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THE EFFECT OF SHEAR SPAN- TO- DEPTH RATIO ON THE FAILURE MODE AND STRENGTH OF PULTRUDED GFRP BEAMS

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ABSTRACT

The use of structural pultruded fibre reinforced polymers (FRP) sections have gained wide acceptance in civil engineering applications due to their favourable structural characteristics like high strength, light weight and durability in severe environmental conditions. However, due to their relatively low modulus of elasticity and thinned walls, these sections are vulnerable to local buckling which can affect their ultimate strength. This paper investigates experimentally the flexural behaviour of pultruded GFRP beams with shear span-to-depth (a/d) ratios in the range of 1.2 to 6 using full scale pultruded profiles. Failure modes, strength and crack patterns are the main parameters that were examined in this study. The study shows that shear span has a minor effect on the failure modes of the beams while it has a noticeable effect on the ultimate strength. In addition, fibre model analysis was used to validate the experimental results. Comparison between the experimental and the theoretical analysis results shows a good approximation of the moment - deflection behaviour and failure moment of pultruded GFRP beams.

1. INTRODUCTION

Pultruded fibre reinforced polymers (FRP) sections have gained wide acceptance in civil infrastructure applications due to their advantageous properties like high strength, light weight and durability in severe environmental conditions. However, local buckling failure has been a major drawback that has an adverse effect on the ultimate strength due to their relatively low modulus of elasticity and thin-walled sections. In this regards, several researches have investigated the elastic properties of these materials [1, 2]. These researches showed that determining the elastic properties is a significant factor in predicting the behaviour of the material. As shear modulus is one of these properties, accurate values need to be known if the elastic theory for the member is to be properly utilized. Therefore, several studies were conducted to determine the shear modulus [3-6]. Similarly, failure mode of GFRP sections has been investigated using end – two – flange and interior – two – flange methods [7-9]. These studies have focused on the shear failure mode but for specific loading conditions like placing the sample on the ground and applying the load using bearing plates at the edge or in the middle of the section.

In order to endorse the use of pultruded GFRP profiles in infrastructure applications, improving the knowledge of their ultimate strength and modes of failure is critical. To the authors' knowledge, there are very limited experimental studies conducted to investigate the effect of shear span on the structural behaviour of full – scale FRP composite beams made of vinyl ester resin with E-glass fibre reinforcement. In this study, the effect of a/d ratios on the strength and failure behaviour of the GFRP beams was analysed. Fibre model analysis was implemented to validate the experimental results.

2. EXPERIMENTAL PROGRAM

Pultruded GFRP square sections (125 mm x 125 mm x 6.5 mm thickness) produced by Wagner's Composite Fibre Technologies (WCFT), Australia were used in this study. Vinyl ester resin and E-glass fibre reinforcement are the main composites of these sections. The density of these pultruded profiles is 2050 kg/m^3. As per standard ISO 1172 [10], the burnout test revealed an overall glass content of 78% by weight in these profiles. The measured compressive modulus and strength in the longitudinal direction are 38 GPa and 640 MPa, respectively. The measured tensile modulus and strength in the longitudinal direction are 42 GPa and 741 MPa, respectively. The measured full scale flexural and shear modulus are 47.5 GPa and 4 GPa, respectively.

Four different shear span-to-depth ratios (a/d) were adopted as shown in Table 1. The load was applied on the top flange at two points with a load span of 300 mm. The constant load span was used to keep the upper face of the section under same condition for all specimens and to be compatible with the length of the test frame. All specimens were tested up to failure under static four point bending test. Lateral supports were provided at the support points to prevent any rotation. Figure 1 shows the experimental set up. A 2000 kN capacity universal machine was used for applying the load. Uniaxial strain gauges (types PFL-20-11-1L-120) were used to measure the strain at the top and bottom faces of the beam in addition to the strain through the shear path. Laser displacement transducer was used to measure the mid span displacement. The applied load and the displacement were recorded using system 5000 data acquisition system. Steel plates were provided at the supports and loading points to minimise indentation failure.

Table 1 Details of the tested specimens

Span length, *L* (mm)	Shear span, *a* (mm)	*a/d*
600	150	1.2
900	300	2.4
1200	450	3.6
1800	750	6

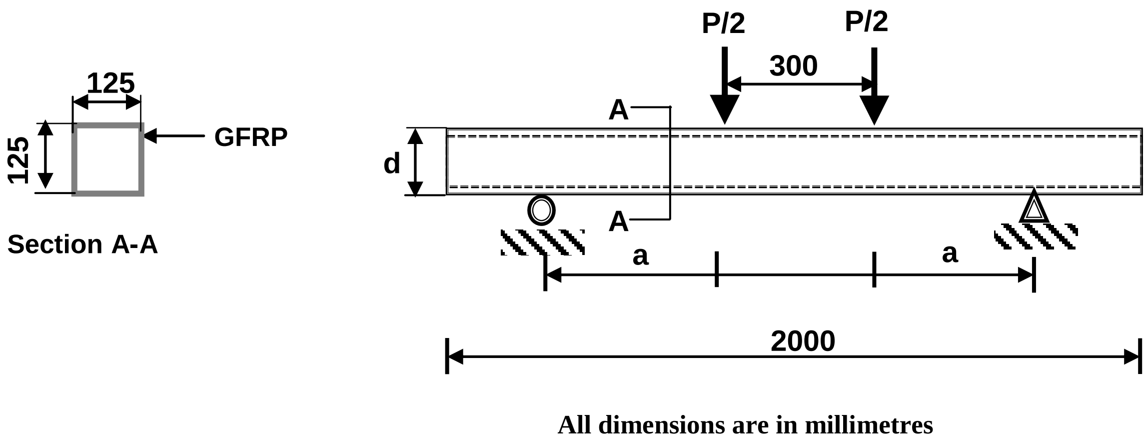


Figure 1 details of experimental set – up

3. RESULTS AND DISCUSSION

3.1. Load-displacement behaviour

The moment - deflection behaviour of the GFRP pultruded beams is shown in Figure 2 which is generally linear. It can be seen from the figure that the moment capacity of the beam is changing with the variation of the shear span to depth ratio. The moment capacity of the GFRP pultruded beams is increased with increasing a/d ratio. All beams show a brittle failure ultimately. As expected from the moment – displacement behaviour that longer beams deflected more than shorter beam specimens.

The strain measurements for the beams at the top and bottom faces are shown in Figure 3. It can be seen that the tension strain at the bottom face is higher than the top face compression strain. On the other hand, there are differences in the stress-strain relationships for the top and bottom side. At the top side, the strain recording was negative demonstrating that the profile is compressed. With the increasing load, however, the values tend to become positive indicating that the top surface of the tube is shifting from being compressed to under tension as shown in Figure 3. This behaviour reflects the local buckling initiation when the load or stress is increased beyond the elastic buckling load; the section starts to fail as a result of separation of the flange from the web (web – flange junction failure) due to high concentrated bearing load. The tensile strain decreases with decreasing shear span. Note that the bottom side of the tested specimens subjected to extensive tensile straining (tension side) however, it experienced no failure even after the compression region at the loading zone was failed entirely. Figure 4 shows the strain at the shear path. The figure showed that shear strain decrease with the increase of a/d. This behaviour reflects the increase in flexural stress and decrease in the shear stress.

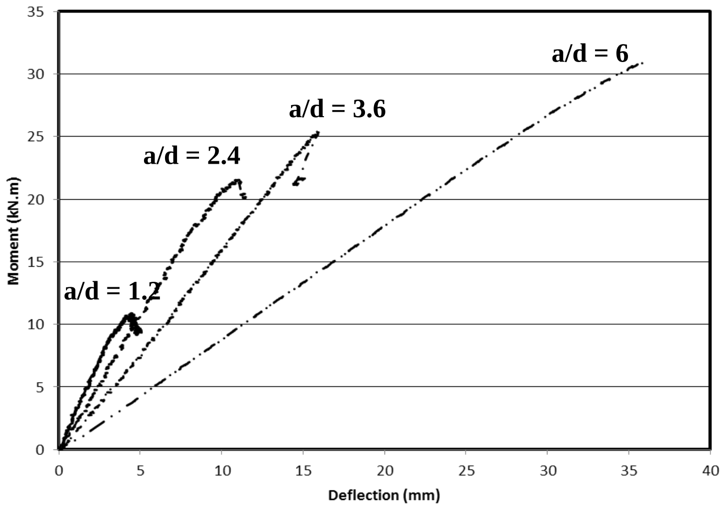


Figure 2 Moment – displacement curves for GFRP beams

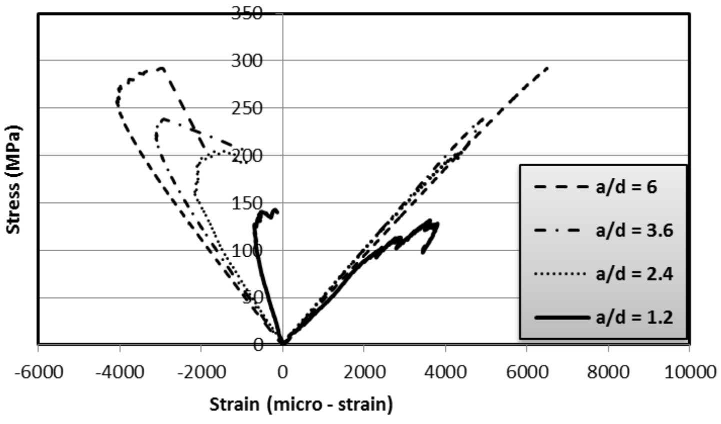


Figure 3 Load versus compression and tension strain

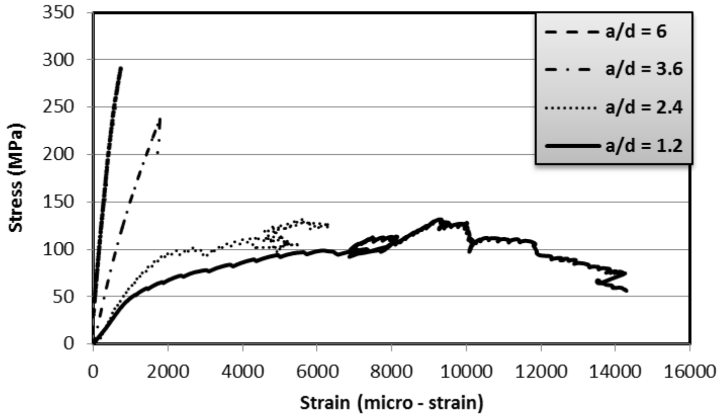
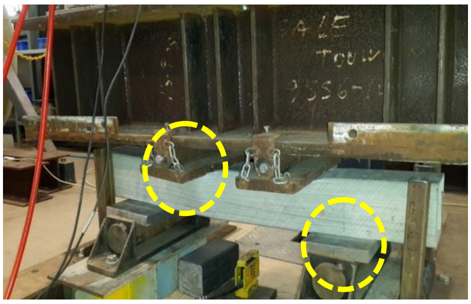


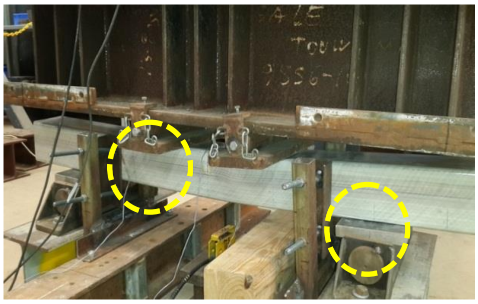
Figure 4 Load versus shear strain

3.2. Failure mode

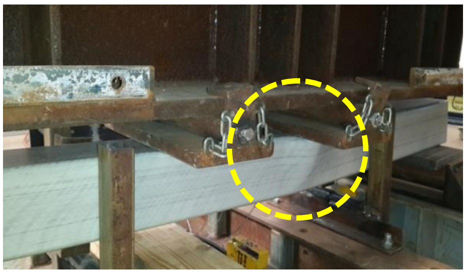
The typical failure modes of the GFRP beams are shown in Figure 5. The observed failure modes can be classified as; flexural failure and transverse shear failure. Beams with a/d ratios of 1.2 and 2.4 experienced an initial failure at the web-flange junctions and followed by premature buckling and crushing in the webs. This failure behaviour is described as a potential failure for pultruded GFRP sections under concentrated bearing load conditions [7]. It was observed that the specimens had cracked and some twisted away from the centre towards one side. For beams with a/d ratio of 3.6 and 6, the failure occurred at the points of loading and distinct cracks on the top surface and side of the tubes could be seen. Furthermore, cracks were developed at the intersection between the flange and the web due to the buckling leading to separation between them. It was also observed that delamination crack happened at the compression surface and later progressed into the sides as shown in Figure 5c and d. These results indicate that the local buckling of the thin wall initiates most failure that finally results in material degradation until final failure of the specimen. Shear crack was not observed for all the tested beams even for the beams with low a/d ratio. The possible reason for that is the presence of the $\pm 45^{o}$ plies in addition to the main fibre on the tube which provides a stronger structural resistance along the transverse direction.



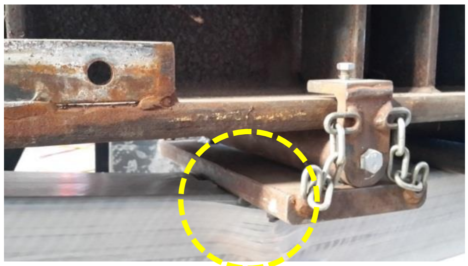
(a) a/d= 1.2



(b) a/d= 2.4



(c) a/d= 3.6



(d) a/d= 6

Figure 5 Failure modes of GFRP beams for different shear span to depth ratio

3.3. Theoretical analysis

A simplified fibre model analysis (FMA) was implemented to predict the failure moment of the pultruded GFRP beams with different a/d ratios. The model as shown in Fig 6 involves the determination of the position of the neutral axis for a given strain of the extreme compression fibre by using the principles of strain compatibility and equilibrium. The analytical procedure starts with dividing the cross- section into a number of strips. The internal force and bending moment are then calculated by performing simple integration of the contributions of the stresses over the section based on the elastic properties of the material. After that, the total deflection at mid span in simply supported beam under four – point bending can be calculated by:

$$\Delta = \Delta_{flexural} + \Delta_{shear} \quad (1)$$

$$\Delta = M\,[a^2/3EI + (L^2/4 - a^2)/2EI] + Pa/2KGA \quad (2)$$

Where M is the calculated bending moment, EI is the flexural rigidity, KGA is the shearing rigidity. Elastic properties of GFRP beams were determined from full scale test and used in the FMA. Values of 47.5 GPa and 4 GPa were used for E and G modulus, respectively.

The moment - deflection behaviour and a comparison between experimental and theoretical moment capacity of the tested beams are presented in Figure 7 and Table 2, respectively. As the moment increases, the displacement also increases in a linear manner. In addition, it is clearly shown in the figure and the table that the theoretical analysis can predict the behavior of GFRP beams with different shear span to depth ratio.

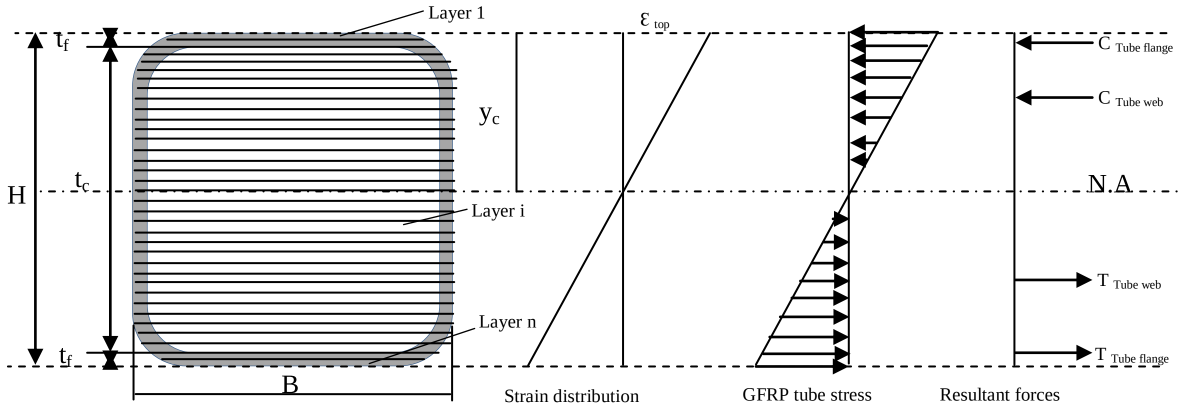


Fig 6 Assumed strain and stress distribution in the FMA

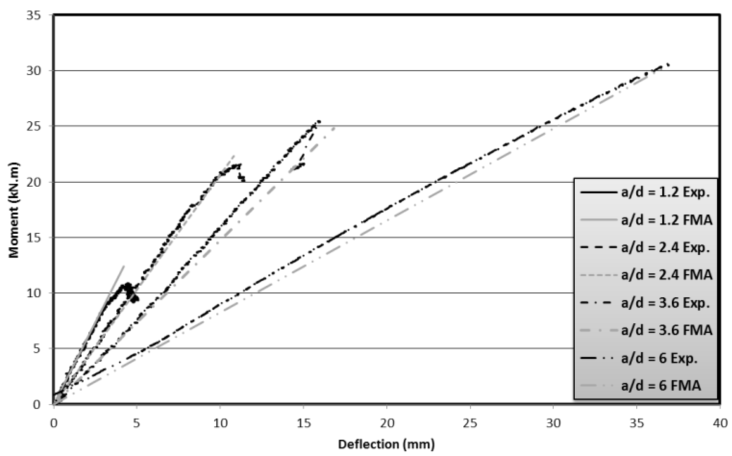


Figure 7 moment – displacement curves (experimental versus theoretical)

Table 2 a comparison between experimental numerical results

Shear span/ depth	Experimental failure moment kN.m	Theoretical failure moment kN.m
1.2	10.5	9.9
2.4	21.5	21
3.6	25	24.7
6	30.5	30.2

4. CONCLUSIONS

Having tested GFRP pultrude profiles with different shear span to depth ratios using four point bending testing, and doing theoretical analysis using FMA, the following conclusions can be made:

- The shear span has an important effect on the strength capacity of the pultruded GFRP beams but has a minor effect on the failure modes of the beams.
- All specimens failed due to compressive buckling with shear failure of the compression flange with no diagonal shear cracks.
- The theoretical analysis using simplified fibre model analysis can reliably predict the failure moment of GFRP beams.

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