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SHEAR STIFFNESS OF HANDY LAY-UP GFRP I-BEAMS

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Abstract— This research work mainly investigates the local production of 6 built up GFRP I-beams using Hand Lay-Up production method (since up-till now there is no pultrusion industry in Egypt). Overall stiffness characteristics of these beams will determined experimentally and compared to those manufactured by Pultrusion process. A total of 6 Glass Fiber Reinforced Plastic (GFRP) built up I-beams were locally manufactured by hand lay-up technique for load-bearing structural engineering applications. For design purposes, both stiffness and strength properties of these structural members are required. The shear stiffness of the locally manufactured GFRP I-beams is considered in the present paper. A procedure is presented to account for the effect of shear deformation on the response of the GFRP beams in terms of an experimentally determined beam section shear modulus. An experimental program was conducted to investigate the stiffness characteristics of the six locally manufactured GFRP built-up I-beams connected with three different methods; bolted, bonded, and bolted/bonded. The ratio between shear deflection and total deflection was investigated. The obtained test results declared the importance of the contribution of shear deflection to the total deflection calculations.

Index Terms— Glass Fiber Reinforced Plastic (GFRP), Built-Up I-beams, Hand Lay-Up, Pultruded beams, Shear stiffness, Shear deformations, Anisotropy ratio, Shear modulus, Flexural modulus.

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1 INTRODUCTION

Fibre reinforced plastic (FRP) has been widely used by civil engineers in the design of new constructional elements. FRP composites offer a number of advantages over conventional materials including superior corrosion resistance, excellent fatigue behavior, improved strength and stiffness, light weight which makes handling and installation very easy, and low thermal coefficient. Due to the large number of fabrication processes available, FRP composites can be made into almost any shape, and can integrate a number of components normally manufactured independently. Structures built out of FRP composites have demonstrated exceptional durability, and effective resistance to environmental exposure. Prestressing tendons, reinforcing bars, grid reinforcement, and dowels are all examples of the many diverse applications of FRP in new structures [5].

The most common of the FRP manufacturing techniques are: lay-up methods, bag molding methods, filament winding, pultrusion, compression molding (CM), resin transfer molding (RTM), reaction injection molding (RM), injection molding, and pre-forming methods. The best structural or mechanical properties are typically achieved by using strong/stiff fibers, tough matrices, long fiber geometries, and high fiber densities. Product forms that achieve these theoretical potentials are often not affordable with present FRP manufacturing processes.

FRP has been used in civil engineering applications in different forms such as internal or prestressing reinforcements for new structures, external plate bonding for strengthening concrete or masonry structures, pultruded sections and ground anchors [1,5]. Application of FRP in Egypt is so far limited to strengthening of existing structures using external FRP plate bonding. This could be attributed to the high cost of FRP reinforcing bars. However, there are also attempts to locally produce GFRP bars, plates and beam sections [1].

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2 MAIN OBJECTIVES

In the present study, the stiffness characteristics of GFRP built-up I-beams locally manufactured in Egypt by Hand Lay-Up technique are investigated. A procedure suggested by Bank, L.C. [2,3,4] is used to account for the effect of shear deformation on the response of FRP beams in terms of an experimentally determined beam section shear modulus. The main objectives of this research are:

1- To investigate the ratio between shear and total deflection of the locally manufactured beams to decide when shear deflection should be considered in the design and when it can be ignored without a significant error.
2- To compare between stiffness characteristics of the locally manufactured beams with those manufactured by Pultrusion process.

3 SHEAR DEFORMATION OF FRP BEAMS

For fibre reinforced composites the ratio of the flexural modulus to the shear modulus is significantly higher than that for conventional isotropic materials. The deflection of FRP beams is more likely to be affected by the deformations due to shearing stresses in the beam cross-section. This shear deformation of the cross-section will cause the beam to deflect in the transverse plane, which together with the bending deflection will give the total beam deflection [2,3,4,6,8].

The shear deformation of pultruded FRP beams was investigated by many researchers [2,3,4,6,8]. The beam section shear modulus property was proposed by Bank [2,3,4] to characterize thin walled FRP pultruded beams.

The beam section shear modulus (G_b) is found from direct experiment on full-size FRP beams and it is a function of the material and the geometrical properties of the beam. The beam section shear modulus (G_b) is used to account for the effect of shear deformation on the response of FRP beams. The general equation governing the deflection (Δ) of pultruded composite beams was modified by Bank [2,3,4] as follows:

$$\Delta(x) = \frac{f_1(x)}{E_b I} + \frac{f_2(x)}{G_b A_w} \qquad (1)$$

where *f1(x)* and *f2(x)* are functions that depend on the loading and boundary conditions , E_b and G_b are the beam section flexural and shear moduli, A_w is the web area, and I is the second moment of area about the strong axis of the cross section.

For a simply supported beam with span L loaded with a concentrated load P at mid-span, the total vertical mid-span deflection Δ_t can be calculated from the following equation [1] as follows:

$$\Delta_t = \Delta_f + \Delta_{sh} = \frac{PL^3}{48E_b I} + \frac{PL}{4G_b A_w} \qquad (2)$$

Where:

$$\Delta_f = \frac{PL^3}{48E_b I} \text{ = flexural deflection}$$

$$\Delta_{sh} = \frac{PL}{4G_b A_w} \text{ = shear deflection}$$

Equation (2) can be written in the following form:

$$y_1 = \left(\frac{1}{E_b}\right) x_1 + \left(\frac{1}{G_b}\right) \qquad (3)$$

Where:

$$y_1 = \left(\frac{4A_w}{L} * \frac{\Delta}{P}\right) \quad \& \quad x_1 = \left(\frac{A_w L^2}{12I}\right)$$

Equation (3) represents a straight line of slope ($1/E_b$) and of intercept ($1/G_b$) with the y-axis as shown in Fig. (1).
Equation (2) can also be rewritten in the following form:

$$y_2 = \left(\frac{1}{G_b}\right) x_2 + \left(\frac{1}{E_b}\right) \qquad (3)$$

Where:

$$y_2 = \left(\frac{48I}{L^3} * \frac{\Delta}{P}\right) \quad \& \quad x_2 = \left(\frac{12I}{A_w L^2}\right)$$

Equation (4) represents a straight line of slope ($1/G_b$) and of intercept ($1/E_b$) with the y-axis as shown in fig. (2).

Both calculation methods from Equations (3) and (4) are used to obtain the beam section flexural and shear moduli. For design purposes, it is recommended to use the average values.

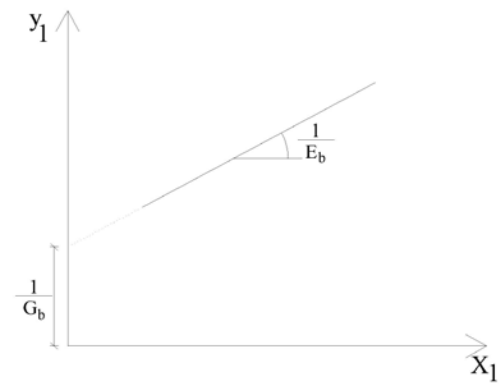

Fig. 1. Graphical representation of equation 3.

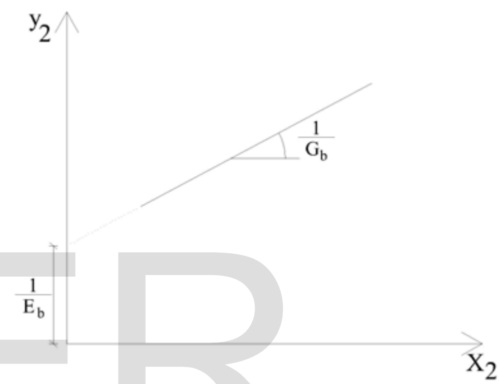

Fig. 2. Graphical representation of equation 4.

3.1 Calculation of the ratio between shear and total deflection

From Equation (2) the shear deflection can be calculated as a ratio from the total deflection as follows [4]:

$$\left(\frac{\Delta_{sh}}{\Delta_t}\right) = \frac{1}{1+K} \qquad (5)$$

Where:

$$K = \frac{\left(\frac{A_w}{12I}\right)\left(L^2\right)}{\left(\frac{E_b}{G_b}\right)}$$

Bank [2,3,4] reported that the effect of shear deformation increases as the section anisotropy ratio "E_b/G_b" increases and the slenderness ratio *L/r* decreases, where *r* is the section radius of gyration about the strong axis of the beam. The effect of shear deformation is most severe for slenderness ratio *L/r* less than 60. It is therefore strongly recommended that the contribution of shear deflection be included in deflection calculations when *L/r* is less than 60, otherwise, the effect of shear deformation is to be negligible (with an error less than10%).

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4 FABRICATION OF BUILT-UP I-BEAMS BY HAND LAY-UP

GFRP composite plates and angles with different fibers lay-out were locally produced using a hand Lay-up technique. E-glass fibers were used for the composite as the load carrying medium with fiber/volume fraction 30% and polyester resin was used as the binding matrix. Table 1 shows the mechanical properties of polyester resin and E-glass fibers used in the manufacture. Table 2 shows the mechanical properties of the flange and web plates in the longitudinal and the transverse directions.

Six built-up I-beam sections of length 1500 mm and height 200 mm were manufactured using flange plates with dimensions 1500x100x10 mm, web plates with dimensions 1500x200x10 mm and connecting angles of length 1500 mm with cross-section 40x40x4 mm. Three different methods were used for connections; two beams were connected using 6 mm steel bolts, two beams were bonded using epoxy and two beams were connected by combination of the above two methods. The manufactured built-up I-beams connected with the three different methods are shown in Fig. (3).

TABLE 1
MECHANICAL PROPERTIES OF GLASS FIBERS AND POLYESTER RESIN

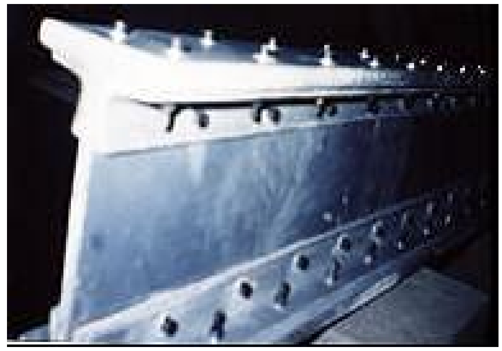
	Specific Gravity	Tensile strength (ton/cm^2)	Tensile Modulus (ton/cm^2)	Strain to Failure %
E-glass	2.54	34.4	723.9	4.8
Polyester	1.2	0.61	36.5	4.3

TABLE 2
MECHANICAL PROPERTIES OF THE MANUFACTURED PLATES

Mechanical Property (kg/cm^2)	Flange Plate	Web Plate
Longitudinal tensile strength	575	383
Transverse tensile strength	304	287
Longitudinal compressive strength	1820	1795
Transverse compressive strength	1759	1800
Longitudinal flexural strength	1285	659
Transverse flexural strength	950	484

-Tension tests were done according to ASTM D 638-99 (Ref. 12)
-Compression tests were done according to ASTM D 695-96 (Ref. 13)
-Flexure tests were done according to ASTM D 790-99 (Ref. 14)

The lay-ups in the horizontal (flange) plates or the vertical (web) plates depends mainly on the stresses carried by the plate .The flange plate carries the flexural stresses while the web plate mainly resists shear forces. By altering the lay-up of the plate of the beam both the magnitude of the flexural deflection and of the shear deflection is affected. The lay-ups in the horizontal and vertical plates that form the cross-section are given in Table 3 in terms of the fiber inclination angle.



(a) Bolted I-beam

(b) Bonded I-beam

(c) Bolted-bonded I-beam

Fig. 3. Manufactured GFRP built-up I-beams

TABLE 3
LAY-UPS OF HORIZONTAL AND VERTICAL PLATES

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

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5 EXPERIMENTAL STUDY

Six GFRP built-up I-beams were tested under three point load arrangements. The load was applied at the mid-span using a load cell of 20 ton capacity and mid-span deflection was measured using a dial gauge having 0.001mm sensitivity. The tested beams were laterally supported to prevent any lateral twisting at the supports. Experimental set-up is shown in Fig. (4). All the beams were tested at span to radius of gyration ratio (L/r) values ranging from 5 to 15 (Five spans values were tested : 1200, 1000, 800, 600, 400 mms). Values of load and mid-span deflection were recorded for all beams with different spans. The relationships between the load and mid-span deflection (the average value of two beams was considered) for bolted-bonded, bonded and bolted beams are illustrated in Fig. (5a-5b-5c).

6. TEST RESULTS AND DISCUSSION

The values of the beam section flexural and shear moduli E_b and G_b are determined using the graphical representation of Equations (3) and (4) for bolted/bonded, bonded and bolted beams shown in Fig. (6). The values of E_b and G_b are given in Table 4.

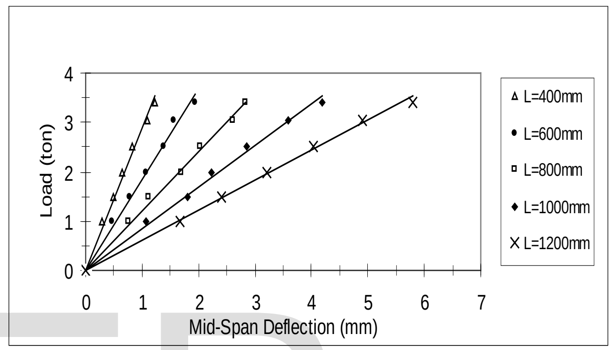
It could be noticed that the value of shear modulus G_b for bonded beam is higher than that for bolted/bonded and bolted beams by 56% and 100% respectively. This could be attributed to the reduction in the load carrying capacity of the beam as a result of cutting some of the load carrying fibers while drilling holes for the used steel bolts. The value of flexural modulus E_b for bonded beam is higher than that for bolted-bonded and bolted beams by 18% and 26% respectively. This shows that cutting holes has more effect on the load carrying capacity of the web than that of the flange.

The anisotropy ratios E_b/G_b for bolted-bonded, bonded and bolted beams are 9.0, 6.85 and 10.9 respectively which means greater shear deformation effects in bolted and bolted-bonded beams than for bonded beams.

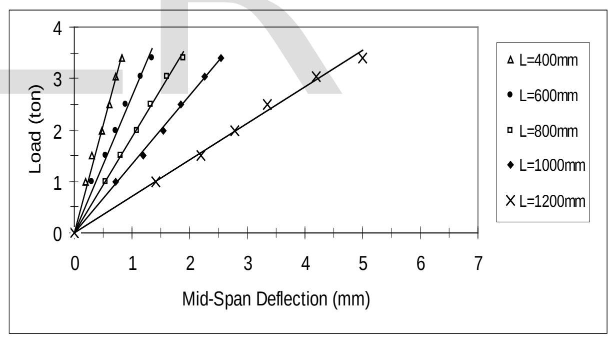
Based on the obtained results, it could be observed that the built-up I-beams locally manufactured by Hand Lay-up technique achieved about 80 to 100 % of the minimum requirements of the flexural modulus E_b of Pultruted I-beams given by manufactures in the United States while the shear modulus G_b of the locally manufactured I-beams achieved about 43% to 87% of the minimum requirements of Pultruted I-beams.

Table 5 gives the ratio between shear deflection and total deflection Δ_{sh}/Δ_t for tested beams with different span to radius of gyration ratios (L/r). Fig. (7) shows the relation between the values of L/r and Δ_{sh}/Δ_t ratio. It could be noticed that the ratio between shear to total deflection for bolted beams is higher than that of bolted-bonded and bonded beams. This shows that the effect of shear deformation increases as the section anisotropy ratio E_b/G_b increases. It is also observed that the effect of shear deformation increases as the slenderness ratio L/r decreases. Based on the regression analysis presented in Fig. (7), it can be concluded that the effect of shear deformation could be ignored (with an error not more than 10%) if L/r is greater than 360 otherwise, the effect of shear deformation must be considered.

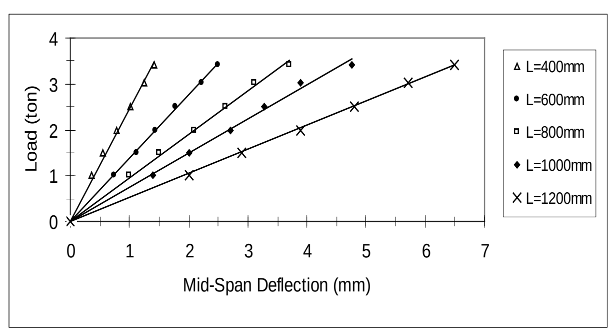
Fig. 4. Test set-up.



(a) Bolted/bonded I- beam



(b) Bonded I-beam



(c) Bolted I-beam

Fig. 5. Load versus mid-span deflection for tested beams

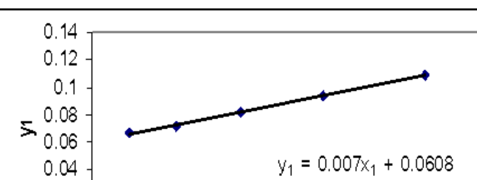


TABLE 4
CALCULATED VALUES OF BEAM SECTION FLEXURAL AND SHEAR MODULI

	E_b (ton/cm^2)			G_b (ton/cm^2)			E_b/G_b
	Eq. 3	Eq. 4	Avg.	Eq. 3	Eq. 4	Avg.	
Bolted-bonded	142.8	151.5	**147.1**	16.2	16.4	**16.3**	**9.02**
Bonded	140.8	208.3	174.6	23.4	27.6	25.5	6.85
Bolted	161.3	114.9	138.1	13.3	12.1	12.7	10.87
Pultruted*	172			29.2			5.89

**The minimum requirements for Pultruted I-beams given by manufactures in the U.S.*

TABLE 5
RATIO BETWEEN SHEAR DEFLECTION AND TOTAL DEFLECTION

	Δ_{sh}/Δ_t x 100				
L/r	5.0	7.5	10.0	12.5	15
Bolted-bonded	92.2	84.2	74.9	65.6	65.9
Bonded	90.0	80.1	69.3	59.1	50.1
Bolted	93.5	86.5	78.2	69.7	61.4

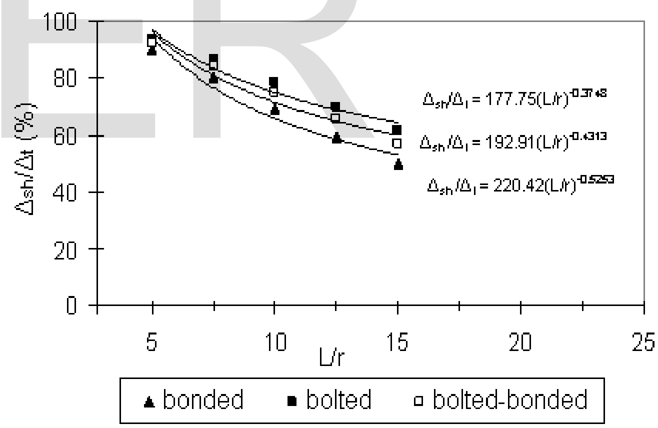


Fig. 7. The relation between the values of L/r and Δ_{sh} / Δ_t ratio

7. CONCLUSIONS

From the test results obtained in the present study it may be concluded that:

1. The values of the flexural and shear moduli E_b and G_b for bonded built-up I-beams are higher than those for bolted/bonded and bolted beams.

2. The locally manufactured built-up I-beams by Hand Lay-up technique achieved about 80 to 100 % of the minimum requirements of the flexural modulus E_b of Pultruted I-beams. While the shear modulus G_b of the locally manu-

factured I-beams achieved about 43% to 87% of the minimum requirements of Pultruted I-beams.

3. For locally manufactured composite I-beams the ratio between the flexural modulus to the shear modulus ranges between 6.85 to 10.9 which is significantly higher than that for steel sections (2.6). So the shear deformation can have a significant effect on the response of composite beams.

4. The ratio between shear deflection and total deflection of FRP composite built-up I-beams increases as the section anisotropy ratio E_b/G_b increases and the slenderness ratio L/r decreases.

5. The contribution of shear deflection has to be included in deflection calculations for locally manufactured composite built-up I-beams when L/r is less than 360, otherwise, the effect of shear deformation is to be negligible (with an error not more than10%).

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