STRENGTH CHARACTERISTICS OF HANDY LAY-UP GFRP I-BEAMS

Mohamed A. Khalaf, Ahmed M. Ebid

Abstract— This research work mainly investigates the local production of 12 built up GFRP I-beams using Hand Lay-Up production method (since up-till now there is no pultrusion industry in Egypt). Overall strength characteristics of these beams will determined experimentally and compared to those manufactured by the Pultrusion process. This comparison will help to estimate to how extent the locally manufactured beams (by Hand Lay-Up technique) can be used in full permanent structures (like pultruded beams) or at least used in light and temporary structures. In order to achieve this goal, the experimental study was divided into two stages:

The first stage is to manufacture GFRP plates using glass fibers and polyester. Two types of plates were produced one for flange plates and the other for web plates. These two types of plates are different in fibers orientation of different layers within the plate thickness in order to reach the possible higher tensile and flexural strength for flange plates and possible higher shear strength for web plates. Longitudinal and transverse tensile, compressive, and flexural strength for these two types of plates were experimentally determined using coupons tests.

The second stage is to produce built-up GFRP I-beams using the aforementioned plates and composite angles. The overall stiffness and modes of failure of these beams were experimentally determined. The obtained results were compared with those of pultruded I-beams manufactured in the United States by pultrusion process. Also three different connecting methods for the 12 tested beams were investigated, namely: Bonding – Bolting – Bolting/Bonding connecting techniques.

Of course it is expected that some local fabrication parameters (like fiber and polymer properties available in the local market, labour, temperature, polymer curing …etc) are expected to affect the properties of the fabricated beams specially that these beams are manufactured manually.

Index Terms— Glass fibers, Handy Lay-Up, I-beams, Locally manufactured, Polyester resin, Strength,

1 Introduction

FRP materials have now many applications in construction industry. The benefits of FRPs over conventional materials are lightweight, high strength to weight ratio, corrosion resistance, electromagnetic transparency, and superior fatigue performance (Nanni 1996). These advantages have brought special attention to FRPs because of their possible use in construction, such as in highway pavements, bridges, and reinforcing systems (Hosny 1996).

In Egypt, applications of FRPs are mainly directed to repair and strengthening of different structural members in concrete and masonry structures. A number of articles related to FRP reinforcing bars (replacing the traditional steel reinforcing bars) have been published. The available studies on composite beams are very limited because the mass production of different structural shapes are done mainly by pultrusion process, and as mentioned before there is no pultrusion industry in Egypt up-till now. In this research work, FRP plates with different fibers layout as well as angles were manually produced by hand lay-up technique using E-glass fibers and polyester resin which are available in the local market. Then, these plates and angles were used to produce 12 composite beams of I-cross section.

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2 Objectives

The main objectives of this research work are:

- To study experimentally the ultimate strength of the locally manufactured plates with different fibers layouts for webs and flanges in two perpendicular directions; the longitudinal and transverse directions of the plate.
- To study experimentally the overall strength and the failure modes of locally manufactured built-up I-beams as structural elements.
- To compare between the overall strength, and the failure modes of the locally manufactured built-up I-beams by hand lay-up technique with those manufactured by the pultrusion process.
- To investigate the efficiency of the considered three types of connecting methods (bolted, bonded, and bolted/bonded).

3 Stage (1): Fabrication and testing of GFRP plates

A total of 40 plates were fabricated using a hand lay-up technique (as shown in Figure 1) because there is no pultrusion industry in Egypt as mentioned before. The used composite system is glass/polyester system where E-grade glass fibers are used as the load carrying medium and polyester as the binding matrix. All the plates are 1 cm in thickness. 26 plates with dimensions 150 cm x 10 cm and 14 plates of 150 cm x 20 cm. For the first 26 plates (150x10x1 cms), 24 of them were used to fabricate the upper and lower flanges of the 12 beams and the last two were used to cut longitudinal and transverse test specimens in tension, compression, and bending. The other 14 plates (150x20x1 cms), 12 of them were used to fabricate the web of the 12 beams and the last two were used to cut longitudinal and transverse test specimens in tension, compression, and flexure. The overall fiber/volume fraction was about 28 % for all plates.

The 1 cm thickness of the flange plates is consisted from 5 layers (2 mm each) with different orientation of fibers in the following order (It has to be noticed that the fibers inclination angle is defined with the longitudinal axis of the plate):

1. The surface layer is a gel coat layer with random chopped glass fibers in order to increase the impact strength of the plates and to be easy in handling because the glass fibers have a harmful effect on the skin.
2. A layer of 0^{o} fibers which called rovings to increase the longitudinal tensile and flexural strengths of flange plates.
3. A layer of 90^{o} fibers to increase the transverse flexural strength of the flange plates.
4. A layer of 0^{o} fibers exactly like layer number 2.
5. The lower surface layer is a gel coat layer with random chopped glass fibers exactly as layer number 1.

The 1 cm thickness of the web plates is consisted from 5 layers (2 mm each) with different orientation of fibers in the following order (It has to be noticed that the fibers inclination angle is defined with the longitudinal axis of the beam):

1. The surface layer is a gel coat layer with random chopped glass fibers exactly like the flange surface layers.
2. A layer of + 45^{o} fibers to increase the shear strength of the web plates.
3. A layer of 0^{o} fibers to increase the tensile and flexural strengths of web plates because the upper and lower parts of webs are usually work with flanges.
4. A layer of - 45^{o} fibers to increase the shear strength of the web plates.
5. The lower surface layer is a gel coat layer with random chopped glass fibers exactly as layer number 1.

Table (1) and figures (2&3) shows the fiber orientation of each layer in both flange and web plates.

In order to investigate the mechanical properties of the fabricated flange and web plates, a total of 48 coupon tests were carried out; 16 tension tests were done according to ASTM D 638-99, 16 compression tests were done according to ASTM D 695-96, and 16 flexure tests were done according to ASTM D 790-99 (references 9,10,11) to determine the ultimate strength of flange and web plates in both longitudinal and transverse directions (four specimens were tested in each case). It has to be noted that the average value of the unit weight for all the plates is 1.32 gm/cm^3. Table 2 gives the ultimate tensile, compressive, and flexural strength in Kg/cm^2 for flange and web plates in both longitudinal and transverse directions.

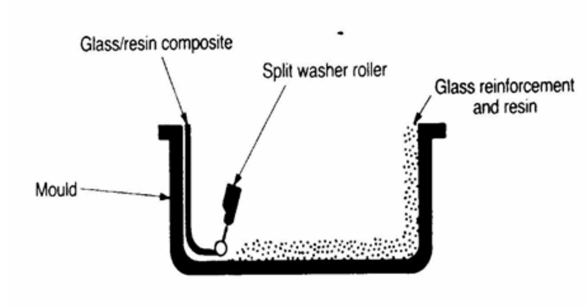

Fig. 1. Lay-ups of Flange and Web plates

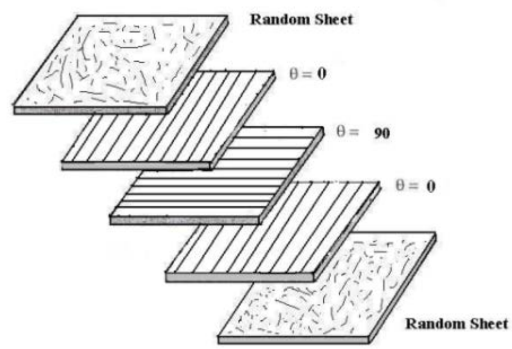

Fig. 2. Fibers orientation of Flange Plates

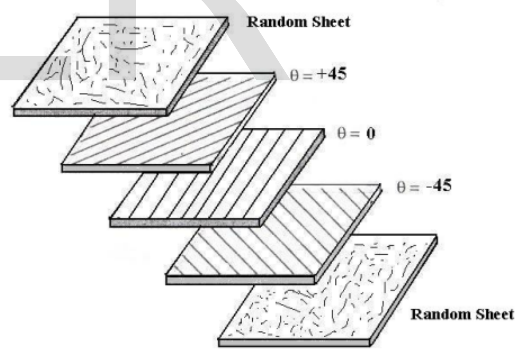

Fig. 3. Fibers orientation of Web Plates

TABLE 1
LAY-UPS OF FLANGE AND WEB PLATES

Layer No.	Horizontal plates (fiber orientation/ binding matrix)	Vertical plates (fiber orientation/ binding matrix)
1	Random / gel coat	Random / gel coat
2	0^{o} / polyester	+ 45^{o} / polyester
3	90^{o} / polyester	0^{o} / polyester
4	0^{o} / polyester	- 45^{o} / polyester
5	Random / gel coat	Random / gel coat

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Discussion of GFRP plates Strength test results

- Based on the obtained results given in Table 2, the tensile and flexural strengths of flanges plates in longitudinal direction are 100% and 58% respectively higher than those in the transverse direction. This increase is attributed to that the longitudinal direction has two layers of 0^o rovings of fibers while the transverse direction has only one layer of 90^o fibers.
- Longitudinal tensile and flexural strengths of the web plates are 53% and 64% respectively higher than those in the transverse directions. This increase is attributed to the presence of only one 0^o roving layer. The transverse direction is still has a reasonable tensile and flexural strengths due to the presence of two 45^o layers.
- For the flange plate in the longitudinal direction (case of the highest strength due to presence of two 0^o rovings) the flexural strength is almost 87% higher than tensile strength because the two 0^o rovings are located around the neutral axis of the plate.
- As given in Table 2, the measured compressive strength of flange and web plates in both longitudinal and transverse directions are almost the same regardless the differences in fiber orientations. This can be attributed to the fact that the compressive stresses are resisted mainly by the matrix which is the same for all cases.
- Variability of test results can be attributed to local fabrication parameters (like fiber and polymer properties available in the local market, labour, temperature, polymer curing …etc).
- In order to compare the obtained tensile and flexural strengths of the fabricated plates with those of the well known mild steel (MS), the values of strength to weight ratio were calculated in [(kg/cm²) / (gm/cm³)] for all the aforementioned cases and compared with that of mild steel [(2400 kg/cm²) / (7.85 gm/cm³) = 305]. Values of strength to weight ratio for all the fabricated plates together with that of mild steel are given in Table 3. Figures 4 and 5 shows the comparison of strength to weight ratios for all the manufactured plates and mild steel in tension and flexure respectively.
- Figures 4 and 5 show very clearly that the flange plate in the longitudinal direction (case of the highest tensile and flexural strengths due to the presence of two 0^o rovings) has tensile strength and flexural strength to weight ratio about 519 and 968 respectively compared to a value of 305 for mild steel. This ratio can be increased by increasing the fiber volume fraction. The problem here is that the used fiber volume fraction depends mainly on the fabrication technique. For hand lay up, we use a fiber volume fraction about 28% which considered reasonable for this manual fabrication technique. In pultrusion industry, the fiber volume fraction can reach up to 70%. This will cause much more increase in both tensile and flexural strengths of FRP plates.

TABLE 2
MEASURED MECHANICAL PROPERTIES OF WEB & FLANGE PLATES

Spec. code	Spec. No.	Tensile Strength kg/cm²	Compressive Strength kg/cm²	Flexural Strength kg/cm²	Average unit weight
FL	1	660	1750	1360	1.32 gm/cm³
	2	675	1890	1300	
	3	635	1810	1270	
	4	770	1930	1180	
	Average	**685**	**1845**	**1278**	
FT	1	295	1800	810	
	2	345	1750	750	
	3	330	1910	890	
	4	400	1780	790	
	Average	**343**	**1810**	**810**	
WL	1	550	1830	890	
	2	480	1800	870	
	3	465	1870	930	
	4	495	1790	710	
	Average	**498**	**1823**	**850**	
WT	1	320	1990	490	
	2	295	1730	510	
	3	390	1800	520	
	4	300	1770	550	
	Average	**326**	**1823**	**518**	

FL: Longitudinal direction of Flange plate, FT : Transverse direction of Flange plate, WL: Longitudinal direction of Web plate, WT : Transverse direction of Web

TABLE 3
(STRENGTH / WEIGHT) RATIOS FOR MANUFACTURED PLATES AND MILD STEEL
(ALL VALUES ARE IN [(KG/CM²) / (GM/CM³)])

Specimen code	FL	FT	WL	WT	Mild Steel (MS)
Strength to wt. ratio in tension	519	260	377	247	305*
Strength to wt. ratio in flexure	968	613	644	392	305*

** This value for tensile and flexural strengths of Mild Steel is based on yield strength of 2400 kg/cm² and unit weight of 7.85 gm/cm³.*

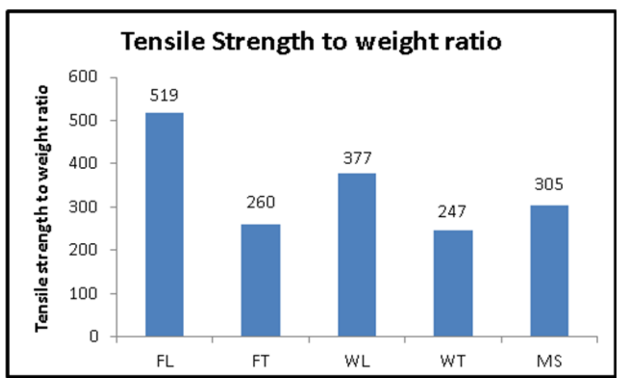

Fig. 4. Tensile Strength to weight ratio(Kg/cm²) /(gm/cm³)

4 Stage (2): Fabrication and Testing of GFRP I-Beams

After manufacturing the flange and web plates, 12 built-up beams were fabricated by connecting these plates using 24 equal leg angles. These connecting angles are 40x4 mm in cross section and 150 cms long manufactured from the same materials as the plates. Each angle has two fibers orientations within its thickness, one in the longitudinal direction of the angle (i.e. 0^o) while the other in the transverse direction (i.e. 90o) taking the same shape of the angle. These angles were used to connect web plates with the upper and lower flange plates. Three different connecting methods were used for the 12 beams:

1. Four bolted beams: where 6 mm diameter steel bolts were used at 8 cms spacing. The bolts used in flange plates and those in web plate are staggered together in order to minimize the strength loss results from cutting the fibers in the location of holes.
2. Four bonded beams: where a SikaDur-30 bonding material was used to connect angles and plates together to form the built-up I-section. The main advantage of bonding is to avoid any cut of the fibers since they considered as the backbone of the composite beam.
3. Four bolted/bonded beams: where the above two connecting methods were used in the same time. Previous research work indicates the superiority of this method which provides a higher safety margin for the beam, because the compression force resulting from bolting helps for better and stronger curing of the bonding material; the compression force reduces percentage of voids in the bonding material which increase the contact area between it and the two faces to be connected.

The aforementioned 12 beams were tested using three point load test arrangements. The beam length was 150 cms, while the effective span was 120 cms. The tested beams were laterally supported to prevent any lateral buckling at the supports because composite beams generally have lower torsional stiffness compared to the conventional concrete or steel beams. The load was applied at the mid-span using a hydraulic jack of 20 ton capacity. Load was applied in intervals of 1 ton each and the corresponding mid-span deflections were recorded in each interval. Test set-up is shown in Figure 7.

The value of the failure load and the obtained mode of failure were recorded for each beam. Table 4 gives the load-deflection test results for the tested beams. Failure load and mode of failure are given also in table 4. Figure 8 shows the load-deflection test results and the stiffness of each beam. Figure 9 shows the obtained mode of failure which was a tension failure starting from the lower flange for all the 12 beams. The lower flange and the two angles connecting it to the web were cut by tension. The bonding material was strong enough to prevent any separation between angles and plates.

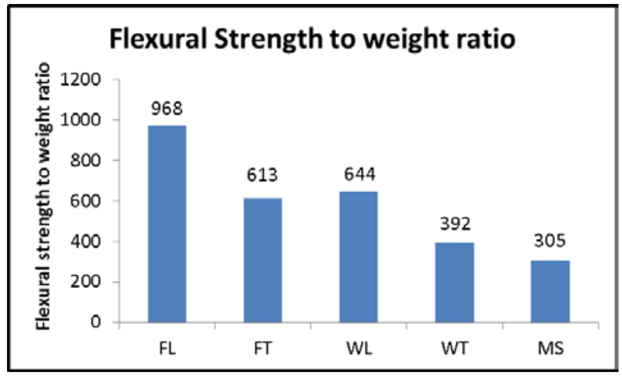

Fig. 5. Flexural Strength to weight ratio (Kg/cm^2) /(gm/cm^3)

(a) Bolted I-beam

(b) Bonded I-beam

(c) Bolted-bonded I-beam

Fig. 6. Manufactured GFRP built-up I-beams

Discussion of GFRP I-beams test results

- In order to evaluate how efficient the hand lay-up fabrication technique is, the measured ultimate strength of the locally manufactured composite beams is compared with values given by different manufacturers in the United states (Bedford, Creative Pultrusion and Strongwell companies) for similar beams manufactured by high technology pultrusion process (MMFG, 1989). The locally manufactured composite beams manufactured by Hand lay-up technique achieved average overall strength about 60% from similar beams manufactured by pultrusion process. This result is considered quiet good.
- The overall Stiffness of these beams is much lower than that of steel beams that is why the design of these beams is controlled mainly by deflection requirements. The total deflection (flexural + shear deflections) is about 10 times higher than that of steel beams of the same dimensions, loading condition, and support conditions. The term overall stiffness is used here because the total mid-span deflection is considered in stiffness calculations not shear and flexural deflections. For this type of beams shear deformation has to be considered in the calculation because, as mentioned in previous researches, the anisotropy ratio of these beams (i.e. the ratio E/G) is higher than that of steel beams.
- The ultimate strengths of bonded beams is about 33% to 38% higher than those of bolted and bolted/bonded beams. This can be attributed to the effect of cutting the load carrying fibers in bolted and bolted/bonded beams during drilling holes for the bolts.
- The ultimate strengths of bolted and bolted/bonded beams are almost the same since both types have the same drilled holes for steel bolts. This result indicates clearly that for bolted beams there is no need for bonding, however, it is mentioned in the previous researches that bolted/bonded beams are superior than bolted beams because bonding in addition to bolting provides a higher safety margin because the compression force resulting from bolting process helps for better and stronger curing of the bonding material.
- It is very important to mention here that however the locally manufactured beams achieve overall strength about 60% from that of pultruded beams, but the production cost is very high. Cost of pultruded beams manufactured by companies is lower than those manufactured manually due to mass production of the pultrusion process. High cost of locally manufactured beams by hand-lay up technique is attributed to many factors such as cost of fibers and polymers, labour cost, transportation cost...etc. The cost issue is affected also by many other factors out of scope from the engineering aspects. Cost of the locally manufactured I-beams in this research approaches approximately about double price of steel I-beams with similar dimensions. Generally, in spite of the cost issue, the locally manufactured beams by hand-lay up technique can be used in light or temporary structures very successfully due to their advantages compared to traditional materials (like steel) as mentioned earlier in this research.

TABLE 4
LOAD-DEFLECTION TEST RESULTS AND FAILURE LOADS FOR BOLTED,BONDED, AND BOLTED/BONDED BEAMS

Load (ton)	**Bolted beams**			
	Beam 1	Beam 2	Beam 3	Beam 4
	Mid-Span Deflection (mm)			
0.0	0.00	0.00	0.00	0.00
1.0	1.29	1.34	1.27	1.36
2.0	2.95	2.98	3.02	2.98
3.0	5.06	5.01	5.06	4.98
4.0	8.14	8.09	8.11	8.06
5.0	10.52	10.63	10.55	10.60
6.0	13.24	13.38	13.31	13.33
7.0				
8.0				
Failure Load	6.7	6.5	6.3	6.6
Avg.	**Pu = 6.53 ton**			
Load (ton)	**Bonded beams**			
	Beam 5	Beam 6	Beam 7	Beam 8
	Mid-Span Deflection (mm)			
0.0	0.00	0.00	0.00	0.00
1.0	1.11	1.09	1.07	1.14
2.0	2.52	2.50	2.49	2.47
3.0	4.27	4.28	4.27	4.26
4.0	6.06	6.06	6.04	6.13
5.0	7.87	7.89	7.81	7.90
6.0	10.16	10.17	10.20	10.15
7.0	12.08	12.00	12.06	12.09
8.0	13.53	13.49	13.43	13.37
Failure Load	9.1	9.3	9.2	8.6
Avg.	**Pu = 9.05 ton**			
Load (ton)	**Bolted/Bonded beams**			
	Beam 9	Beam 10	Beam 11	Beam 12
	Mid-Span Deflection (mm)			
0.0	0.00	0.00	0.00	0.00
1.0	1.27	1.34	1.29	1.37
2.0	2.95	2.98	3.03	2.98
3.0	5.06	5.03	5.05	4.97
4.0	8.12	8.08	8.14	8.11
5.0	10.59	10.59	10.57	10.58
6.0	13.20	13.30	13.33	13.29
7.0				
8.0				
Failure Load	6.5	6.7	7.1	6.8
Avg.	**Pu = 6.78 ton**			

5 Conclusions

From the above discussion, it can be concluded that:

1. Strength to weight ratio for the locally manufactured GFRP flange plates in the longitudinal direction (i.e. the fibers direction) is about 1.7 times that of the mild steel in tension and about 3.17 times in flexure.
2. Compressive strength of GFRP I-beams is controlled mainly by matrix properties regardless the fiber direction.
3. The locally manufactured GFRP I-beams manufactured by Hand lay-up technique achieved about 60% from similar beams manufactured by the high technology pultrusion process.
4. The overall Stiffness of these beams is much lower than that of steel beams, that is why the design of these beams is controlled mainly by deflection requirements.
5. The ultimate load of bonded beams is about 33% to 38% higher than that of bolted and bolted/bonded beams.
6. The ultimate strengths of bolted and bolted/bonded beams are almost the same.

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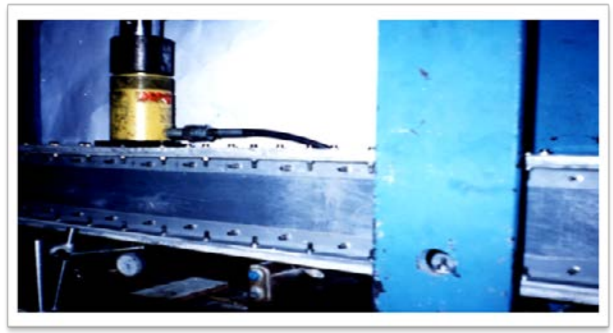

Fig. 7. Test set-up of 3 point load flexure test

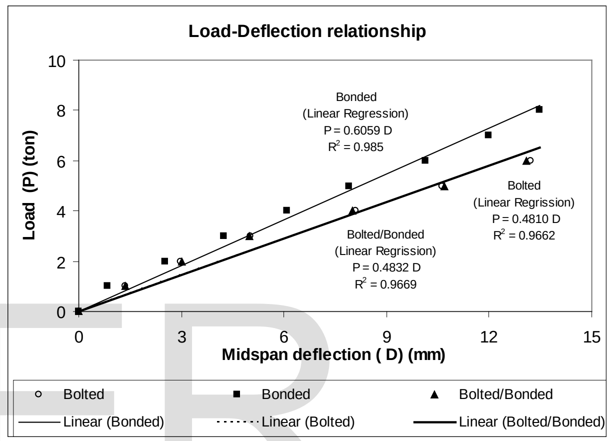

Fig. 8. Load-Deflection relationships for bonded, bolted and bolted/bonded GFRP I-beams (Beams 1,5,9)

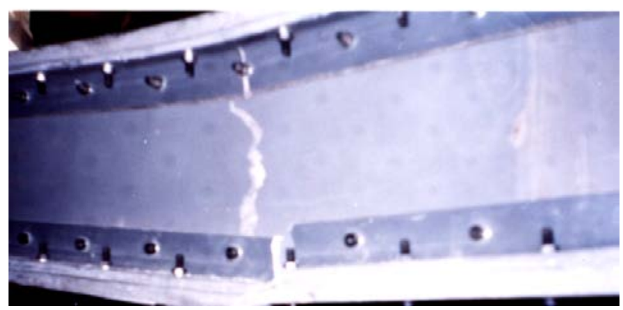

Fig. 9. Tension failure for GFRP I-beams

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