not have a distinct yield point but exhibit elastic-plastic behaviour, the 0.2 % off-set proof stress can be used to estimate the yield strength. The use of this method to composite materials has not been specified by the standard (i.e. ASCE 2010) while the 0.2 % off-set strength estimation is included in the shear test standard (i.e. ASTM D7078).

Detailed stress-strain responses of transverse compression and shear tests are shown in Figures 4a and 4b, respectively. In each figure the estimated characteristic strength, as well as short-term and long-term design strengths are also included. The design strengths are calculated by multiplying the tested strength by a strength reduction factor. In particular, a resistance factor of 0.65 (for rupture of material) is multiplied by 1.0 (for short-term) and 0.4 (for long-term) (ASCE 2010). This equates to short-term and long-term strength reduction factors of 0.65 and 0.26, respectively. Finally, the 0.2 % off-set line (based on averaged moduli) is plotted for comparison in Figure 4.



(a) Transverse compression (90 °) (b) Shear (±45 °)

CS=Characteristic strength, ST=Short-term strength (0.65), LT-Long-term strength (0.26)

Figure 4. Characteristic and design values

Considering the estimated short-term and long-term strengths, the stress-strain responses of transverse compression tests show relatively linear behaviour compared with shear test results. The elongations (90° and ±45°) for short-term design strength are not more than 1 % for both transverse compression and shear. Also, the estimated shear strains range from 1.1 to 1.8 %.

For transverse compression strength, the off-set strengths (i.e. stress at the intersection point of 0.2% off-set line and stress-strain curve) range above the characteristic strength but some test specimens did not elongate until reaching the off-set line. As the shear strain was estimated by adding two ±45 ° direction elongations, the shear strains and off-set lines intersect well below that of the two elongations (Figure 4b). It should be noted that the strain gauge measurement at ultimate may not be reliable and the reverse strain measurement (i.e. decreased strain with load increasing in Figure 3) may occur due to localised failure under the strain gauge and/or loss of gauge adhesion.

The importance of permanent deformation under service load should be recognised and considered for estimating the design strength of structural materials. There is, however, no clear guidance for composite materials to date. Further research on plastic deformation under short-term and long-term loading, as well as the corresponding design limits of resin dominant properties is recommended.

CONCLUSIONS

A procedure for evaluating the characteristic values of fibre composite sections was presented in this paper. Detailed information on the test method in addition to relevant references were reported. A simple classification of composite material under various load conditions was also presented based on the test results. Finally, discussion on the non-linear material behaviour of composite materials under transverse compression and shear has also been given along with recommendations for future works.

ACKNOWLEDGEMENTS

The program of study reported herein is part of commercialising Wagners Composite Fibre Technologies pultruded products. Further information shall be provided to the wider public in the future by means of publications and commercial brochures.

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