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EXPERIMENTAL BEHAVIOUR OF HOLLOW ±55° FILAMENT WOUND GFRP TUBES UNDER MONOTONIC FLEXURAL LOADS

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ABSTRACT: In this study, the flexural behaviour of hollow ±55° GFRP tubes is examined experimentally. A total of 15 tubes were tested under four-point bending: three identical tube specimens for five different tube types. The main test parameter was the effect of the tube inner diameter (76.2 mm and 203.2 mm) and the nominal pressure rating (350 kPa, 700 kPa and 1050 kPa) which is correlated to the tube wall thickness. For each test, the load was measured using a 250 kN load cell, the deflection was measured using a string potentiometer and the strains in the extreme tension and compression fibres were measured using strain gauges with a gauge length of 6mm. All measurements were recorded at a sample rate of 10 Hz. The results of the tests show that the ultimate moment increased with both tube diameter and wall thickness and that the tubes all exhibited the same failure mechanism: a progressive tensile weakening in the bottom of the tube until an ultimate failure in compression at the top. The mechanical behaviour of these tubes is important to understand in order to effectively use them in structural systems, such as concrete-filled FRP tubes.

1. Introduction

The use of fiber-reinforced polymers (FRPs) in infrastructure has been increasing in the recent past, specifically for use in reinforcing and rehabilitation concrete columns. One predominant part of this field is the study of confinement of concrete columns using FRP wraps or tubes (Bakis et al. 2002; Berthet et al. 2005; Fam et al. 2003; Fam and Rizkalla 2001; Lam and Teng 2004; Sadeghian and Fillmore 2018). Using concrete filled FRP tubes (CFFTs) for column applications has benefits in addition to providing confinement. Because of their high corrosion resistance, FRP tubes act as a protective barrier for the concrete, especially when reinforced with steel. The FRP tubes also act as a stay-in-place formwork which increases the sustainability of structure by removing the need for temporary formwork thereby reducing construction waste.

The oil and gas and municipal sectors use filament wound glass FRP (GFRP) tubes regularly because of their corrosion resistance and design flexibility. Due to their resistance to both internal pressure and axial loads, ±55° filament wound GFRPs are suitable for piping applications. For this reason, they are readily available and have become a popular choice for use in structures such as CFFTs. Shao and Mirmiran (2004, 2005) examined the cyclic behavior of ±55° filament wound GFRP tubes. They tested the tubes under a four-point bending configuration under cyclic displacements ranging from ±6.4 mm to ±127 mm and found that the ±55° tubes exhibited a ductile, elastoplastic behavior. Zaghi et al. (2012) tested a 1/5 scale two-column bridge pier under seismic loading conditions using a shake table. One of the columns was fabricated as a traditional RC column and the other was fabricated as a ±55° CFFT structure. Their tests showed that the two columns performed similarly, but that the RC column was more susceptible to concrete spalling which could potentially lead to corrosion of the steel reinforcing. Echevvaria et al. (2015) tested RC columns and ±55° CFFTs under blast loading. Their tests showed that the post-blast CFFTs exhibited less loss in strength and ductility than their RC counterparts.

In order to use CFFTs in structural applications, it is necessary to have an in depth understanding of the principal components, such as the FRP tubes. In the study by Natsuki et al (Natsuki et al. 2003) the bending strength of ±55° tubes was investigated analytically using the maximum stress criterion, however, there remains limited information on the experimental flexural behavior of these tubes. In a previous study, Betts et al. (2019) have looked at the tension and compression behaviour of ±55° GFRP tubes and found that they behave in a nonlinear manner. In this study, the flexural behavior of ±55° GFRP tubes is investigated experimentally by testing hollow tubes with different diameters and wall thicknesses.

2. Experimental Program

2.1. Test Matrix

As a part of this study, a total of 15 tubes were tested under four-point bending. The main test parameters were the tube wall thickness and diameter, which can be normalized by analysing the effect of the D/t ratio on strength and stiffness. The test matrix is presented in Table 1. Note that the following specimen naming convention was followed: PX-DY-#, where X is the nominal pipe pressure rating in kPa (i.e. 350, 700, or 1050), Y is the inner diameter in millimeters (i.e. 76 or 203), and # is the sequential number used to distinguish each of the three identical specimens of each set. For example, the first pipe tested with an inner diameter of 76 mm and a pressure rating of 350 kPa would be distinguished as P350-D76-1.

Table 1 – Test Matrix

Specimen Group	Nominal Pressure Rating (kPa)	Inner Diameter (mm)	D/t	Quantity
P350-D76	350	76.2	44.8	3
P1050-D76	1050	76.2	20.1	3
P350-D203	350	203.2	75.3	3
P700-D203	700	203.2	43.2	3
P1050-D203	1050	203.2	30.3	3

2.2. Test Set-up

The test set-up is presented in Figure 1. The span lengths of the tests were 3048 mm and 1143 mm for the D203 and D76 tubes, respectfully. The distance between loading points (i.e. loading span) was 457 mm and 171 mm for the D203 and D76 tubes, respectfully. For each tube diameter the supports were rollers at each end and at each loading point. A string potentiometer was used to measure deflection at the mid-span and a strain gauge was applied to the top and bottom at the extreme fibres at mid-span. All bending tests were performed at a rate of approximately 15 mm/min.

3. Results and Discussions

In this section, the results of the tests will be presented and discussed. First, the failure modes will be shown followed by the behaviour of the tubes under four-point bending. All test data was processed and analysed using a python script written using the scientific package, Anaconda.

3.1. Failure Modes

In all tests the same failure method was observed: weakening in the tension face until ultimate failure due to buckling/crushing in the compression face. Fig. 2 shows an example of two specimens after ultimate failure.

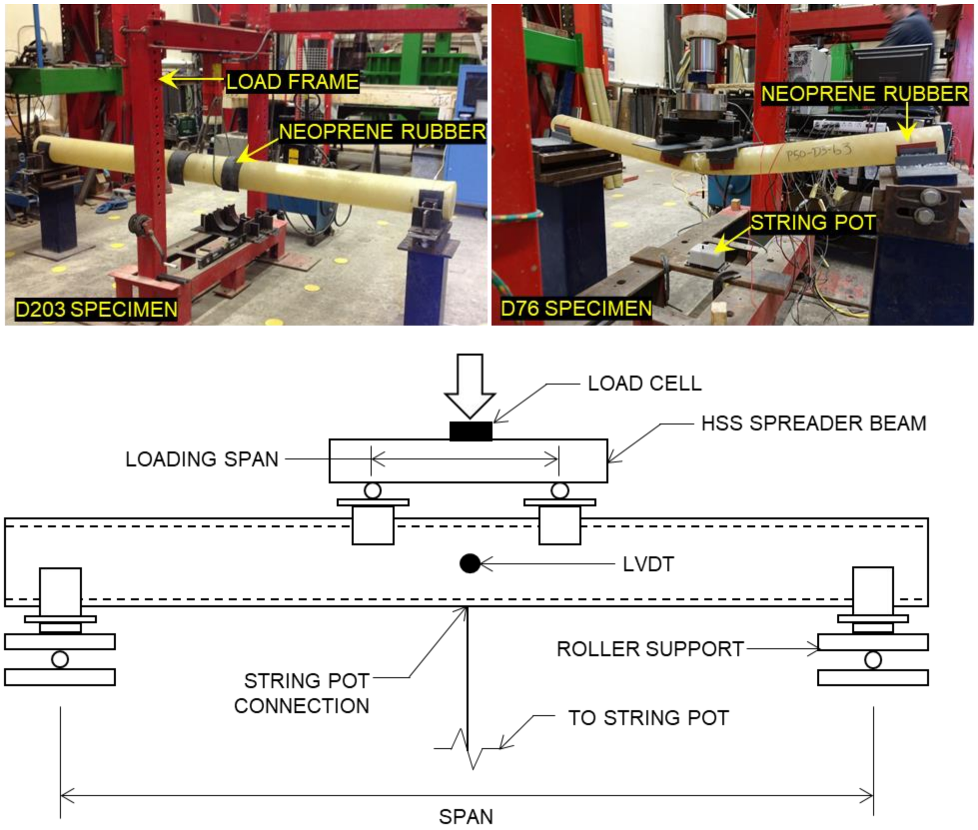
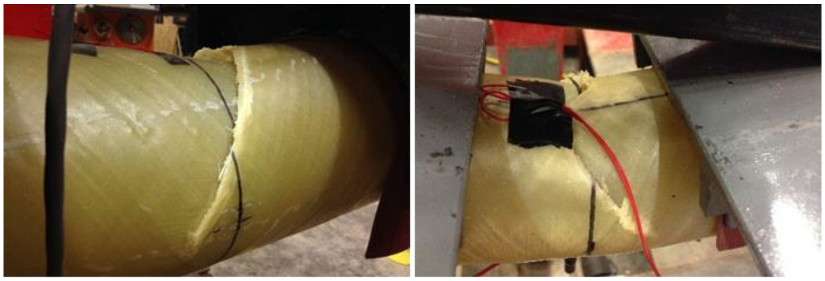


Fig. 1 – Test Set-up



(a) (b)

Fig. 2 – Failure Modes: (a) Top of Failed D203 Specimen (b) Top of Failed D76 Specimen

3.2. Flexural Behaviour

Fig. 3 shows the load-deflection, load-strain, and moment-curvature plots of all the tests. Fig. 4 shows a bar chart showing the effect of pipe pressure rating on the moment capacity and elastic modulus of the GFRP pipes. The elastic moduli were calculated based on the first linear slope of the moment curvature diagram, which is the flexural rigidity ($D = EI$). For both the D203 and D76 tubes. It can be seen in Fig. 4 that the pressure rating does not have a significant effect on the pipe modulus, however, the ultimate moment capacity of the tubes increases with pressure rating.

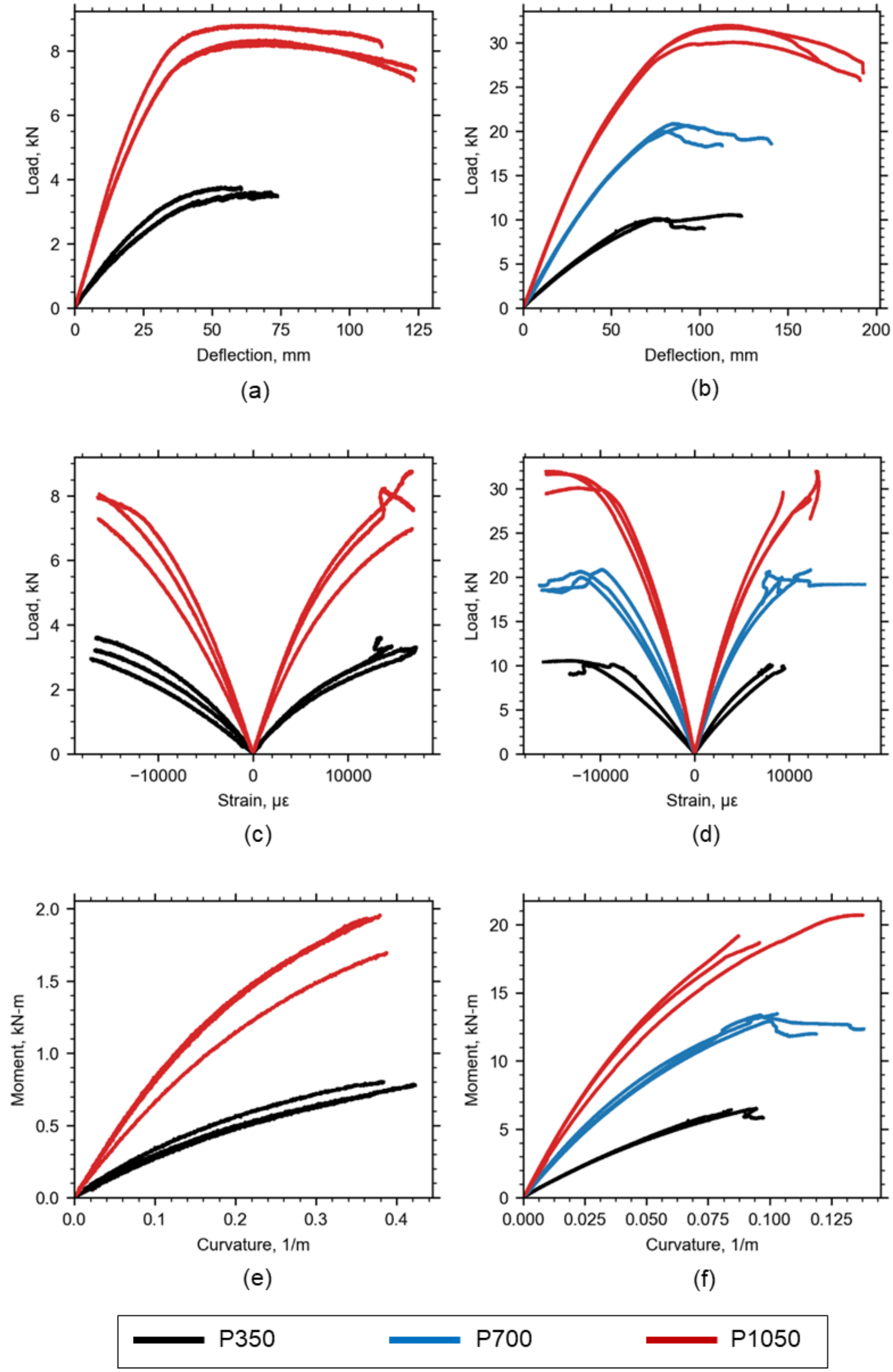


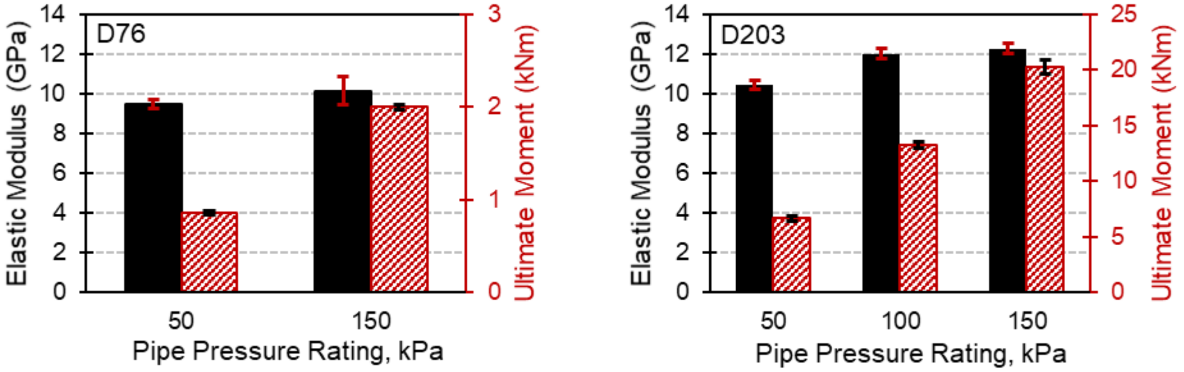
Fig. 3 – Test Results (a) D76 Load-Deflection (b) D203 Load-Deflection (c) D76 Load-Strain (d) D203 Load-Strain (e) D76 Moment-Curvature (f) D203 Moment-Curvature

The curvature shown in Fig. 2 was calculated based on the strains from the top and bottom faces and the outer diameter of the pipe in question. The modulus presented in the bar charts in Fig. 3 is a general elastic modulus for a pipe section under flexural loads. It was determined by taking the average of two modulus calculation methods: the load-deflection method and the moment-curvature method. For both methods, the first linear slope of the plot in question is determined by fitting a linear trendline to the applicable data. Using the slope of the plot, the "load-deflection modulus" was calculated by rearranging Eq. 1. Likewise, the "moment-curvature modulus" was determined by rearranging Eq. 2.

$$P = \left[\frac{48EI}{a(3l^2 - 4a^2)}\right] \times \Delta \tag{1}$$

$$M = [EI] \times \psi \tag{2}$$

where P is the total force on the pipe, E is the elastic modulus, I is the moment of inertia, a is the distance from the support to the closest load point, Δ is the deflection, ψ is the curvature, and the terms in the square brackets are the first linear slopes of the respective plots.



(a) (b)

Fig. 4: Effect of pressure rating on moment capacity and bending elastic modulus for (a) D76 tubes and (b) D203 tubes (Note: the solid black bars represent the elastic moduli and the hatched bars represent the compressive strength.)

4. Conclusions

This paper presents the results of a series of four-point bending tests on filament wound GFRP pipes with diameters of 76 mm and 203 mm. Based on the test results, the tubes all failed in the same manner, a progressive tensile weakening of the bottom face until an ultimate failure in compression on the top face. Additionally, it was noted that the modulus of elasticity is not greatly affected by the pressure rating of the tube, but the ultimate moment increases with tube pressure rating. The 76 mm diameter tubes and 203 diameter tubes had an average elastic modulus of 9.82 ± 0.58 GPa and 11.57 ± 0.87 GPa, respectively.

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