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Theoretical and Experimental Bending Properties of Composite Pipes

M. Stefanovska, S. Risteska, B. Samakoski, G. Maneski, B. Kostadinoska

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***Abstract*—**Aim of this work is to determine the theoretical and experimental properties of filament wound glass fiber/epoxy resin composite pipes with different winding design subjected under bending. For determination of bending strength of composite samples three point bending tests were conducted. Good correlation between theoretical and experimental results has been obtained, where sample N^{o}4 has shown the highest value of bending strength. All samples have demonstrated matrix cracking and fiber failure followed by layers delamination during testing. Also, it was found that smaller winding angles lead to an increase in bending stress. From presented results good merger between glass fibers and epoxy resin was confirmed by SEM analysis.

***Keywords*—**Bending properties, composite pipe, winding design.

I. Introduction

THE greatest benefit of polymeric composite pipes to the chemical, petroleum and processing industries is the reduction of capital costs of projects and operating expenses. Polymer composites offer many cost advantages over metals, due to a considerably higher strength-to-weight ratio. For instance, an increase in the ease of handling decreases the amount of manpower and size of equipment needed for construction and installation. The cost saving in transportation must also be emphasized. Thus, the limiting factor in transporting pipe shifts from weight for steel to volume for composites, thereby decreasing the transportation cost [1].

The important mechanical properties of composite pipe are strength, stiffness, and service life, which make it imperative to determine leakage integrity and reliability of a piping system. Depending on the purpose, composite pipes, especially in constructions of complex pipelines can be subjected to bending [2]-[4]. In that case exceeding of allowed stresses can cause failures which are seen in cracked fibers, crack of matrix and delimitation. Different models of failure are developed in dependence from pipe structure. In constructions of complex pipelines, except classical loading because of inner pressure, pipes can be subjected to bending.

MSc. Maja Stefanovska is with Institute of Advanced Composites and Robotics, Prilep, 7500 Macedonia (phone: +389-48-400-100; fax: +389-48-411-886; e-mail: majas@iacr.edu.mk).
Ass. Prof. PhD. Svetlana Risteska is with Institute of Advanced Composites and Robotics, Prilep, 7500 Macedonia (e-mail: svetlanar@iacr.edu.mk).
Prof. PhD. Blagoja Samakoski was with Institute of Advanced Composites and Robotics, Prilep, 7500 Macedonia (e-mail: blagojas@iacr.edu.mk).
MSc. Student Gari Maneski and MSc. Student Biljana Kostadinoska are with Institute of Advanced Composites and Robotics, Prilep, 7500 Macedonia.

In the case of exceeding of allowed tensile strength on outer surfaces it causes damages that lead to cracking of pipes. Therefore, it is important to establish reliable criteria of behavior for composite pipes exposed to bending [5]-[7].

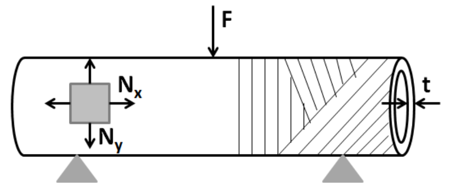
II. Experimental

A. Theoretical Part

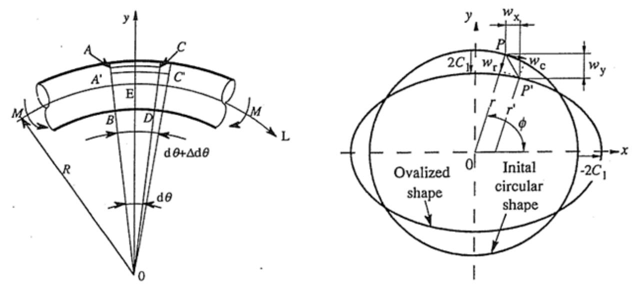
Composite samples with different number of layers and winding angles were used in the theoretical calculations to investigate the influence of smaller (10^o, 30^o, and 60^o) and bigger (90^o) winding angels on bending properties of composite pipes (Table I).

TABLE I
Winding Design and Dimensions of Composite Pipes

N^o	Winding design	Pipe dimensions (mm)	Resin mass fraction (%)
1	$[90_2/60_5]$	ø100x1000x6	22.5
2	$[90_2/60_{11}]$	ø100x1000x10	21.0
3	$[90_2/10_3/90_2/30_4/60_2]$	ø100x1000x10	24.0
4	$[90_2/10_2/90/10_2/90/\ 30_4/60]$	ø100x1000x10	23.5



(a)



(b)

Fig. 1 Bending of pipe (a) Three point bending test of composite pipe, (b) Illustration of pipe under bending [8]

Theoretical calculations were conducted with help of Composite Oracle software which gives the micromechanical and macromechanical analysis for each lamina followed by macromechanics of laminate according to different failure criteria [9]. These analyses can be performed on cylindrical,

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and plate shapes of structures. One can find fiber/creel, unidirectional, off-axis tensile and off-axis compression properties of composite structure. Stiffness, coupling and bending matrices, modulus of elasticity, shear modulus, thermal expansion and Poison's ratio can be determined together with physical properties of composite sample, such as internal and external diameter of composite pipe, wall thickness, cross section area, moment of inertia, polar moment of inertia, static area and weight. Calculated results are presented in tabular and graphical forms.

B. Experimental Part

Composite samples with dimensions and winding design given in Table I were manufactured with 10 bobbins of E-glass fiber roving 185P with 1200 tex from Owens Corning, impregnated in epoxy resin system Araldite LY564/ Aradur 917/ Accelerator 960-1 from Huntsman. Production of samples was conducted on steel mandrel with pins on both sides with help of laboratory filament winding machine MAW FB 6/1 manufactured by Mikrosam A.D. Before winding, the mandrel was previously prepared with mold release agent QZ 13 from Huntsman for easier release of the sample after curing. The used machine had six axes of freedom, mechanical creel and roller type resin bath with knife edge that adjusts the amount of resin adhered to the roller. Calculated mass ratio between fiber and resin according to standard ASTM D3171 is given in Table I. Winding Expert^{TM} software was used to create the filament winding programs for each sample. After winding, samples were cured with industrial heater on 100^{o}C for 6 hours and without any surface preparation were tested on bending. Samples before testing are shown in Fig. 2.

Fig. 2 Prepared composite samples before testing

Shape, dimensions and test procedure of prepared samples were defined according to standard ASTM D790 [2]. Before testing, thickness and width of composite samples were measured with micrometer with accuracy of ±1 %.

The tests were conducted on servo-hydraulic testing machine with 400 kN maximal power of load, where hydraulic jaws and two cylindrical supports set on 800 mm distance were used in order to assure accurate values of measuring. During testing central loading rate with 5 mm/min was applied.

III. Results and Discussion

Results received from theoretical calculations of bending strength of composite pipes are shown in Table II. It can be noticed that double increase of radial layer's in the theoretical calculations steady increase the bending strength of composite pipes. This can be seen between samples N^{o}1 and N^{o}2, even though the difference between wall thicknesses is significant. Implementation of smaller angles in the calculations had led to upward trend in bending strength of sample N^{o}3 reaching the value of 171 MPa. However, in sample N^{o}4 increase of number of layers with winding angle 10^o and phase out one layer wound with 60^o, leaded to significant growth in bending strength by 9.5 % in comparison to sample N^{o}3, even though both samples have same wall thicknesses.

TABLE II
Theoretical Results from Bending Tests

N^o	L (mm)	t (mm)	D_{ins} (mm)	D_{out} (mm)	I_x (mm^4)	σ_f (MPa)
1	800	6.0	100	111.9	2792457	80
2	800	10.4	100	120.9	5566718	83
3	800	10.5	100	121.1	5658881	171
4	800	10.5	100	121.0	5596996	189

To compare theoretical with experimental results three point bending tests were conducted, where bending strength of composite samples was determined (Fig. 3). Maximum axial fiber stress occurred on a line under the loading nose or more specific on the middle of bending where crack of sample was observed.

Different technique of bending loading has been reported by [10] and [11]. In [10] numerically and experimentally bending and buckling behavior of thin-walled composite cylinders has been studied, where pure bending test rig was used to apply an end-rotation to each end of composite samples. Shadmeri [11] applied large bending moments at both ends of thermoplastic tail boom of a helicopter with help of pure bending test rig of large loading capacity. Further, AFP-made thermoplastic composite tube with pure bending test has been tested in [12]. It was found that this technique is superior alternative test compared to the conventional three-point and four-point bending tests in testing composite tubes.

During testing for each composite sample force-deflection plots were received (Fig. 4). Each plot can be divided in three parts. In first part, sharp increase of applied force with negligible deflection was seen or first ply failure (FPF) was detected. In second part, slight rise of force and notable deflection was observed, which means that composite sample is damaged but still can endurance the applied force. In final part of the plot, linear fall of applied force and displacement

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were detected, meaning that composite sample failed and can't be used further.

(a)

(b)

(c)

(d)

Fig. 3 Three point bending of composite samples (a) Sample N°1, (b) Sample N°2, (c) Sample N°3, (d) Sample N°4

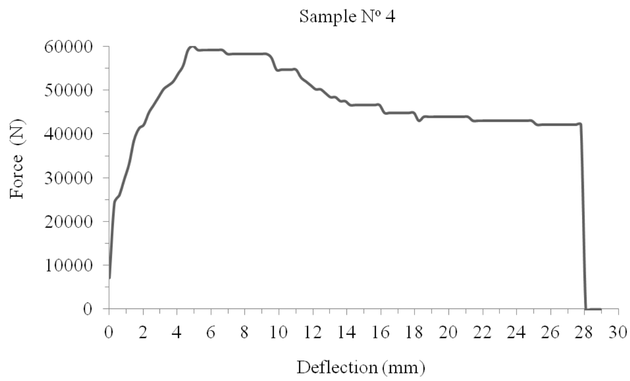

Fig. 4 Force-deflection diagram of sample N°4

Bending strength σ_f equal to the stress in outer layer for each pipe was determined by using (1), whereas M (N·m) is calculated bending moment, y (mm) is vertical distance away from the neutral axis and I_x (mm^4) is the moment of inertia.

$$\sigma_f = \frac{My}{I_x} \tag{1}$$

$$I_x = \frac{\left(D_{out}{}^4 - D_{ins}{}^4\right)\pi}{64} \tag{2}$$

TABLE III
EXPERIMENTAL RESULTS FROM BENDING TESTS

N°	L mm	t mm	D_{ins} mm	D_{out} mm	I_x mm^4	σ_f MPa
1	800	6	100	112.0	2813829.4	55.7
2	800	10.45	100	120.9	5576008.8	78.1
3	800	10.55	100	121.1	5645542.6	126.6
4	800	10.51	100	121.0	5617687.7	129.3

Results from experimental calculations of bending strength of composite pipes shown in Table III differ with theoretical calculations up to 30%. The smallest deviation in the results has been marked by sample N°2, where theoretical and experimental results differ by 6% (Fig. 5). However, composite sample N°4 has displayed the highest bending strength, followed by sample N°3. It is well known that during bending tests the outer layer of manufactured composite samples is always exposed to tension and inner layer to pressure, which cause delamination of composite structure.

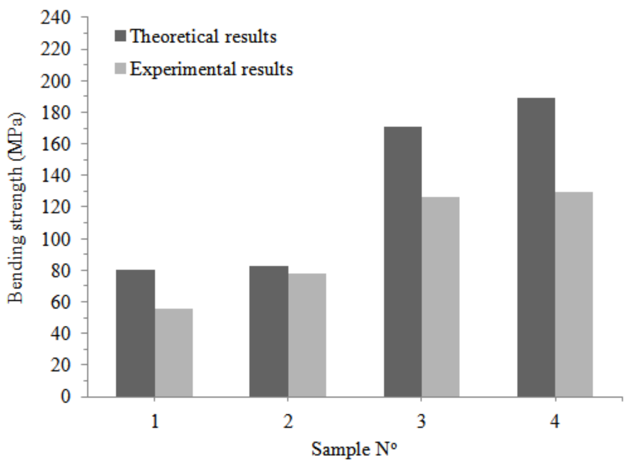

Fig. 5 Theoretical and experimental bending strength of composite samples

Putić et al. [5] have investigated bending strength, bending module of elasticity and deflection of glass fiber/polyesters composite pipes with different inside diameters. With help of three point bending tests was concluded that enlargement of bending strength causes an increase of pipe's hardness. Also, according to [5] similar or even same mechanisms of break appear in both samples, which are not dependent of dimensions of cross section or wall thickness of samples.

Krstić et al. [13] have conducted an investigation in micromechanical failure analysis of glass fabric/epoxy resin composites under bending. From conducted analysis it has

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been found that specific weave of glass fabric and different load placement had determined different time failure of glass fibers. Increased loading lead to shear, which is reflected through the "slip" of fiber layers cross sample's thickness and cause disturbances in stresses and strains in the layers.

Test fixture which can be used to evaluate the flexural properties of thin-wall composite tubes has been developed in [14]. According to [14] use of rubber load applicators makes it possible to transfer sufficient loads to induce failures from the applied bending moment without causing localized damage.

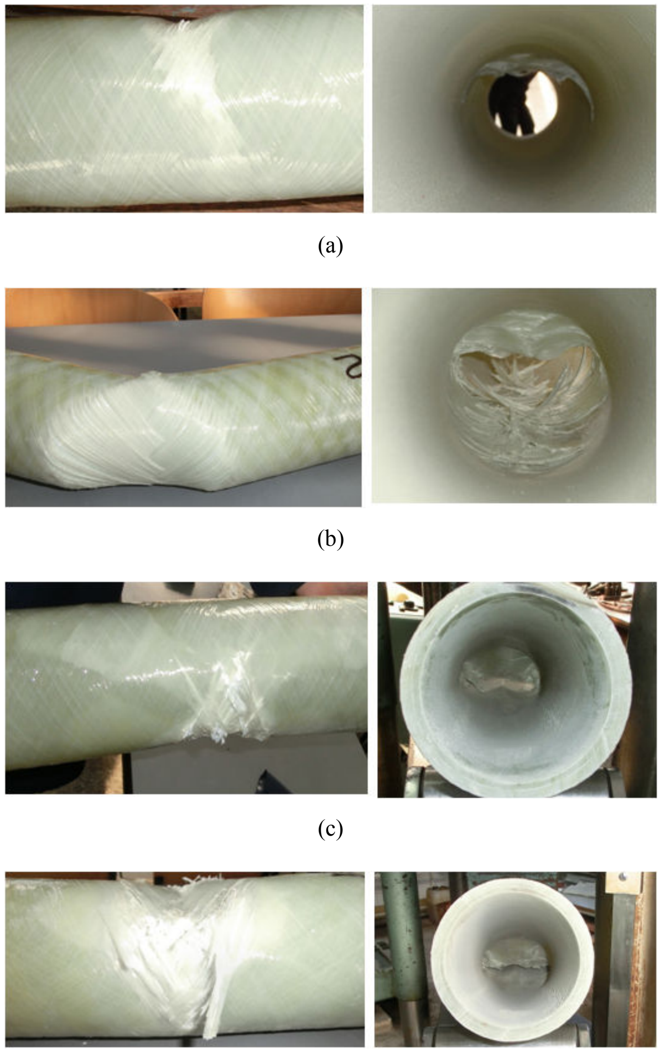
Akkus et al. [8] have reported about improvement of bending strength of thin circular carbon fiber/epoxy resin pipes with reinforcing nodes. Composite samples winded with different winding angles were tested under four-point bending test. It has been concluded that, final strength of composite pipes can be increased by not only introducing reinforcing nodes but also decreasing the winding angle. According to [8], [15] the lower the winding angle, the stronger the pipe becomes. Also, winding angle determines resistance to pressure and resistance to diameter expansion of composite pressure vessels manufactured with filament winding technology [7].

Numerical method for prediction of mechanical properties of glass fiber/epoxy composites panels with different specific mass and different structure has been studied in [16]. The research shows that composite specimens made with smaller angles demonstrated smaller bending strength and modulus of elasticity in comparison to the samples with design $0/90^{o}$. According to [16] relatively good agreement can be obtained from analytically and experimentally results, even though higher values were obtained experimentally. But, considering disagreement of 15-30 % in the results, represented model can be useful where there is a need to get approximate bending properties, and the experiments can't be performed because of the price or the lack of samples.

Elastic constants and flexural properties of laminated composite material with different fiber direction have been reported by [17].

Failure surfaces obtained during bending tests of all samples are given in Fig. 6. In all samples, crack was initiated on pipe's outer layer subjected to loading. Occurrence of the failure was at the moment of reaching critical state of stress in the material which causes the occurrence of critical value of crack and its unstable growth. The place of critical crack is related to fiber-matrix debonding after which the fibers cracked. It is obvious that on the spot where the first break appeared (outer layer) exist more broken fibers which were previously debonded and pulled out from the matrix. This led to disorder in fracture zone and stresses which cannot be coincide on every sample, and therefore different maximum load force at failure and different fiber failure in time occurs.

During tests, sample $N^{o}1$ and sample $N^{o}2$ have shown same deflection. Failure region of sample $N^{o}1$ was characterized with fiber/matrix cracks under the loading nose (Fig. 6 (a)).



(a) (b) (c) (d)

Fig. 6 Crack damages of composite samples (a) Sample $N^{o}1$, (b) Sample $N^{o}2$, (c) Sample $N^{o}3$, (d) Sample $N^{o}4$

Contrary, sample $N^{o}2$ have shown permanent bending characteristic with broken fibers and matrix cracks in the inner layers due to applied load, whereas fibers in the outer layer on the opposite site of loading nose were still caring the load, even though shear delamination between layers was observed (Fig. 6 (b)).

Further, sample $N^{o}3$ (Fig. 6 (c)) and sample $N^{o}4$ (Fig. 6 (d)) have demonstrated bending effect during loading, but straight after load release both samples have received their primary shape, manifesting their deflection properties. These samples have suffered debonding followed by interlaminar failure and fiber/matrix cracking on the place where load was applied.

IV. SEM ANALYSIS

To see the quality of composite samples after performed bending tests, scanning electron microscopy (SEM) analysis were performed. Received results with different magnification are presented in Fig. 7.

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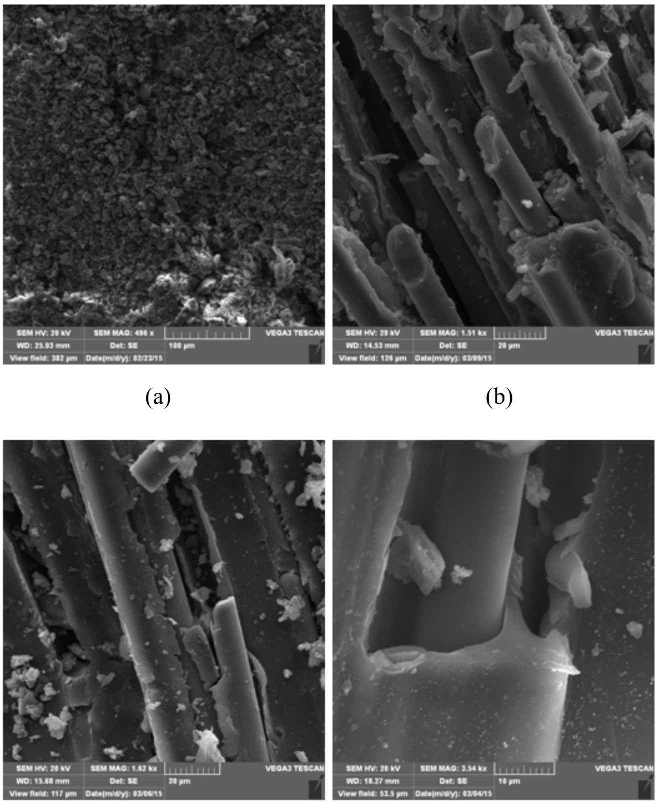
From obtained images delamination between layers and matrix craking has been detected as bending consequence. Also, fiber-matrix debonding has been seen, due to applied stress. Before failure fibers have undergone some elastic deformations, which was demonstrated with crack propagation at an angle. This type of failure has been different from fiber failure reported in [13].



(a) (b) (c) (d)

Fig. 7 SEM analysis of composite samples (a) Delamination between layers, (b) Crack propagation at an angle of glass fiber, (c) Fiber-matrix debonding, (d) Matrix failure

V. CONCLUSION

Bending properties of glass fiber/epoxy resin composite pipes have been determined with theoretical and experimental methods, where good compatibility in bending strength was achieved.

From received results can be concluded that highest bending strength have demonstrated sample N^{o}4 followed by sample N^{o}3, which deflection properties have been pronounced during the tests. These results confirmed theoretical predictions, that lower winding angles (10^o and 30^o) increase bending stress and reverse.

During the tests fiber-matrix failure under the loading nose has been the dominant failure mechanisam followed by delamination in all samples. From SEM images was seen that fibers have undergone some elastic deformations before failure, which suggest that good merge between fiber and matrix has been obtained.

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