Properties of Composite Trapezoidal Parts Manufactured with help of Filament Winding Technology using Taguchi Method

PhD. Svetlana Risteska, PhD. Blagoja Samakoski, MSc. Maja Stefanovska
Institute for Advanced Composites and Robotics (IACR)
Prilep, Macedonia

***Abstract* — Aim of this work is to determine the influence of fiber orientation and winding tension on the structural and mechanical properties of trapezoidal glass fiber/epoxy resin beams, manufactured with help of filament winding technology. In the first part, with help of Taguchi method was achieved similar wall thickness on trapezoidal sides and corners. Beams with similar thickness where used for mechanical testing, described in the second part in this research. Values for stress, strain and module of elasticity were calculated using three-point bending test carried out on Shimadzu universal machine. Further, the paper investigates the content of voids inside the structure using optical and scanning electron microscope.**

Keywords—composite, filament winding, taguchi method, trapezoidal beam.

I. INTRODUCTION

The importance of composite materials in today's society is well known. Due to the high strength-to-weight ratio, good stiffness properties, inherent corrosion resistance, low electromagnetic reflectance, thermal conductivity and weight, their use in different kinds of applications is accelerating rapidly [1]. Composite materials have become common engineering materials designed and manufactured for various applications and industries including automotive components, sporting goods, aerospace parts, consumer goods, marine, oil and infrastructure [2]. Decks for both pedestrian and vehicle bridges across waterways, railways and roadways are now a commercial reality in both North America and Europe, with some pedestrian bridges being built entirely from composites [3], [4]. The bridge deck sections, composed of hexagon and double-trapezoid profiles are bonded with a high-strength adhesive under controlled conditions. Composites can significantly reduce maintenance and replacement costs because of the material's excellent resistance to corrosion and fatigue. In essence, composite durability not only improves life-cycle costs but extends the life-cycle itself [5], [6]. During filament winding (FW) process voids are formed inside the composite structure due to a number of reasons, such as air entrapment during resin system mixture and moisture absorption during material storage or processing. These voids affect the material properties of the composite. Zhu et.al, [7] studied the microstructure of voids and investigated their influence on tensile strength and modulus of carbon/epoxy fabric laminates. They have reported, that the tensile strengths decreases with increased void content and cracks emanate in the composite when void content is 8.0% and 9.0% after tensile strength test. However, no cracks were found emanating from the voids in the composite parts with the void content of 0.4%.

Because of the cost of failure tests of large structures, laboratory tests must be conducted on a much reduced scale. Thus, it is essential to have a correct method to extrapolate the results obtained from small laboratory specimens to much larger structural parts.

In this paper, study of the influence of fiber orientation on the structural and mechanical properties of trapezoidal glass fiber/epoxy resin beams manufactured with help of filament winding technology is presented. With help of Taguchi method was achieved similar wall thickness on the sides and corners of manufactured trapezoidal beams, while mechanical properties studied include values of stress, strain and modulus of elasticity.

II. MATERIALS AND EQUIPMENT

Trapezoidal beams used in this study are composed from long E-glass roving fibers (P185 1200tex from Owens Corning) impregnated in epoxy resin system Araldite LY564/Aradur 917/Accelator 960 from Huntsman, based on diglycidylether of bisphenol A with an anhydride hardener. Contained volume fraction of glass fiber in composite beams is 55%. Wet winding process was carried out on laboratory filament winding machine MAW FB 6/1 with six aches, roller type resin bath and mechanical creel manufactured from Mikrosam AD. The glass fibers from the creel are passed through the resin bath, causing resin impregnation. The temperature of the resin bath was held constant, 37^{o}C. The trapezoidal shape was fabricated by winding the roving fiberglass onto a rotating collapsible trapezoidal mandrel with pins. Mandrel length was 1200mm and 200mm high. Base at the bottom was 287mm width and base at the top was 172 mm width. It was coated with release agent (QZ13 from Huntsman) that allows easy removal of the part after processing. For smooth inside surface of produced beam and easy removal from the mandrel, firstly was used polypropylene film with 18g/m^2 surface weight and 50mm width, applied in few layers and after that was winded Viledon® T1702 with 100mm width from Freudenberg, with 50% overlap. Each trapezoidal beam was manufactured with 11 winding layers with already specified winding design and

10 bobbins. At the end, produced beam was cured with help of industrial heater at 100°C for 5 hours.

III. EXPERIMENTS AND RESULTS

Improvement of beam's characteristics was done in two parts. In the first part was improved the difference in wall and corners thickness (Δt) and in the second part was enhanced the bending strength of the beam.

A. Influence of parameters on the thickness of the corners and walls of trapezoidal beam (Taguchi Method)

Manufactured trapezoidal beams had different wall thicknesses on the sides and corners. To investigate the influence of winding tension and fibers orientation on wall thicknesses Taguchi method L4 was applied. Therefore, it was used winding tension in two levels, 120N (Level 1) and 180N (Level 2) and winding design in 3 levels, whereas winding speed was held constant, 30m/min. From 100% winded layers in composite beam in Level 1 46% belongs to winding angles 10°, 36% belongs to winding angles 90° and 18% belongs to winding angles 45°. In Level 2 were utilized 46% of winded layers with winding angles 20°, 18% from 90° and 36% from 45°. Beam winded with winding design in Level 3 had 18% from winding angles 10°, 36% from winding angles 90° and 46% from winding angles 45°. Table 1 shows three factors in three levels used in the experiment. If two levels were assigned to each of these factors and factorial experimental design was employed using each of these values, number of permutations would be 2^2 which reduce the number of experiments to four. The orthogonal array of L4 type was used and is represented in Table 2.

TABLE I. LEVELS OF PROCESS PARAMETERS

Symbol	Factor	Level		
		1	***2***	***3***
A	***Winding design***	46%10⁰/36% 90⁰/18% 45⁰	46% 20⁰/18% 90⁰/36% 45⁰	18% 10⁰ /36% 90⁰/46% 45⁰/
B	***Tension (N)***	120	180	180
C	***Winding speed (m/min)***	30	30	30

TABLE II. TAGUCHI L4 ORTHOGONAL ARRAY

N°	Factors		Δt
	A	***B***	***mm***
1	1	1	4.675
2	1	2	4.633
3	2	1	4.988
4	2	2	4.800
5	3	2	3.435

From given parameters in table 2 were produced four trapezoidal beams marked as N°1, N°2, N°3 and N°4. The wall thickness of the parts was measured on eight points shown on Fig. 1. Differences between the thickness (Δt) of the walls and corners of each beam are given in table 2. Thicknesses of sample walls were bigger than their corner thicknesses. For sample N°1, Δt was 4.675mm. Similar result 4.633mm for Δt, were received at sample N°2 where same design but bigger tension were used for winding. Difference in wall thickness of the trapezoidal part from 4.988mm was achieved at probe N°3. In comparison to this sample, improved results were reached by probe N°4 with Δt from 4.8mm. Here winding design was same as in probe N°3, but with bigger tension, 180N. Samples were repeated. The end results according to Taguchi method L4 show that winding design has the biggest influence on the thickness difference between trapezoid walls and corners in almost 6%. Also, winding tension is showing an impact on the difference in wall and corners thickness in 0.8%. Similar issues were reported by Schultz [8] using epoxy pre-impregnated tow T300 12k and Fortafil 50k carbon fiber for winding geometries with circular and square cross section. Used mandrel had a square cross section that was about 62mm per side. Each corner had radius of 12.7mm.

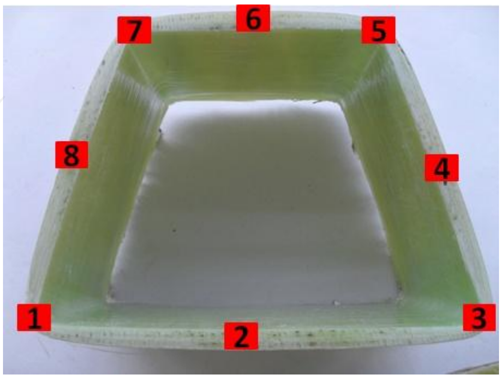
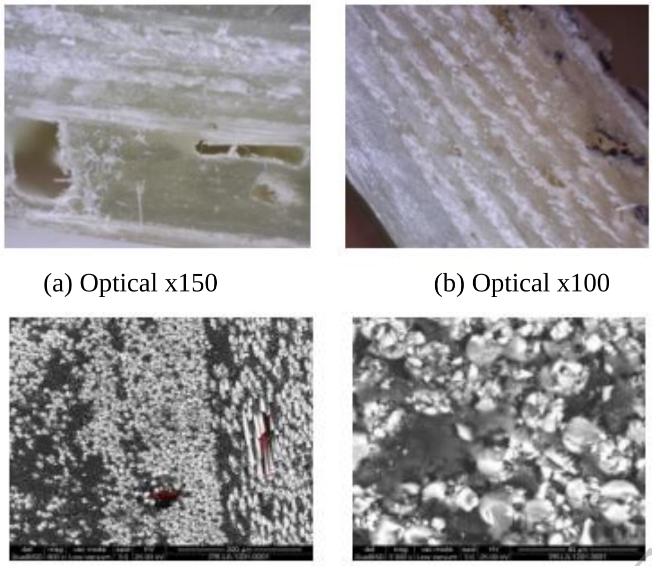


Fig. 1. Points of thickness measurement.

Similar tests but not with FW works Hubert [9]. He had investigated the effect of fiber orientation, bagging conditions, material and tool type on compaction behavior for concave and convex shapes made of carbon-epoxy composites: AS4/3501-6 and AS4/8552. However, for both materials, convex shapes with [90] laminates are thinner at the corner. Almost identical findings are presented by Yang et. al, [10] for study of FRP tubes with square transversal cross section. Wall thickness of special shape which utilizing both circular and square geometry in transversal cross section was measured. In both cases was mentioned difference between sides and corners thickness.

Very important characteristic for all produced parts is the presence of voids on the walls of each sample (Fig. 2 and Fig. 3). In comparison to them, on the corners there were no kinds of voids visible to the human eye. Void formation was observed in the work of Hubert [9]. More voids were presented at the corner compared to the flat section of the laminate, due to entrapped air during the lay-up, moisture in the material, volatiles released during the cure, difference between resin and resin viscosity.

To investigate the effect of bigger winding angles presented in more per cents in a sample, was manufactured trapezoidal beam with the third design mentioned in table 1 and table 2 (sample N^{o}5-Level 3). Exchange of 10^o winding angle with winding angle from 20^o in filament winding technique is showing worse results. It is supposed that more voids are created when samples are produced with this angle. This is confirmed by the mechanical testing. Samples with 20^o winding angle (N^{o}4) presents smaller bending properties even from samples with 45^o (sample N^{o}5), which theoretically was not expected.



(a) Optical x150 (b) Optical x100

(c) SEM x400 (d) SEM x3000

Fig. 2. Optical (a, b) and SEM (c, d) results on voids presence in the sample.

Reason for this is the percents of voids, which are showing an influence on the mechanical characteristics of the composites [11-13].

Smaller Δt in the results are showing samples N^{o}2 and N^{o}5, where in more percents were used 45^o winding angles. Due to the good interaction between the mandrel and winding angle, fewer voids were formed. Winding process had pressed the impregnated resin to the surface on the walls and corners.

B. Mechanical Testing

To see if the fibers orientation and winding tension are showing an influence on the mechanical properties of the beams, three point bending tests were carried out. The bigger basis of the trapezoidal composite part was cut into 6 or 7 rectangular forms according to ISO 14125 with span-to-width ratio of 10 (Fig. 4). Micrometer was used to measure dimensions and thickness of the specimens. Values of the measurements are reported in table 3. The tests were carried out at room temperature on computer controlled universal testing machine from Shimadzu with maximal load 250N at a speed of 20 mm/min to minimize any dynamic effects. Load and displacement were recorded by an automatic data acquisition system for sample N^{o}1 and N^{o}3. To see the influence of winding angle 45^o on the module of bending and flexural strength band samples from sample N^{o}5 were cut. A total of twenty bend specimens were involved in this testing, thus allowing six to seven reproducibility tests of each sample. Specimens where mounted on a two cylindrical supports with radii of 5mm. Central loading with radii of 5mm was located above the crack (Fig.5). Load-displacement curves were plotted for every sample and afterwards values for stress, strain and module of elasticity were calculated. The average results are shown in Fig. 6. The flexural stress, σ_f in the outer surface of the test specimens occurred at the midpoint. These stresses were determined from the relationship:

(a) sides of samples (b) corners of samples

Fig. 1. Optical pictures from the sides and corners of the samples.

$$\sigma_f = \frac{3FL}{2bh^2} \quad (1)$$

Where, σ_f is the flexural stress in MPa, F is the load in N, L is the support span in mm, b is the width of beam tested in mm, and h is the thickness of beam tested in mm.

Flexural modulus of elasticity is:

$$E_f = \frac{L^3}{4bh^3}\left(\frac{\Delta F}{\Delta s}\right) \quad (2)$$

Where, E_f is the flexural modulus of elasticity in MPa, Δs is the difference between beam mid-point deflections in mm, ΔF is the load difference in beam mid-point deflections in N.

Flexural strain, ε_f of the composite specimens was determinate using the fallowing equation:

$$\varepsilon_f = \frac{6sh}{L^2} \qquad (3)$$

In (3) ε_f is the strain in the outer surface in mm/mm, s is the maximum deflection of the center of the beam in mm, h is the thickness of beam tested in mm and L is support span length in mm. Received average results from three-point bending tests are shown in table 4.

TABLE III. DIMENSIONS OF THREE-POINT BENDING SPECIMENS

Sample Number	b (mm)	h (mm)	lo (mm)	L (mm)
1-1	30.8	11.37	400	300
1-2	30.62	12.1	400	300
1-3	30.53	12.35	400	300
1-4	30.68	12.32	400	300
1-5	30.56	12.78	400	300
1-6	30.54	12.65	400	300
1-7	30.65	10.67	400	300
3-1	30.82	12.17	400	300
3-2	30.74	13.41	400	300
3-3	30.7	12.77	400	300
3-4	30.66	13.62	400	300
3-5	30.54	13.38	400	300
3-6	30.61	12.08	400	300
5-1	30.6	10.91	400	300
5-2	30.66	11.6	400	300
5-3	30.69	11.23	400	300
5-4	30.52	11.76	400	300
5-5	30.72	11.81	400	300
5-6	30.63	11.93	400	300
5-7	30.36	13.38	400	300

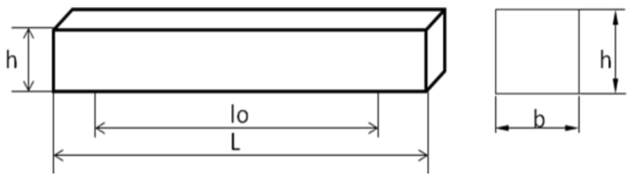


Fig. 2. Geometry of three-point bending specimens.

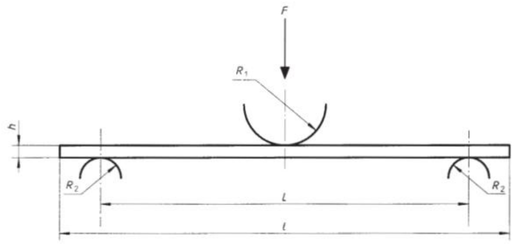
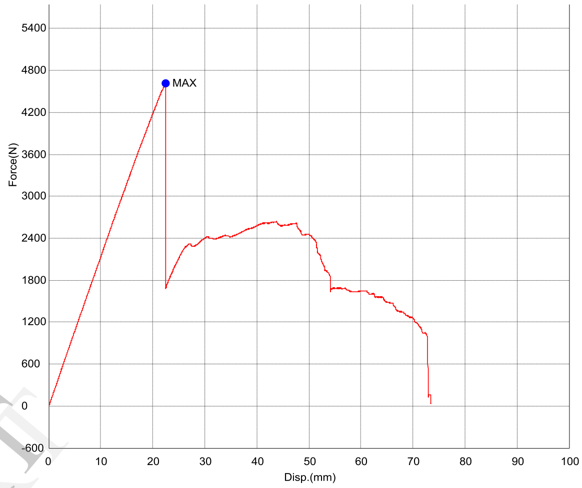
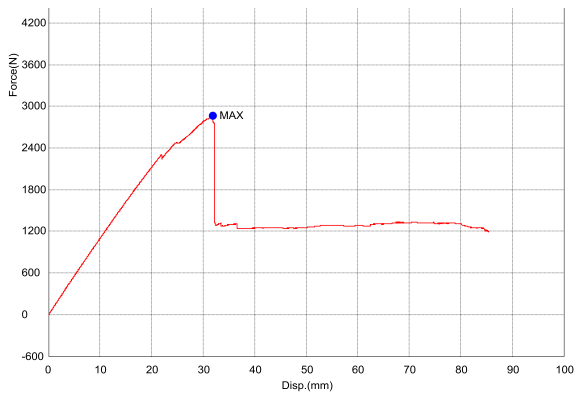


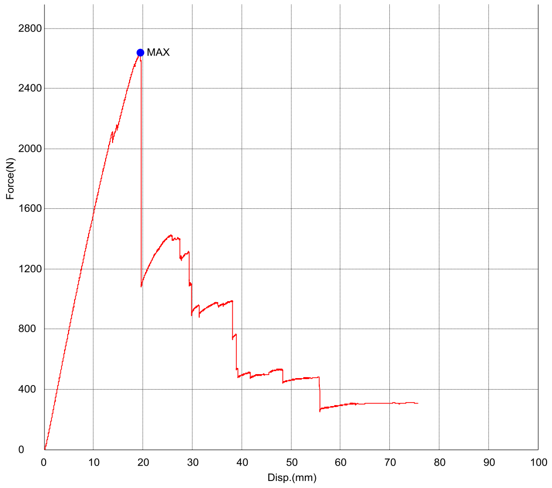
Fig. 3 Three-point loading arrangement according to ISO 14125.



(a) Average load-displacement curve for sample N^o1.



(b) Average load-displacement curve for sample N^o3.



(c) Average load-displacement curve for sample N°5.

Fig. 4. Average force-displacement curves for conducted test-samples.

The results above shown that with change of angles and tension can be achieved very good results in Δt by sample N°5. But bending results here are much smaller in comparison to samples N°1 and N°3 due to the smaller Δt. It can be seen that sample N°1 have shown the best mechanical properties.

Bumpus [14] had been investigating the mechanical properties of fiber reinforced composite structures manufactured with resin transfer molding technique using DOE. It has been reported values between 144MPa and 274MPa for maximal flexural stress. Further, flexural strain at maximal stress has been estimated between 1.65 and 2.24% and module of elasticity between 7.28 and 20.8GPa. The selection of our design (sample N°1) shows better results.

TABLE IV. AVERAGE RESULTS FROM THREE-POINT BENINDG TESTS

N°	**σ_f average**	**τ average**	**E_f average**
	MPa	***MPa***	***GPa***
1	495.26	9.96	24.574
3	237.97	5.11	14.113
5	333.11	6.39	16.554

Composites made of glass fiber/epoxy resin and carbon fiber/epoxy resin made by vacuum bagging technique were investigated in the work of Rathnakar et. al, [15] using three-point flexural test for evaluation of strength and stiffness. There have been presented load vs. displacement graphs, which had shown linear behavior until failure, similar with the graphs in Fig. 6. Results with improve performance of a laminate gives Brooks [16]. In [16] three-point bending tests on Hexcel glass fiber reinforced polymer (GFRP) samples of rectangular cross section with 16:1 support span-to-depth ratio have been done. Maximal stress reported had value between 475.67MPa and 528.66MPa. GFRP laminates exhibit progressive failure consisting of fiber failure, debonding and delamination. In this paper isn't discussed or calculated the content of voids. However, voids with bigger dimensions can be observed on some places (optical and SEM image) who will cause reduction of laminates mechanical characteristics.

Mathematical model of the influence of the parameters on the content of voids in trapezoidal beams will be present in future.

IV. CONCLUSION

The experimental results confirmed that the best winding design for manufacturing trapezoidal beams by FW technology have shown sample N°1 with large flexure stress. These results have confirmed the theoretical calculations. If bigger winding angles are used, less bending strain will be initiated and vice versa. Using these angles smaller Δt will be reached with less voids. The purpose of this paper is to choose proper combination of winding angles for production of laminate that will have high flexure stress. Since the fact that main cause for occurrence of voids in the laminate of the final product is not a novel issue, the idea of this paper is to initiate the use of appropriate design for production of trapezoidal beam for bridges with FW technology. Validity of this study lies in high efficiency of fabrication of trapezoid by FW technology, better quality of the composite trapezoid final products and competitive advantage for the producers and beneficiaries of these products.

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