Behavior of pultruded multi-celled GFRP hollow beams with low-strength concrete infill

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ABSTRACT: The structural performance of multi-celled GFRP hollow beams is highly affected by the local buckling failure. Therefore, this study introduces pultruded multi-celled GFRP beams filled with low strength concrete. The flexural behaviour of beams made up of 1, 2 and 3 pultruded GFRP square sections (125 mm x125 mm x 6.5mm) and filled with concrete having low compressive strength was investigated. The composite beams were subjected to four-point static bending test to determine the strength, stiffness and failure mechanisms. The results of the experimental investigations showed that the failure stress of 2 and 3 cells beams is 98% and 85% compared with single cell beam, respectively. However, the filling percentages are 50% and 33%, respectively. All the tested beams were failed due to compression failure of the GFRP profile. Furthermore, the effective stiffness of 2 and 3 cells is 95% and 96%, respectively compared with single cell section.

1 INTRODUCTION

Advance composite materials have recently gained much attention in the civil engineering applications like bridge superstructure including decks and beams. However, fibre reinforced polymer (FRP) composites are making limited progress in the field of highway structures due to their high initial cost compared with conventional materials and their relatively low elastic modulus(Chakrabortty et al., 2011). Although the problem of high initial cost has been addressed using large volume automated process such as pultrusion, the low modulus of glass FRP (GFRP) still limited the composites serviceability and prevented full use of its strength. Similarly, FRPs are susceptible to local buckling, compression buckling failure and web-flange junction failure (Mottram, 1992;Bank, 2006;Bai et al., 2013;Muttashar et al., 2015). These limitations of pultruded GFRP sections have been addressed by innovative design and applications.

Several researches proposed different geometrical configurations and materials combination to improve the structural performance of hollow pultruded FRP profiles. Two main designs were proposed as possible alternatives to overcome the aforementioned problem. First design highlighted the use of hybrid beams system where GFRP box beam either combined with concrete layer cast onto the top flange and a thin layer of carbon fibre bonded to the tension side (Triantafillou and Meier, 1992;Canning et al., 1999;Van Erp et al., 2002) or by filling GFRP tubes with concrete (Fam and Rizkalla, 2002;Gautam and Matsumoto, 2009;Aydin and Saribiyik, 2013;Muttashar et al., 2016). The second design proposed multi-cell hollow beams by gluing the GFRP tubes together to make a new section (Kumar et al., 2004;Hejll et al., 2005). Despite of the advantages provided by each design, one of the main drawbacks associated with filling GFRP sections with concrete is losing the light weight feature which represents a significant characteristic of FRP materials. On the other hand, buckling failure of the top flange of the pultruded profile and web-flange junction and twisting of the top layer of the beam were observed to be the principle location of failure of glued beams. It therefore becomes necessary to study different combinations between pultruded profiles and concrete.

In this paper, the authors partially filled the top layer of the glued pultruded sections to get benefit from the advantages of multi-celled beams and hybrid composite-concrete systems. The aim of this study is to investigate the flexural behaviour of these partially filled pultruded GFRP sections and compared with multi-cell hollow beams. Four-point bending tests were performed on GFRP beams with different number of layers and their behaviours are presented in this paper.

2 EXPERIMENTAL PROGRAM

2.1 *Materials*

The pultruded GFRP hollow square tubes examined in this study was 125 mm x125 mm x 6.5 mm. Tensile and compression tests using coupons cut from the GFRP tube and following standards ASTM Standard D 695 (2010) and ISO 527-2 (1996) gave the strength and stiffness properties. The measured tensile modulus and strength in the pultrusion direction are 47.2 GPa and 596 MPa, respectively. The modulus and strength in transverse direction are 13 GPa and 550 MPa, respectively. Shear modulus of 4 GPa was determined from tests of the whole section in earlier study by Muttashar et al (2015). In addition, burnout test conducted as per ISO 1172 standard (ISO 1172, 1996) revealed that the density and the fibre volume fraction are 2050 kg/m3 and 78% by weight, respectively.

Low strength concrete (Bastion premix concrete) was used as infill to the pultruded sections. Five plain concrete cylinders have been sampled and cured under the same conditions as the beam specimens. The 28-day average compressive strength for the infilled concrete was 15 MPa.

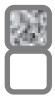
2.2 *Samples*

The descriptions of the tested beams are listed in Table 1. In the table, the specimens were identified by codes. The identifications of the section are given by the initial SH and SF which indicate square hollow and square filled section, respectively. The numbers 1, 2 and 3 refer to the number of bonded cells. The number 0 and 15 are used to indicate the type of concrete used to fill the specimens. A square (125x125x6.5) mm pultruded section represents the main component of the multi- cell beams. The length of each beam depends on the total depth of the beam to maintain same shear span to depth ratio of (a/d = 4.2). Regarding to the sample preparation, the surfaces of the square sections were properly grinded and cleaned using acetone. A number of GFRP profiles were assembled and bonded together in 2 and 3 cells with an epoxy adhesive provided by the manufacturer. The bonding process was undertaken at ambient temperature and an approximate of 1 mm bond line was applied. The bonded sections were then clamped to form necessary bond pressure during adhesive curing. Extra adhesive was squeezed out and cleaned from the sides of the bonded beams. Only the top cell of each specimen was filled with concrete to support the flange from buckling and prevent the mature failure of the section. After filling, the specimens were cured for 28 days at ambient temperature before they are tested.

2.3 *Test set-up procedure*

A static four – point bending test of the pultruded beams was performed following the ASTM D7250 standards (ASTM Standard D7250, 2006) as shown in Figure 1. The load was applied in two points with a load span equal to 300 mm. A 2000 kN universal machine was used to conduct all the tests at a load rate of 2 mm/min. A laser displacement transducer was used to measure the mid span deflection. A plastic square inserts were used for the hollow and filled beams at the loading and support points to prevent any indentation and/or crushing at those points and allow the beam to fail at the location of the maximum and constant bending moment. Additional steel angles and steel chains were used at the supports to avoid any rotation or lateral buckling. Uni–axial strain gauge type PFL-20-11-1L-120 was provided to measure the strain at the top and bottom faces of the beams. The applied load and the displacement were measured and recorded using a data logger System 5000. All specimens were tested up to failure to observe the failure mechanisms of the beams.

Table 1. Descriptions of the pultruded GFRP tested beams.

Specimen	Shape	*B* mm	*D* mm	L_t mm	*L* mm	*a* mm	f'_c MPa
SH-1-0		125	125	2000	1350	525	-
SF-1-15		125	125	2000	1350	525	15
SH-2-0		125	250	2750	2400	1050	-
SF-2-15		125	250	2750	2400	1050	15
SH-3-0		125	375	3700	3450	1575	-
SF-3-15		125	375	3700	3450	1575	15

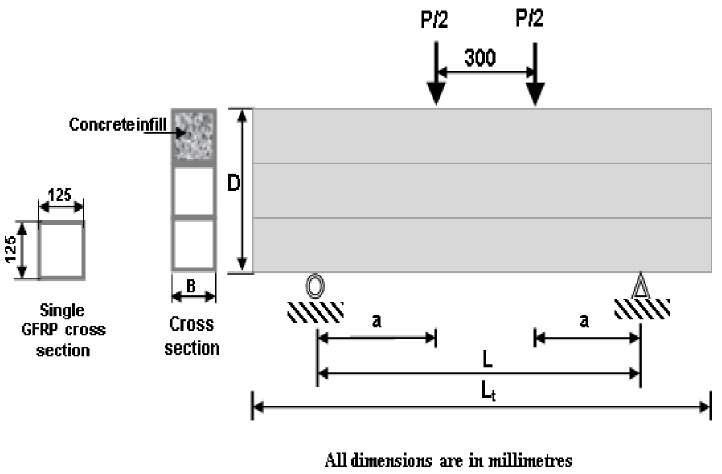


Figure 1. Flexural test set-up for single and mutli-celled beams.

3 EXPERIMENTAL RESULTS

Table 2 summarized the major experimental results for all the specimens, with relation to moment-displacement responses, load-stain behaviour and failure modes as discussed in this section.

3.1 *Moment-displacement behaviour*

The moment versus vertical displacement curves of single and multi-cell GFRP pultruded beams are presented in Fig.2. The obtained moment-displacement behaviours are almost linear for both hollow and filled sections. The linear behaviour reflects that the behaviour of the filled beams is controlled by the behaviour of the GFRP tube (Muttashar et al., 2016). All the tested sections showed brittle failure due to the compressive buckling of the top flange of the top cell at the constant moment region. The failure moments were 23.8, 79.4 and 147.6 kN.m for specimens' SH-1-0, SH-2-0 and SH-3-0, respectively. As a result, the flexural failure stresses were 227, 280 and 254 MPa, respectively which are approximately 41, 50 and 46% of the compression failure stresses determined from coupon test. It is interesting to see that hollow beams failure stress is approximately similar. The main reason of this behaviour is the local buckling failure of the compression flange observed in all the hollow beams. On the other hand, the filled sections failed at 43, 114 and 214 kN.m for specimens' SF-1-15, SF-2-15 and SF-3-15, respectively indicating that the concrete filling has a significant effect on the capacity of the beams. The concrete filled beams failed at a load of 106, 43 and 45% higher than 1, 2 and 3 cells hollow beams, respectively. However, the percentages of filling were 100, 50 and 33%. The increase in the capacity of the filled beams reflects the contribution of the filling concrete by preventing and delaying the compression buckling of the GFRP tube, thereby improving the strength of the section. Consequently, this improvement results in an increase of the failure stresses to reach 85, 83 and 72% of the ultimate failure stresses determined from coupon test. Furthermore, filling the sections by only 50% and 33% of its total area result in failure stresses of 98% and 85% for 2 and 3 cells beams compare with 1 cell beam.

Figure 2 also clearly shows an increase in the flexural stiffness of the filled beams compare with its hollow beams counterpart. The results showed that the flexural stiffness increased by 22, 18 and 17% for specimens' SF-1-15, SF-2-15 and SF-3-15, respectively. Accordingly, these values represent 96 and 95% of the stiffness of the single section beams.

Table 2. Pultruded GFRP beams experimental results.

Specimen	failure load kN	failure moment kN.m	Def. (mm)	bottom strain μ ε	top strain μ ε	failure mode
SH-1-0	90.6	23.8	18.8	5500	4000	[a] LB
SF-1-15	161.5	43	29.8	9104	8113	[b] CF
SH-2-0	151.2	79.4	34.7	6324	4242	LB
SF-2-15	217	114	42.7	7520	6928	CF
SH-3-0	187.5	147.6	42.4	5469	3979	LB
SF-3-15	261.6	214	55.8	7331	6675	CF

[a] LB= Local buckling failure

[b] CF= GFRP material failure at the compression side

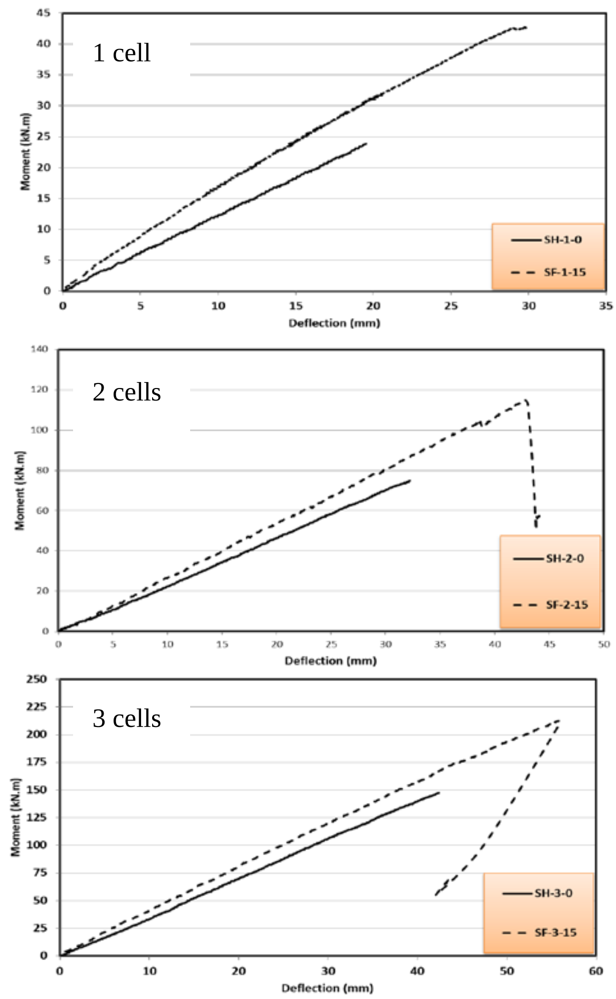


Figure 2. Moment-displacement behaviour of single and multi-cell (hollow and filled) GFRP pultruded beams.

3.2 *Load-strain behavior*

Figure 3 shows the load-strain relationship of 1 and 3 cells of hollow and filled pultruded GFRP specimens. The figure clearly shows that the strains in compression side increased non-linearly until failure. This behaviour reflects the effect of local buckling of the top flange of the tested specimens. It can be seen from Fig. 3 that the specimens failed at a compression strain around 4000 microstrains and a tension strain around 5500 microstrains. The figure also shows a linear increase of the tension strain values for all the tested beams. The linear behaviour of the strain up to failure of multi-cells specimens shows that full composite action could be considered between the bonded square profiles.

The filled beams display similar load strain behaviour for tension side to that of hollow beams. However, the compression side showed linear instead of non-linear behaviour experienced by its hollow counterpart beams due to the contribution of the concrete core in preventing the local buckling. The compression failure strains were 8113, 6928 and 6675 microstrains for specimens' SF-1-5, SF-2-15 and SF-3-15, respectively. The specimens of 2 and 3 bonded cells showed lower strain failure values due of the effect of stress concentration which increased with the increase of the section's depth. Another possible reason for that is the lower deflection/ span ratio of the 2 and 3 cells beams compared with 1 cell beam. Beams with 1 cell showed 23% of deflection/ span ratio compared with 19 and 16% for 2 and 3 cells beams, respectively.

3.3 *Failure mode*

The typical failure modes of 1, 2 and 3 cells hollow section are presented in Fig.4. Similarly, the failure modes of 1, 2 and 3 cells filled section given in Fig.5. The experimental investigations showed that the hollow sections experienced an initial failure at the top compression flange due to the local buckling (LB) of the thin walls which finally result in total failure of the beam. For all the hollow sections, the failure occurred under one of the points loading and varied cracks appeared on the top surface of the top cell of the section. Then, the cracks developed perpendicular to the longitudinal axis of the section and then it progressed to the web-flange junction due to the effect of buckling and finally these cracks propagated into the web which leading to the final failure of the specimens as shown in Fig.4. this behaviour is similar to the observed behaviour by Guades et al. (2014) and Kumar et al. (2004). They report that for hollow tubes tested under flexural loading, the local buckling of the thin walls initiates most failure mode which results in material degradation until final failure of the tube. No damage was observed in the second and third cells of the multi-celled beams in addition there was no delamination or slipping occurred on the glue line. These results suggest that an efficient glue joint was achieved between the pultruded sections which provided by the structural epoxy adhesive used.

On the other hand, filled sections showed different failure mechanism due to the presence of concrete core. The failure started near the web-flange junction and then progressed to the webs. The presence of concrete has contributed to load resistance of the section in addition to prevent the local buckling of the compression flange which results in higher failure strain compared with the hollow beams. With increasing of the applied load, the concrete block cracked and followed by transverse shear cracks and delamination of the compression flange which results in final failure. As a consequence, the flexural compression failure was the dominant failure mode of all the filled beams as shown in Fig.5. It is interested to see that the failure of the multi-cell sections was due to top cell failure which did not result in a total collapse of the beam. This behaviour might be considered to be appropriate for structural engineering designs, as the failure was not really catastrophic. Furthermore, the proposed concept of using of multi-celled hollow beam filled partially with low concrete provided stable section with high flexural strength, high stiffness and lower catastrophic failure.

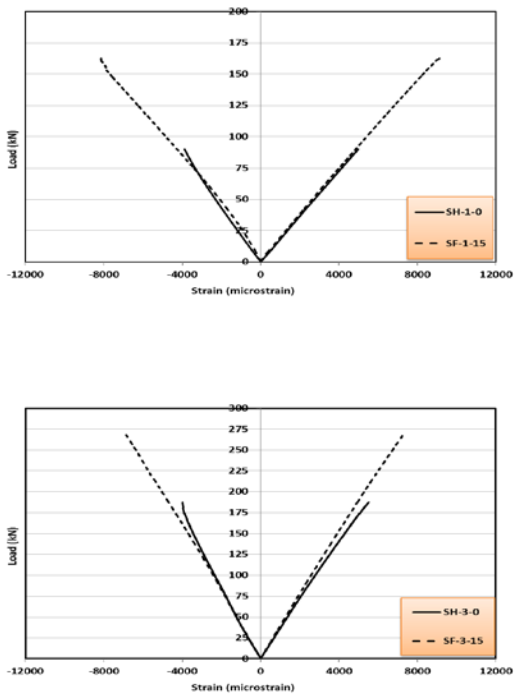


Figure 3. The load-strain relationship of 1, 2 and 3 cells of hollow and filled pultruded GFRP beams

Figure 4. The mode of failure of filled pultruded GFRP beams.

4 CONCLUSIONS

This study has presented the results of four point bending tests on hybrid multi-cell hollow and concrete filled GFRP tubes. The main parameters examined in this study are moment- displacement behaviour, load strain behaviour and failure mode. Based on the results, the following conclusions can be drawn:

- The failure stress of hollow beams represents approximately 50% of the stress level determined from coupon test due to the effect of local buckling failure of the compression.
- The failure of the multi-cell sections was due to top cell compression failure which did not result in a total collapse of the beam. As a result, the flexural strength of the filled section increased by 105, 43 and 45% higher than that of hollow sections.
- Although the filling percentage of 2 and 3 cell beams are 50% and 33%, respectively, their failure stresses are 98% and 85% compare with single cell filled section.
- Flexural stiffness of the filled section showed a noticeable increased with 22%, 18%, 17% for 1, 2 and 3 cells section respectively, than that of hollow sections. In addition, the flexural stiffness of 2 and 3 cells section represent 96% and 95% of the stiffness of single cell section.
- Using low strength concrete to fill the GFRP tubes can be considered as a practical solution to prevent local buckling and improve the overall flexural behaviour.

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