Tensile strength of GFRP plates manufactured manually by Hand-Layup technique with different fiber angle orientations

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Abstract— Fiber Reinforced Polymers (FRP) materials are used extensively in the field of repair and strengthening of different types of structures. The used FRP can be in the form of sheets or plates. There are different manufacturing techniques used to produce these plates either manually or mechanically. This research work studies the ultimate tensile strength of locally manufactured FRP plates by manual hand lay-up technique with different angle orientations of fibers. The used materials are glass fibers and polyester polymer. Five different fiber angle orientations were considered in this research (0°, 30°, 45°, 60° and 90°). The obtained tensile strengths of the manufactured plates were compared with those of similar plates manufactured mechanically by the pultrusion process which used in USA and Canada. Test results were compared also with those calculated from the well-known rule of mixture considering the materials properties given by the manufacturer.

Test results showed that the values of the ultimate tensile strength of the locally manufactured plates were between 50% and 55% from which manufactured by the pultrusion process. Test results have showed also that the well-known rule of mixture can be used with a reasonable degree of accuracy to calculate the ultimate tensile strength of the manufactured plates.

1. INTRODUCTION

Recent interest in glass fiber reinforced plastics (GFRP) structural members has been attributed to the increased demands for better performance materials to meet the contemporary construction and durability needs. These needs include better resistance to environmental loads and higher life expectancy than conventional construction materials. Until recently, composite materials were used in structures requiring high performance standards, such as those in the aerospace industry. The expansion of fiber reinforced plastics (FRP) industry, however, has led to many applications ranging from consumer goods to construction applications. The benefits of FRPs over conventional materials are lightweight, high strength to weight ratio, corrosion resistance, electromagnetic transparency, and superior fatigue performance. These advantages have brought special attention to FRPs because of their possible use in construction, such as in highway pavements, bridges, and reinforcing systems.

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 the pultrusion industry in Egypt is still in the preliminary stages. In this research work, FRP plates with different fibers orientations were manually manufactured by hand lay-up technique using E-glass fibers and polyester resin those are available in the local market. Results of ultimate tensile strength of these plates were compared to similar plates manufactured by the pultrusion process. Figure 1 shows a sketch for the hand lay-up process and Figure 2 shows a sketch for the different steps of the pultrusion process.

2. OBJECTIVES

1- The main objective of this research work is to compare between the effectiveness of Hand Lay-up manufacturing method used in the local market and the Pultrusion process used in different countries such as USA. This comparison will be done by evaluating the ultimate tensile strength of GFRP plates produced by the two manufacturing methods with five different fiber angle orientations (0°, 30°, 45°, 60° and 90°). This comparison will show the difference between manual manufacturing techniques versus fully automated mechanical manufacturing technique under high control level.

2- The second objective of this research is to evaluate the accuracy of using the well-known rule of mixture to calculate the unidirectional strengths of the manually manufactured GFRP plates by Hand Lay-up technique.

3. FABRICATION AND TESTING OF PLATES

A total of five plates were fabricated manually using a hand lay-up technique because as mentioned earlier the pultrusion process in Egypt is still in the preliminary stages. The used composite system is glass/polyester system where E-grade glass fibers are used as the load carrying medium and polyester resin as the binding matrix. Tables 1 and 2 give the properties of glass fibers and polyester resin respectively given by the manufacturer. All plates are of dimensions 100mm x 300 mm and 4mm in average thickness. Variation of plate thickness from one point to another is due to non-uniform hand compaction of polyester. Compaction of the polyester resin in this method is done manually. Fiber orientations of these five plates are making angles of (0°, 30°, 45°, 60° and 90°) with the longitudinal axis of the plate (as shown in Figure 5). Fiber volume fraction was about 35% for all the manufactured plates.

Figures 3A to 3D show the different steps of manual manufacturing of FRP plates by Hand Lay-Up method. Figures 3A and 3B show the preparation of glass fibers into the mold for two different fiber angle orientations (0° and 45°) respectively. Figure 3C shows the step of adding the polyester resin in the mold. Figure 3D shows the last step of manual compaction and smoothing the plate surface. Tension test specimen was cut from every plate from the manufactured five plates; the shape of the tension test specimen is shown in Figure 4. The tension force applied on these five specimens was along the longitudinal axis of all the specimens as shown in Figure 5. Figure 6 shows the tension test set up used in this research.

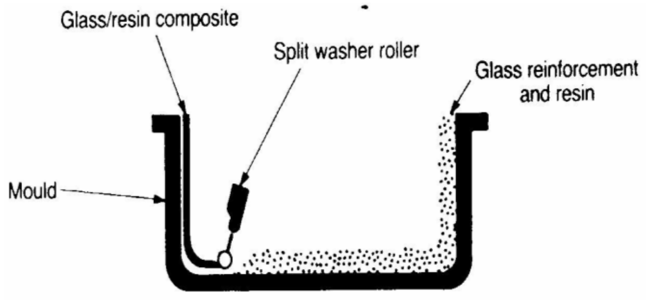


Figure 1: Hand Lay-Up Technique (Manual method)

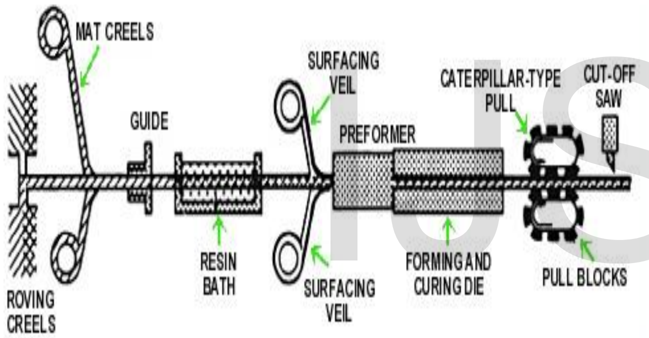


Figure 2: Steps of Pultrusion Process (Mechanical method)

Table 1: Glass fibers properties (Manufacturer data)

Fiber type	E –Glass fiber
Weight per unit area	430 g/m^2
Tensile strength	2250 N/mm^2
Tensile E-modulus	70000 N/mm^2
Strain at failure	3.1 %
Fabric length per roll	≥ 50m
Fabric width	300/600 mm
Shelf life	Unlimited
Packing	1 roll in card board box

Table 2: Polyester resin properties (Manufacturer data)

Appearance	Clear yellow
Specific gravity	1.1
Tensile strength (N/mm^2)	60
Tensile modulus (N/mm^2)	3650
Flexural strength (N/mm^2)	95
Flexural modulus (N/mm^2)	3200

Figure 3A: Preparation of fibers into the mold (0° Fibers)

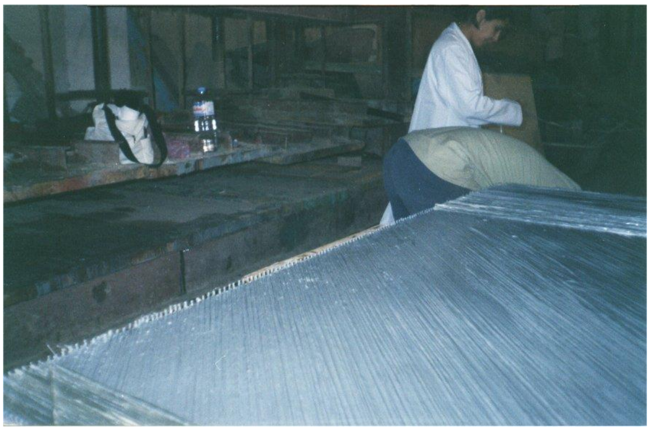


Figure 3B: Preparation of fibers into the mold (45° Fibers)

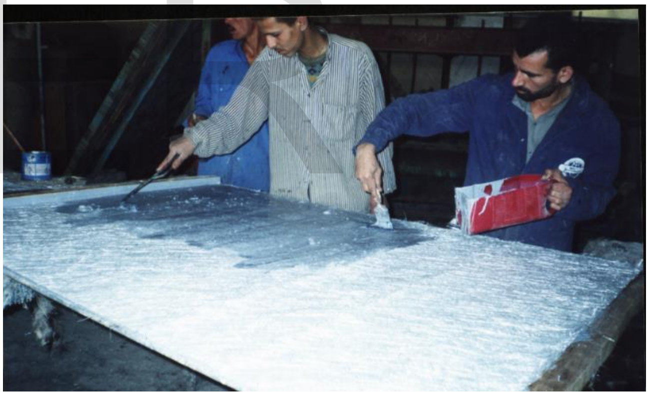
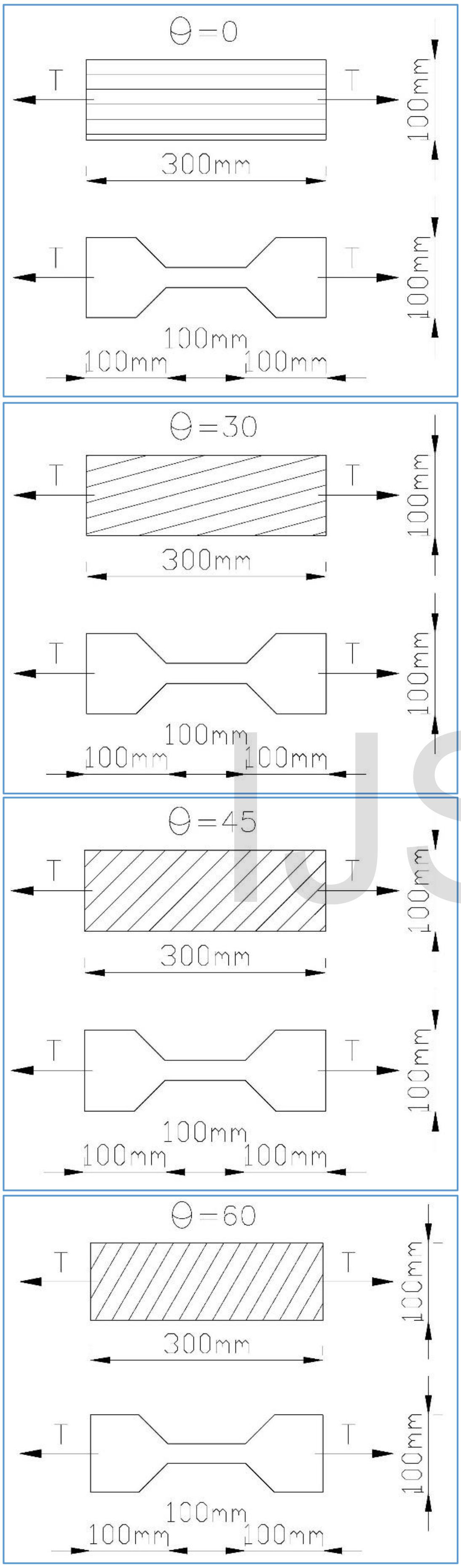


Figure 3C: Adding the polyester resin

Figure 3D: Compacting the resin manually

Figure 4: Shape of tension test specimen



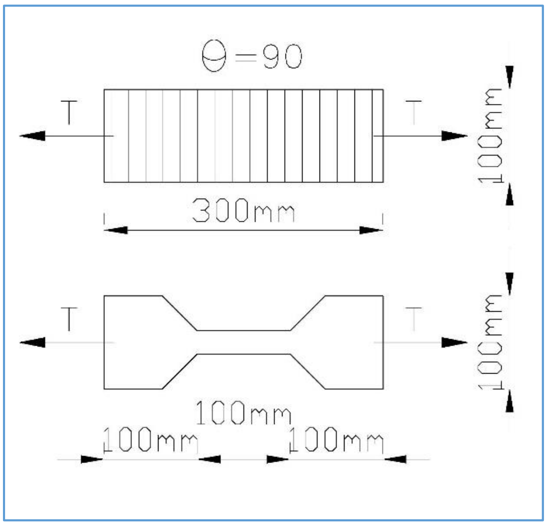


Figure 5: Tension force acting on the five specimens cut from plates with different fiber angle orientations (0°, 30°, 45°, 60° and 90°)

Figure 6: Tension test set up

4. Test Results

As mentioned before, five plates were manufactured by Hand Lay-up technique of the same dimensions (100x300) and 4mm average thickness. The fiber angle orientation of these plates are 0°, 30°, 45°, 60° and 90° with the longitudinal axis of each plate. From each plate, a tension test specimen was cut with dimensions as shown in Figures 4 and 5. Fiber volume fraction of all the five platters was 35%.Tension tests were done on the five specimens with different fiber angle orientations where the tension load was applied along the longitudinal axis of the specimens (as shown in Figure 5). A hydraulic universal testing machine of capacity 30 ton was used to apply the load on all the test specimens (as shown in Figure 6). All tests were done in materials laboratory, Ain Shams University. All specimens were failed in tension in the middle zone. Tensile strength of each specimen was calculated from dividing the failure load by the cross sectional area of the test specimen. Values of the tensile strength of all the five specimens (in N/mm^2) are given in Table 3.

Table 3: Measured tensile strength of all test specimens

Specimen Number	Fiber angle orientation	Tensile strength N/mm^2
1	0°	755
2	30°	446
3	45°	223
4	60°	115
5	90°	71

5. Discussion of Test Results

- For FRP plates and sheets, it is well known that the maximum tensile strength is in the direction of fibers (i.e. 0°). The unidirectional strength along the fiber direction is considered the major tensile strength of FRP plates and sheets. Inclination of fibers by any angle (ϴ) will cause a drop in the tensile strength because only a component of fibers will resist the tension force. This drop will increase by increasing the inclination angle (ϴ). Fiber angle orientation (ϴ) of 30°, 45° and 60° causes a drop in the tensile strength 41%, 71% and 85% respectively from the case of unidirectional fibers (case of ϴ=0°) (as given in Table 4 and shown in Figure 7). Most of the literature in this area recommended that the fiber angle inclination should not exceed 6° to avoid a major drop in the unidirectional tensile strength. This means that in order to obtain the maximum benefit from FRP, the fiber direction should be in the same direction of the applied tension force.
- In the case of fiber direction is perpendicular to the tension force (case of ϴ=90°), the fibers have no role in resisting the tension force (i.e. with zero component). The tensile strength in this case depends mainly on the polymer tensile strength alone. The measured value of tensile strength in this case is 71 N/mm² which is not far from the polymer tensile strength given by the manufacturer (60 N/mm² as given earlier in Table 2). Generally it should be noted that the properties given by the manufacturer are a little bit more conservative than the measured properties.
- In order to compare between the measured tensile strengths of FRP plates locally manufactured by Hand Lay-Up (manual technique) with those manufactured mechanically by the Pultrusion process (fully automated mechanical technique), two plates were considered : the first one is the unidirectional plate (ϴ=0°) and the second one is the plate of inclination angle of fibers (ϴ=45°). Tensile strength of the first plate (ϴ=0°) is 755 N/mm² which represent about 50% from that of the pultruded plate (1500 N/mm²). On the other hand, the tensile strength of the second plate (ϴ=45°) is 223 N/mm² which represent about 55% from that of the pultruded plate (400 N/mm²). Tensile strengths of the pultruded plates (made from glass fibers and polyester resin with 35% fibers volume fraction) are taken from the literature [ref. (12) MMFG data of pultruded sections] as given in Table 4. This means that the efficiency of the Hand Lay-Up manufacturing technique (which is used in Egypt) is in the range of 50% to 55% compared to the pultrusion process which is commonly used in other countries. Lower tensile strength of FRP plates manufactured by Hand Lay-Up technique (compared to pultrusion process) can be attributed to the following reasons:

- Lower compaction of Hand Lay-Up technique resulting more voids in polyester resin than the voids resulting from the pultrusion process (which are almost negligible). Generally, manual compaction causes more voids than mechanical compaction.
- Lower degree of fibers straightness of Hand Lay-Up technique compared to the pultrusion process. Full mechanical control of pultrusion process has a major effect on fibers straightness and consequently on the obtained tensile strength of the manufactured plates. Tensile strength of FRP plates is sensitive to the degree of fibers straightness.
- By using manual Hand Lay-Up fabrication technique, the plate thickness cannot be uniform 100%. On the other hand, pultrusion process produces uniform thickness plates due to full mechanical control on all the fabrication steps. Uniformity of thickness and the overall dimensions of the plates has a remarkable effect on their mechanical properties. Generally, manual compaction causes more variable thickness than mechanical compaction.

- Tensile strength of FRP plates can be calculated from the well-known rule of mixture. The rule of mixture states that :

$$F_u = (F_{fu})(V_f) + (F_{mu})(V_m)$$

Where:

Fu = FRP unidirectional tensile strength of the plate
Ffu = Tensile strength of fibers
Vf = Fibers volume fraction = 35%
Fmu = Tensile strength of polyester resin
Vm = Polymers volume fraction = 65%

By using fibers and polymers tensile strengths (2250 and 60 N/mm² respectively) given by the manufacturer, the resulting unidirectional tensile strength of FRP plate is 826.5 N/mm² as given in Table 5. The measured value is 755 N/mm² which represent about 91% from the calculated value. This level of accuracy can be considered acceptable for the design purposes.

Table 4: Tensile strength of test specimens compared to similar sections manufactured by Pultrusion process

Specimen Number	Fiber angle orientation	Tensile strength (Hand Lay-Up) N/mm²	Tensile strength (Pultrusion)** N/mm²
1	0°	755 (100%)	1500
2	30°	446 (59%)	----
3	45°	223 (29%)	400
4	60°	115 (15%)	----
5	90°	71 (only polymers resist tension)	----

** Taken from MMFG data of pultruded sections (35% fibers volume fraction) (ref.12).

Table 5: Tensile strength of test specimens compared to values calculated from rule of mixture for unidirectional fibers (0°)

Specimen Number	Fiber angle orientation	Tensile strength (Hand Lay-Up) N/mm²	Calculated from Rule of Mixture N/mm²
1	0°	755 (91%)	826.5 (100%)
2	30°	526	----
3	45°	223	----
4	60°	130	----
5	90°	71	----

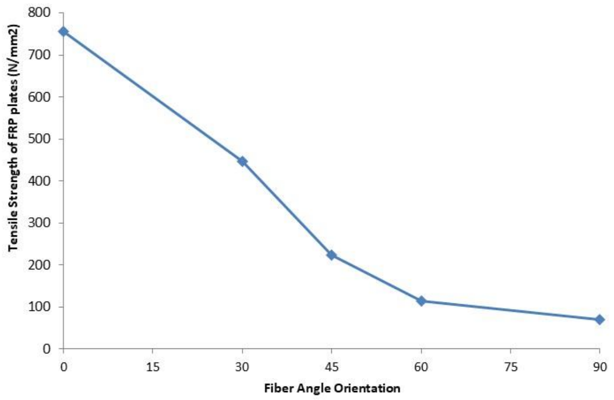


Figure 7: Effect of fiber angle orientation on tensile strength of FRP plates

6. Conclusions

Based on the obtained test results and the above discussion it can be easily conclude the following points:

- Tensile strength of FRP plates manufactured by Hand Lay-Up technique (locally used in Egypt) is in the range of 50% to 55% from similar plates manufactured mechanically by the Pultrusion process.
- Rule of mixture can be used with a reasonable degree of accuracy to calculate the tensile strength of the FRP plates manufactured by Hand Lay-Up technique based on the manufacturer data.

7. References

1- Marco Morgado*, João R. Correia*, Fernando A. Branco "TENSILE AND COMPRESSIVE BEHAVIOUR OF GFRP PULTRUDED PROFILES AT ELEVATED TEMPERATURE" 16th International Conference on Composite Structures ICCS 16 A. J. M. Ferreira (Editor) © FEUP, Porto, 2011.

2- Majid Muttashar1,2, Warna Karunasena1 , Allan Manalo1 and Weena Lokuge "Behaviour of hollow pultruded GFRP square beams with different shear span-to-depth ratios", Journal of Composite Materials 2016, Vol. 50 (21) 2925–2940.

3- Yujun Qi,1,* Lei Xie,2 Yu Bai, 2 Weiqing Liu,1 and Hai Fang1 "Axial Compression Behaviours of Pultruded GFRP–Wood Composite Columns" Journal ListSensors (Basel) v.19(4); 2019 Feb PMC 6412685

4- Barbero E.J. "Pultruded structural shapes: Stress analysis and failure prediction" Advanced composite materials in Civil Engineering, 1991, pp. 194-204.

5- Sara Black "Pultrusions growing in construction: new EPTA report European Pultrusion Technology Assn.", Frankfurt am Main, Germany, 2017.

6- Barbero E.J. and Sonti S.S. "Micromechanical models for pultruded composite beams" 32nd. Structural Dynamics Conference, American Institute of Aeronautics and Astronautics, Baltimore, Maryland, May 8-10, 1991.

7- Joneja S.K. "Matrix contribution to fatigue behavior of glass reinforced polyester composites" 41st. Annual Conference, Session 10-A, Reinforced Plastic Composite Institute, The Society of Plastics Industry, January 27-31, 1986.

8- Bank L.C. and Bednarczyk P.J. "A beam theory for thin walled composite beams" Composite Science and Technology, Vol.32, 1988, pp. 265-277.

9- Nanni A. " Fiber Reinforced Plastic materials" Proceedings from the first middle-east workshop on structural composites, Sharm El-Shiekh, Egypt, June 1996, pp. 1-24.

10- Gibson R.F. "Principles of composite material mechanics" Text book, McGraw-Hill Series in Mechanical Engineering, ISBN 0-07-023451-5, 1994.

11- Hosny Abdel-Hady and Mahfouz Ibrahim " Introduction and Overview to Advanced Composite Materials" Proceedings from the first middle-east workshop on structural composites, Sharm El-Shiekh, Egypt, June 1996, pp. I-XIX.

12- MMFG "Extern Fiberglass Structural Shapes Design Manual" Bristol, Va., Morrison Molded Fiber Glass Company, 1989.

13- Mottram J.T. and Zheng Y. " Analysis of a pultruded frame with various connection properties" Proceedings from the second international conference on composites in infrastructures, Tucson, Arizona, USA, January 1998, Vol. II, pp. 261-274.

14- Salim H.A., Davalos J.F. and Kiger S.A. " Torsion of open and closed FRP composite shapes" Proceedings from the second international conference on composites in infrastructures, Tucson, Arizona, USA, January 1998, Vol. II, pp. 369-381.

15- Brown N.D., Mottram J.T. and Anderson D. " The behavior of columns for the design of pultruded frames: Tests on isolated columns" Proceedings from the second international conference on composites in infrastructures, Tucson, Arizona, USA, January 1998, Vol. II, pp. 248-302.

16- Qiao P. and Davalos J.F. " Experimental characterization of global buckling response of FRP structural beams" Proceedings from the second international conference on composites in infrastructures, Tucson, Arizona, USA, January 1998, Vol. II, pp. 289-302.

17- Barbero E.J. "Introduction to composite materials design" A book review, Journal of composite for construction, Aug. 1999 pp. 151-152.

18- Bank L.C. and Yin J. "Failure of web-flange junction in postbuckled pultruded I-beams" Journal of composite for construction, Nov. 1999pp. 177-184.

19- Foster D.C., Richards D., and Bonger B.R. " Design and installation of fiber reinforced polymer composite bridge" Journal of composite for construction, Feb. 2000 pp. 33-37.