Effect of Shear on the Flexure of Pultruded GFRP Tubes

by

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Introductory Remarks

- In primary structures circular cross-section GFRP tubes are usually used to resist axial loads
- Several experimental studies have been reported on their compression buckling response
- Circular cross-section GFRP tubes are rarely used as *beams* in primary structures
- Beams are required to have maximum flexural stiffness with respect to the major-axis of flexure
- Circular cross-sections have the same flexural stiffness for all flexural axes
- Hence, circular cross-sections are inefficient in flexure compared to other cross-sectional shapes, e.g. wide flange (WF) profiles

Introductory Remarks (Cont'd)

Fig 1: Guard rail comprised of circular cross-section GFRP tubular posts and rails with multi-part mechanically fastened joints

- **In secondary structures flexural loads are very much lower than in primary structures**
- **Pultruded GFRP circular cross-section tubes are widely used in secondary structures such as guardrails/safety barriers and the flexural loads are generally low**
- **Their advantageous properties: high strength to weight ratio, ease of fabrication, high corrosion resistance, long maintenance-free service life etc. more than outweigh their low flexural stiffness**

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Introductory Remarks (Cont'd)

- Since 2012 a number of experimental/numerical investigations of GFRP guardrails fabricated from circular cross-section tubes have been carried out in the Engineering Department

- The primary loads (specified in the codes) are applied to the top rail normal to the plane of the guardrail.

- Hence, both the top rail and the posts are subjected to flexure

- As far as the Authors are aware, the effects of shear deformation on the flexural properties of the tubes has been ignored, even though sometimes span to diameter ratios may be low

- Because the shear modulus of steel is about 40% of its elastic modulus, shear effects are ignored. However, the corresponding shear modulus percentage for GFRP is about 4%

- Therefore, it is of interest to determine how much a significantly lower shear modulus impacts on the flexural response of pultruded GFRP tubes

- This issue is explored by means of torsion and flexure testing of the GFRP tubes for a range of spans

Constituents of the Pultruded GFRP Tubes

- The tubes used in the experimental investigations were manufactured by the pultrusion process – a long-line process

- The E-glass fibre reinforcement is in the following forms:-

  Rovings – bundles of parallel fibres which run longitudinally along the tube and provide its longitudinal stiffness and strength

  Continuous filament mat (CFM) which provides most of the tubes circumferential stiffness and strength

- A lightweight CFM is used on the tube’s outer surface to promote a resin-rich surface for safe handling and enhance corrosion resistance

- The matrix which encapsulates the fibre reinforcement and facilitates load transfer to the fibres is an isophthalic polyester resin

Torsion Investigation - Test Specimens

Table 1: Mean values of the geometric properties of the pultruded GFRP tubes used in the torsion tests

Test Number	Mean Torsion Span (L) [mm]	Mean Outer Diameter (D_o) [mm]	Mean Inner Diameter (D_i) [mm]	Mean Cross-Sectional Area (A) [mm^2]	Mean Second Moment of Area (I) [mm^4]	Mean Polar Second Moment of Area (J) [mm^4]
1	500	50.0	39.8	719	1.84×10^5	3.67×10^5
2	1000					

- Two lengths of pultruded GFRP tube were used in the torsion tests
- The ends of the tubes were cleaned and deburred prior to measuring their dimensions
- Mean values of their geometric properties are given in Table 1 above

Torsion Test – Test Specimens (Cont'd)

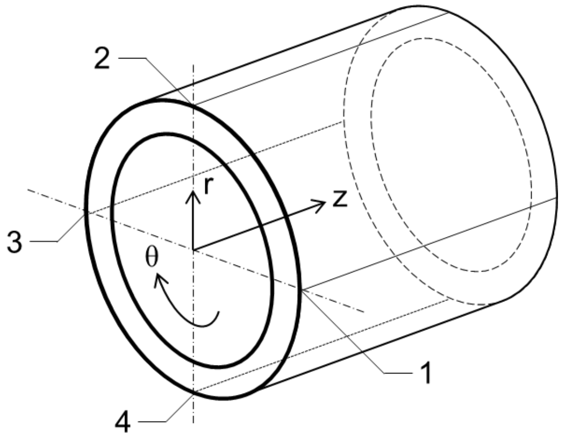

Fig. 2 Cylindrical co-ordinate axes and lines 1 – 4 define the load orientations for the three-point flexure tests

- **Two longitudinal seam lines 180^o apart on the tube surface (see Fig. 2) were labelled 1 and 3**
- **A further two lines – 2 and 4 – oriented at 90^o to lines 1 and 3 are also shown in Fig. 2. The latter lines were helpful for positioning strain gauges on the tube surface**
- **Vernier calipers were used to measure the inner and outer diameters and wall thicknesses of the tubes at the ends of lines 1 - 4**

Torsion Equations the Determining the In-Plane Shear Modulus

- Assuming the GFRP tubes are orthotropic with coincident principal material and geometric axes, then the outer surface shear stress is:-

$$\tau_{\theta z} = \tau_{z\theta} = \frac{TD_0}{2J}$$

- The polar second moment of area is:-

$$J = \frac{\pi}{32}\left(D_0^4 - D_i^4\right)$$

- The in-plane shear modulus is:-

$$G_{\theta z} = \frac{\tau_{\theta z}}{\gamma_{\theta z}}$$

- Using the geometric properties from Table 1 and the known torque, the shear stress in the tube's surface may be determined from the first two equations.

- Using the shear stress together with the measured shear strain, the shear modulus may be found from the third equation

Tube Instrumentation, Test Set-Up and Procedure

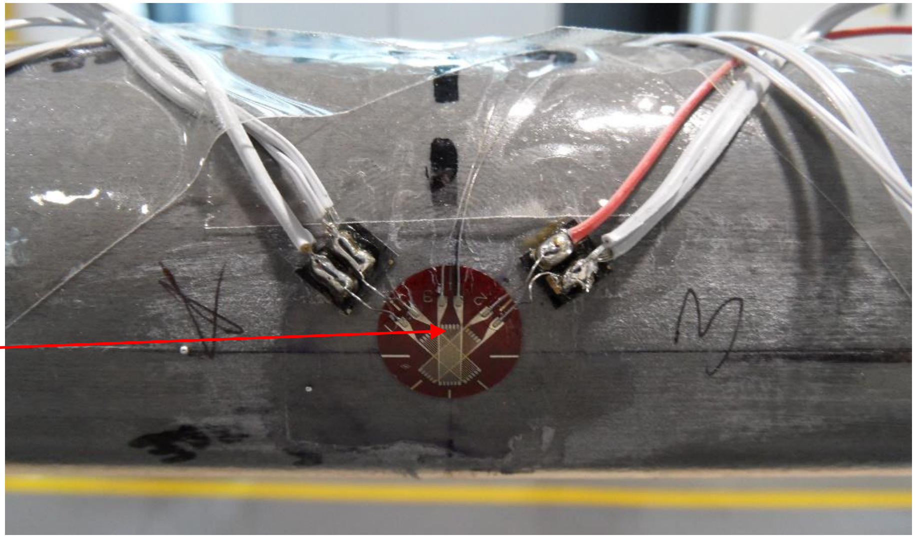

Fig. 3(a): Biaxial strain gauge bonded to the tube wall along Line 1

- **The longer tube (1070 mm) had a 35 mm long plug bonded into each end to give a torsion span of 1000 mm**

- **Two biaxial strain gauges were bonded to the tube at mid-span – one on each of lines 1 and 3**
- **The gauges had their sensitive axes inclined at +/- 45^o to the tube's z-axis**

- **The tube was installed in the torsion rig and the gauges were connected to the data logger and both strain and torque readings were zeroed**

Tube Instrumentation, Test Set-Up and Procedure (Cont'd)

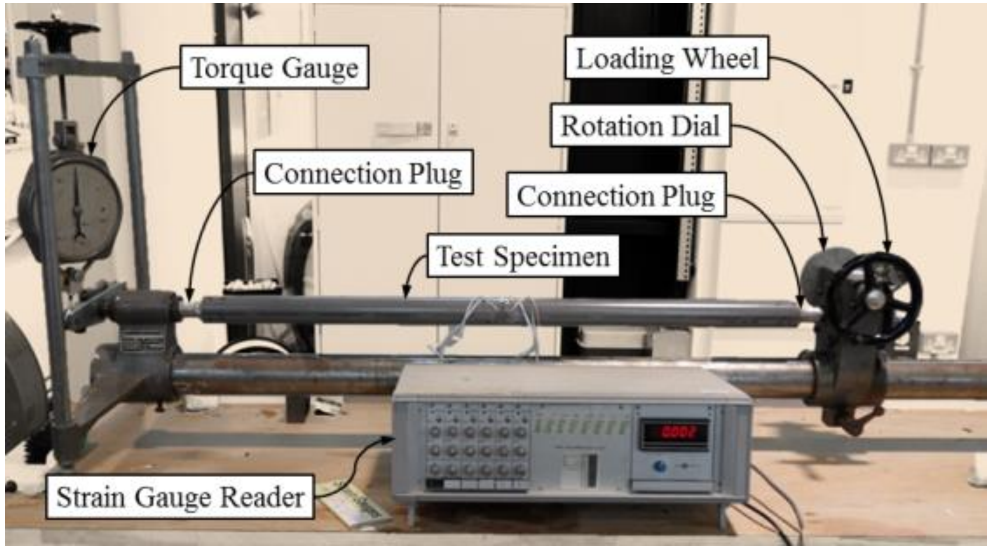

Fig. 3(b): Torsion rig showing the loading arrangement and instrumentation

- The tube was loaded in torsion by axial twist increments of 1° using the loading wheel up to a total twist of 10°
- Readings of torque and strain were recorded for each twist increment during both loading and unloading. This procedure was repeated three times
- The tube was then shortened to a torsion span of 500 mm and the test procedure was repeated

Tube Instrumentation, Test Set-Up and Procedure (Cont'd)

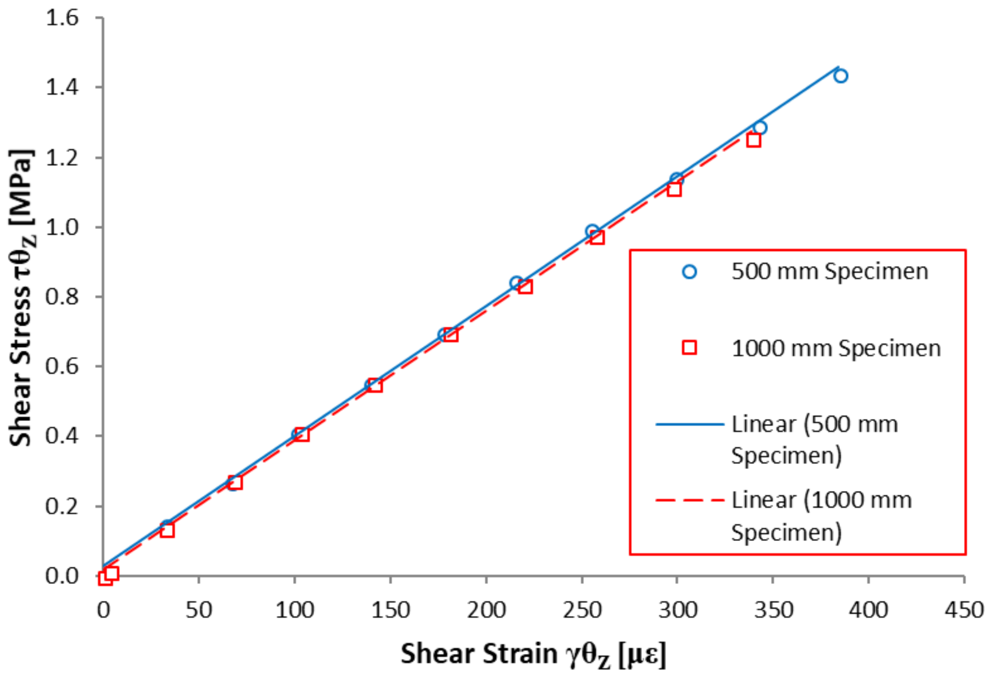

Fig. 4 Shear stress vs shear strain graph of torsion tests on 500 and 1000 mm long pultruded GFRP tubes

- The torsion test data were used to calculate the shear stress for each increment of twist
- The shear strains were determined from the mean biaxial strain data and the shear stress vs shear strain graphs were produced for both spans
- Regression lines were fitted to the data, gave $G_{\theta z}$ values of 3.734 and 3.720 GPa for the 500 and 1000 mm torsion spans, respectively

Three-Point Flexure Investigation – Equations for Elastic Moduli

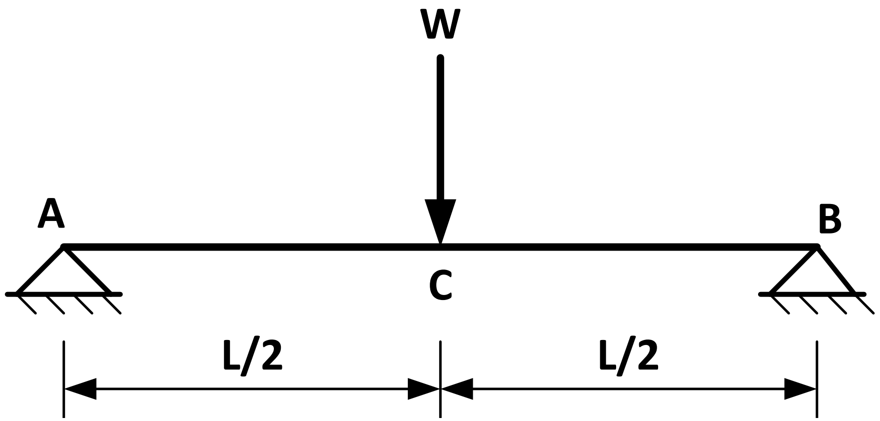

Fig. 5 Three-point flexural loading on a simply supported pultruded GFRP tube

- **Based on shear-rigid Euler-Bernoulli beam theory, the tube's mid-span deflection is:-**

$$\delta_c = \frac{WL^3}{48E_b I}$$

- **Likewise, based on Timoshenko shear deformation theory, the tube's mid-span deflection is:-**

$$\delta_c = \frac{WL^3}{48E_{bs} I} + \frac{WL}{4G_{\theta z} A}$$

- **In the above equations E_b is the elastic bending modulus, $I = J/2$ is the second moment of area, E_{bs} is the elastic bending-shear modulus and A is the cross-sectional area**

Three-Point Flexure Investigation – Equations for Elastic Moduli (Cont'd)

- The deflection equations may be re-arranged to give expressions for the bending and bending-shear moduli:-

$$E_b = \left(\frac{W}{\delta_c}\right)\left\{\frac{L^3}{48I}\right\} \qquad E_{bs} = \frac{E_b}{\left\{1 - \frac{L}{4G_{\theta z}A}\left(\frac{W}{\delta_c}\right)\right\}}$$

- Hence, by measuring the mid-span deflection for each three-point flexure test, the quotient $\left(\frac{W}{\delta_c}\right)$ may be determined for each span and substituted into the first equation to give the E_b values
- Likewise, substituting the $\left(\frac{W}{\delta_c}\right)$ and shear modulus $G_{\theta z}$ values into the second equation together with the mean cross-sectional area A for each span into the second equation, the E_{bs} values may be determined
- It is self-evident from the second equation that $E_{bs} \geq E_b$

Three-Point Flexure Test Set-Up and Test Results

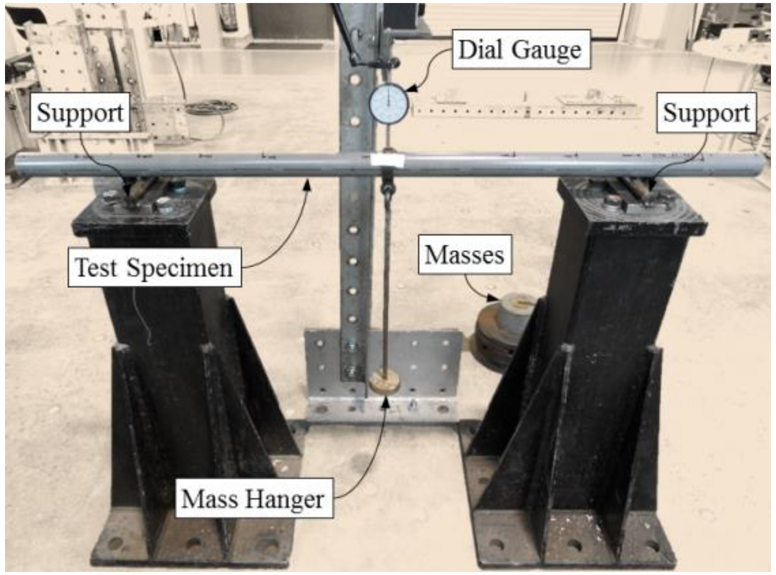

Fig. 6 Experimental test set-up for three-point flexure tests on Pultruded GFRP tubes

- **Three-point flexure tests were carried out at spans of 1250, 1000, 750 and 500 mm on the same tube by successively reducing its original length of 1500 mm**
- **For each span the tube was tested three times with each of the lines 1 – 4 uppermost in turn**
- **Mid-span deflections were recorded for each load increment up to a total load of 981 N**

Three-Point Flexure Test Set-Up and Test Results (Cont’d)

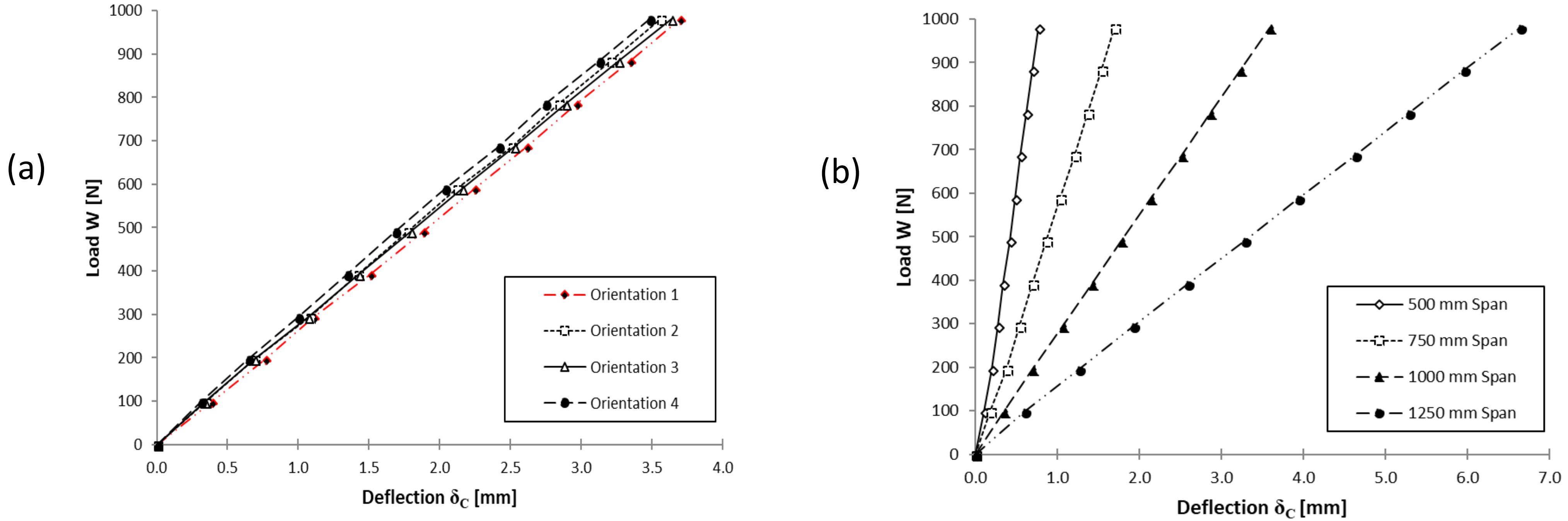

Fig. 7 Load versus mid-span deflection: (a) four orientations of 1000 mm span and (b) mean values of 4 tests at 500, 750, 1000 and 1250 mm spans

- **Fig. 7(a) shows the load versus mid-span deflection for the four test orientations of the 1000 mm span tube**

- **Fig. 7(b) shows the best-fit straight lines to the twelve load versus mid-span deflection results for each of the four test spans.**

Three-Point Flexure Test Set-Up and Test Results (Cont'd)

Table 2 Three-point flexure test spans, elastic moduli and their differences due to shear deformation effects

L [m]	W/δ_c [$NM^{-1} \times 10^5$]	E_b [GPa]	E_{bs} [GPa]	$\Delta E = (E_{bs} - E_b)$ [GPa]	$(\Delta E/E_{bs}) \times 100$ [%]
0.50	13.208	18.596	19.808	1.212	6.12
0.75	5.8163	27.655	28.820	1.165	4.04
1.00	2.7220	30.689	31.483	0.794	2.52
1.25	1.4694	32.368	32.929	0.561	1.70

- **The mean values of $\frac{W}{\delta_c}$ presented in Table 2 together with the mean value of the in-plane shear modulus $G_{\theta z} = 3.727\,GPa$ have been used to determine the E_b and E_{bs} values for each span, as shown in Table 2, together with the differences (and percentage differences) due to shear**

Concluding Remarks

- The tests on the 1000 mm long pultruded GFRP tube reveal that its flexural stiffness is consistent irrespective of the test orientation
- The same consistency of the flexural stiffness was observed for the other test spans
- The stiffness results consistency observed in the axial torsion and three-point flexure tests suggests that the distribution of the E-glass rovings and CFM is uniform and indicative of the high quality of the manufacturing process – pultrusion
- The test results show that the effect of shear deformation has minimal impact, i.e. less than 6% for the practical range of span to diameter ratios, on the flexural modulus of pultruded GFRP circular cross-section tubes
- Circular cross-section shapes display excellent properties in torsion and resist shear deformation more effectively than flat plates and provide confidence in their use in safety barrier/guardrail applications

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