INVESTIGATION OF TORSIONAL BEHAVIORS OF CARBON/EPOXY SHAFTS AT A DIFFERENT ORIENTATION ANGLES BY EXPERIMENTAL AND FINITE ELEMENT METHOD WHICH MANUFACTURED WITH FILAMENT WINDING METHOD USING COMPOSITE MATERIALS

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Abstract— In this study, the torsional stresses of hollow circular shafts manufactured from composite materials and with different orientation angles were researched. For hollow circular composite shafts; carbon fiber were used as the fiber materials, while epoxy resin was used as the matrix material. 80mm, 200mm and 250mm long composite shafts of different inner diameters were used. The hollow circular composite shafts were manufactured at θ=45°, 60°, 75°, 80°, 88° orientation angles. Filament winding method was preferred when manufacturing the composite shafts. The mechanical torsion tests of hollow circular composite shafts were separately repeated for each sample. The obtained results were evaluated among themselves in terms of the length of the shafts, the diameter of the shafts and the orientation angle, after which they were transferred to the graphics. The obtained results of experimental and numerical analyses were presented in graphs and the necessary considerations were made. The experimental and numerical analysis results were found to be close to each other.

Key words: *Composite shafts*, *Filament winding*, *Orientation angle*, *Torsion test*

1. Introduction

Apart from the fact that shafts, which are used in every field of technology, are among the most important power transfer elements, they are exposed to tensile, compression, bending and torsional stresses due to their operational characteristics. Since shafts transmit power from one machine element to the other, they become exposed to torsional stress, which is the most hazardous one of all. Since shafts are exposed to bending due to the elements found on the top of them as well as being exposed to torsion due to rotating, the calculations are generally made according to combined stresses, and accordingly, their constructions and designs are performed. However, hollow shafts are usually preferred in the cases in which lightness (weightlessness) is required, which, then, causes weakness in strength/endurance by almost 6%; yet, 25% of lightness is achieved. For this reason, hollow shafts are quite frequently used, particularly in automotive industry and in aviation and space industries. The following studies were found when a topic-related literature review was made. Bert and Kim carried out an analytical solution to compute torsional buckling of composite drive shafts. They calculated the torsional buckling load of composite drive shafts with various lay-ups with good accuracy by considering the effect of off-axis stiffness and flexural moment. Their theory can predict the torsional buckling of composite drive shafts under pure torsion and combined torsion ad bending [1]. Chen and Peng performed numerical simulation using a finite element method to study the stability of composite shafts under combined loading conditions. The predicted the critical axial load of a thin-walled composite drive shaft under rotation [2]. Kim et al. manufactured hybrid shaft which had stainless steel surface and composite core. Carbon/epoxy layers were laid in to the steel tubing. They found that hybrid shaft had less tilting angle and higher natural frequency compared to that of non-hybrid steel shaft [3]. Kim and Lee studied the performance of hexagonal, elliptical lap and adhesively bonded circular joints. Adherents were carbon fiber epoxy and steel shafts. Among three joints investigated, hexagonal joint was the best fo torque transmission. The double lap joint performed better than single lap joint. Hexagonal single lap joint and circular double lap joint performed almost the same [4]. Kim et al. conducted both experimental and numerical study to predict behaviour of the adhesive-bonded composite shaft. Carbon and glass composite tubes are joined together using adhasive bonding. Various length of bonding has been investigated. It was reported that the bonding length of 16 mm and larger was enough for 3500 Nm toque capacity. The yoke thickness, diameter of shaft, and adhesive thickness were 4,8 mm, 90 mm and 0,2 mm, respectively [5]. Hahn and Erikson, used pin and glue together to transfer load between thin-walled torsion test specimen. Studies regarding torsional behaviour of composite tubes are very limited. They studies usually report the result of few isolated torsional test. However meaningful conclusions can only be drawn by conducting adequate number of tests. Hence easy gripping methods needed for the torsion tests of composite tubes [6]. Soden et al. performed a number of experiments to determine the failure and strength of E-glass/epoxy tubes with various winding angles of the fibres. They obtain theoretical failure envelopes by using lamination theory and netting analysis, and predicted the initial and ultimate failure loads satisfactorily [7]. Mistry et al. investigated the effect of the winding angle on the strength of GRP pipes using finite element analysis, and predicted first ply failure loads and an optimal angle close to 80°, instead of 55°, as reported by netting analysis elsewhere for internal pressure loading [8,9]. Caroll et al. presented the rate-dependent behaviour of ±55 filament wound glass/epoxy tubes under biaxial loading [10]. Swanson et al. studied the failure of hand layed uo quasi-isotropic carbon/epoxy laminates subjected to biaxial stress. They suggested a maximum fiber strain failure criterion, a progressive failure model that incorporates ply stiffness changes and a nonlinear model for the matrix shear response. Failure tests, involving torsional shear combined with axial tension or compression of unidirectional hoop wound cylinders, were also carried out to examine matrix failure under multiaxial stress coniditions [11, 12]. Fujii et al. investigated the strength and nonlinear stress/strain response of plain woven glass fiber laminates, fabricated using the wet winding technique, under biaxial loading, and also estimated the strength using the Tsai-Wu and Tsai-Hill criterion and 2nd Piola-Kirchhoff stress [13, 14]. Ferry et al. studied the fatigue damage of both bending and torsion loading on unidirectional glass-fibre/epoxy composite bars, observing that damage processes occurred throuhgh the fibre failure, delamination and matrix cracking. These authors concluded that damaging occurred by several complex processes, depending on both the ratio between bending and torsion stresses and the ratio between minimum and maximum stresses [15].

2. Materials

Within the scope of this study, carbon (800 gr/m^2) was used as the fiber material, whereas epoxy was used as the matrix material. The fiber volume ratio (V_f) of the carbon composite material was determined as 67%. Dimensionally; composite shafts of 80mm, 200mm and 250mm in size, with D_o=17mm-outer diameter and D_i=12mm and 13mm-inner diameters were used.

3. Manufacturing method

In this study, the method referred to as the filament winding method in the literature, which is the most commonly-used one, was applied as the manufacturing method (Fig. 1). The carbon fibers were wound over the rollers in the form of three layers at the orientation angles, θ=45°, 60°, 75°, 80°, and 88°. The manufactured hollow circular composite shafts were designed in given lengths according to ASTM standards and were made available for torsion tests, again, in accordance with ASTM standards (Fig. 2).

Figure 1. Filament winding machine

Figure 2. A test specimens of carbon/epoxy

4. Experimental Studies

4.1. Torsion Tests

The hollow circular composite shafts manufactured from 80mm, 200mm and 250mm-long carbon/epoxy material with D_i=12mm, D_i=13mm inner diameters and D_o=17mm outer diameter, which consisted of three layers, were subjected to torsion tests separately. The torsion tests were performed at room temperature through the location-type Shimadzu AG-X universal device with 250 kN load cell.

a b

Figure 3. The samples of 250 mm long carbon / epoxy; a) before torsion, b) after torsion

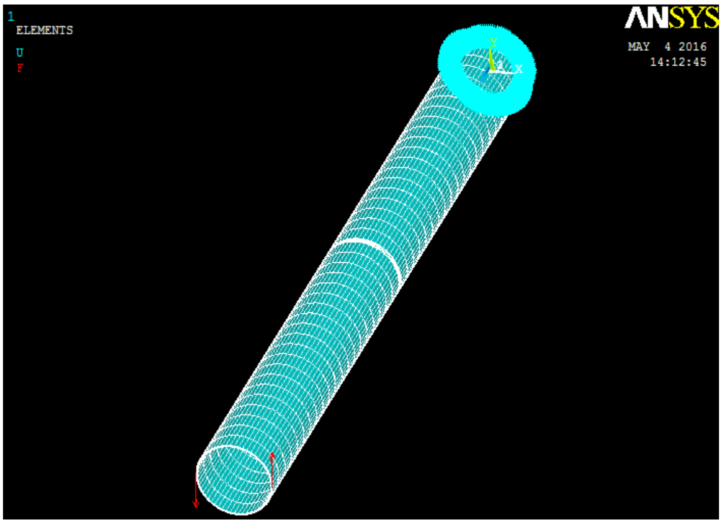


Figure 4. Boundary condition applied to the shafts of carbon / epoxy

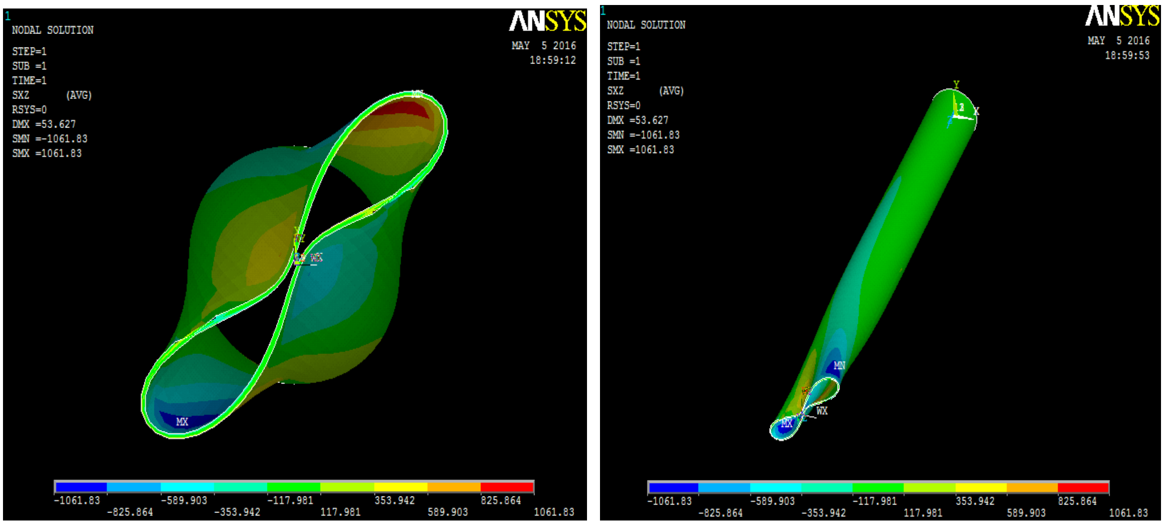
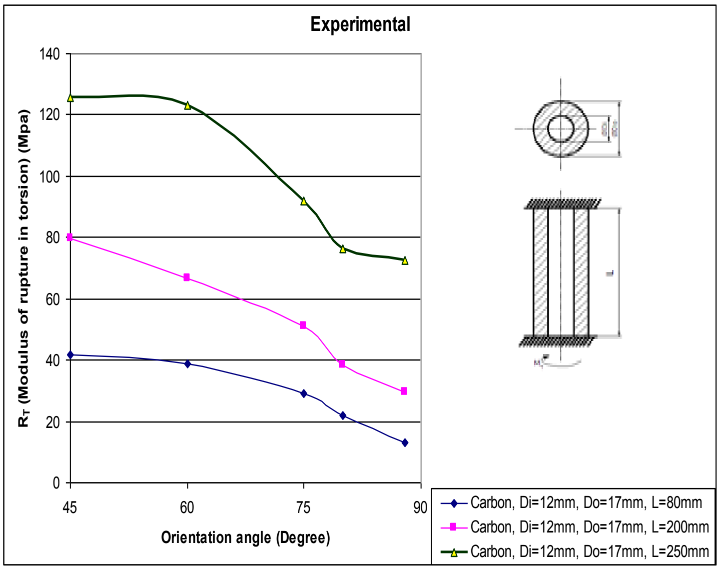


Figure 5. The solution of L = 250mm diameter carbon / epoxy sample under torsional stress in ANSYS

5. Results and discussions

5.1. Effects of orientation angles on modulus of rupture in torsion (R_T)



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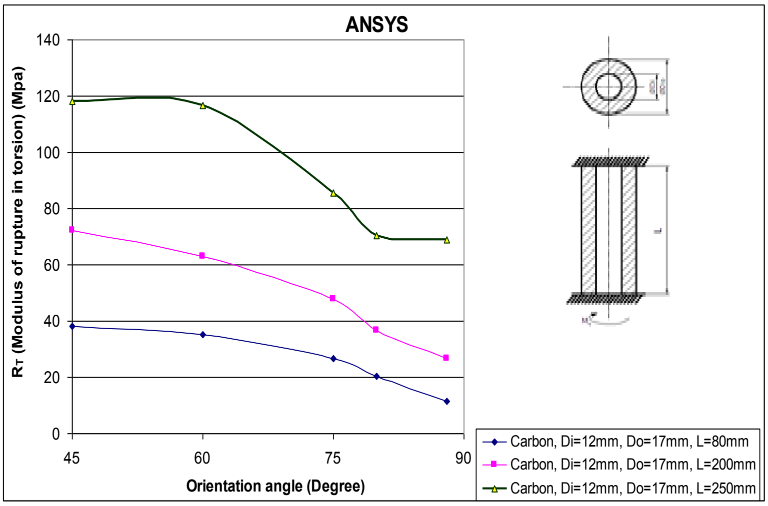


b

Figure 6. Torsion stress- orientation angle and length curve of carbon for torsion stress; **a)** Experimental **b)** Ansys

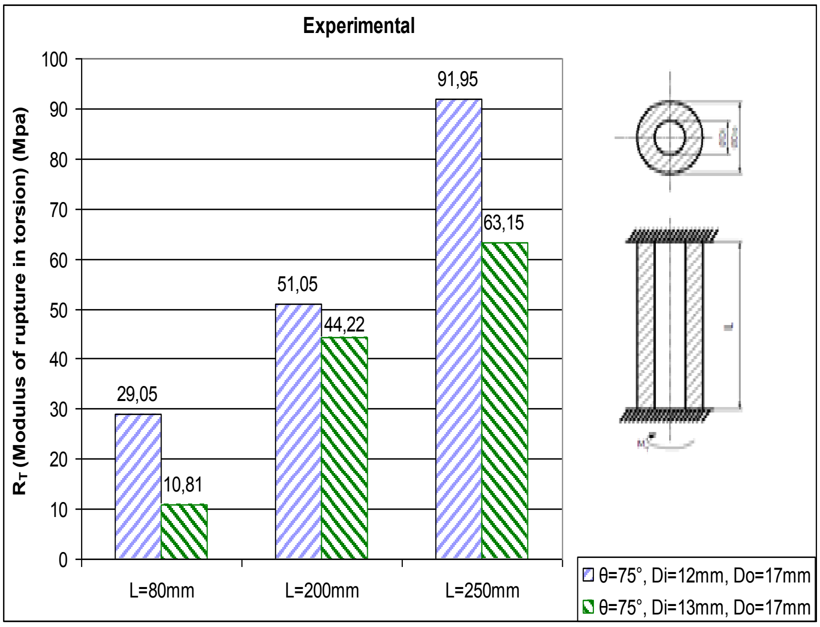
The values of modulus of rupture in torsion (R_T) of hollow circular carbon/epoxy composite shafts were analyzed both experimental and ansys according to the orientation angle. Accordingly;

As will be seen in the graphics; it was observed that as the orientation angle of the fiber increased, the values of the modulus of rupture in torsion of each reinforcement materials decreased (Fig. 6).

It was seen that the modulus of rupture in torsion had reached the maximum value when it was at 45° orientation angle (Fig. 6). Separately, since the number of translocations among the fibers will increase once the orientation angle is extended, the values of modulus of rupture in torsion diminishes, as well.

As will be seen in the graphics; the experimental and numerical analysis results were found to be close to each other.

5.2. Effects of wall-thickness on modulus of rupture in torsion (R_T)



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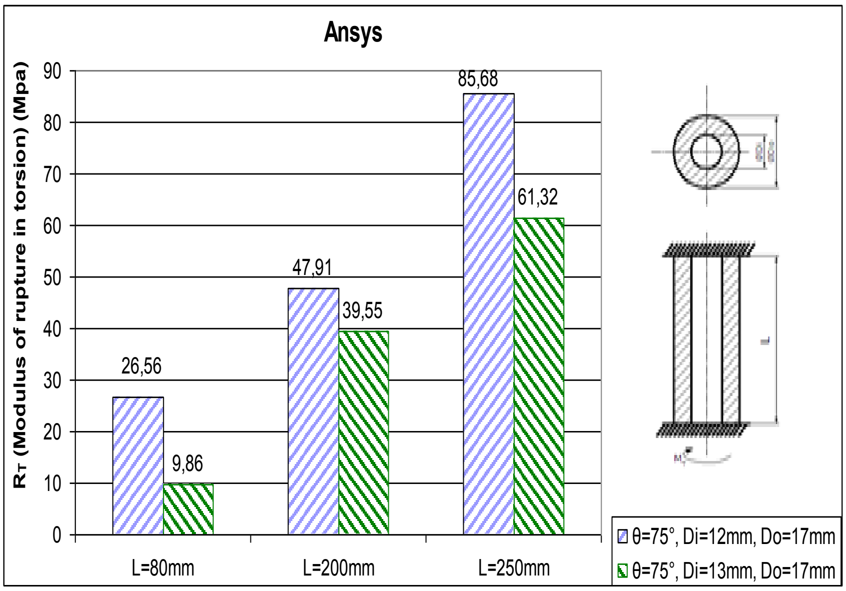

b

Figure 7. Effects of wall-thickness for carbon on torsion stress, **a)** Experimental **b)** Ansys

The values of modulus of rupture in torsion (R_T) of hollow circular carbon/epoxy composite shafts were analyzed both experimental and ansys according to the wall-thickness. Accordingly;

It was seen that the values of modulus of rupture in torsion of the circular hollow carbon /epoxy composite shafts with the inner diameter D_i=12mm, and at θ=75° orientation angle, which were in different lengths, were higher than the values of modulus of rupture in torsion pertaining to those with the inner diameter D_i=13mm (Fig. 7).

It was ascertained that the values of modulus of rupture in torsion of the hollow circular composite shafts had also increased as the wall thickness increased (Fig. 7). The reason for this is that the endurance/resistance values drop down because the rate between the outer and inner diameters declines, in other words, because the wall thickness diminishes.

Therefore, it can also be seen in the graphics that the wall thickness in the hollow circular composite shafts, as it diminishes, will pose a risk in terms of all the stresses. The shear stresses in all the loaded (non-hollow) circular composite shafts increase in a linear way, from the center of the shafts towards their surface. In other words, the shear stresses take ‘zero’ value at the center of the shafts but reach the maximum value while they move towards the outer surface. However, the minimum shear stress in the circular hollow composite shafts reaches the maximum value, starting from the inner diameter value towards the outer diameter.

As will be seen in the graphics; the experimental and numerical analysis results were found to be close to each other.

5.3. Effects of lengths of reinforcement material on modulus of rupture in torsion (R_T)

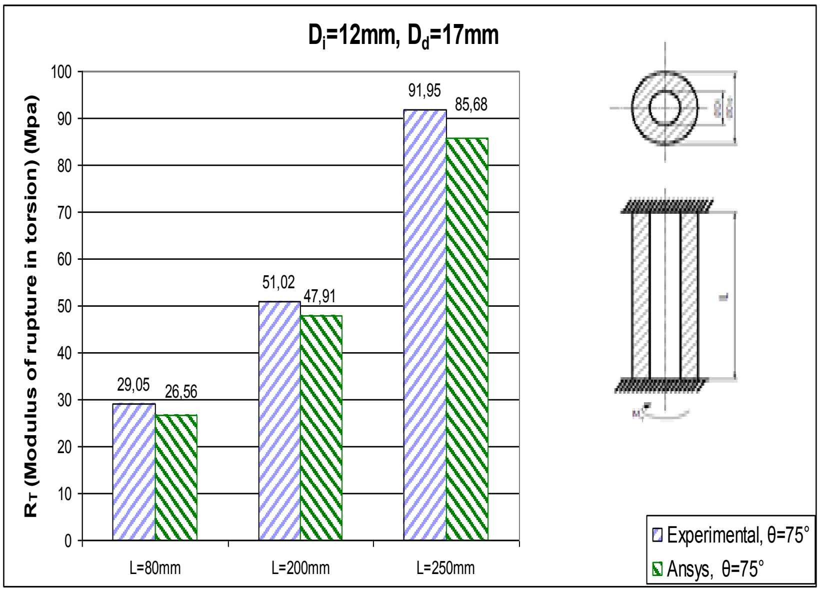

Figure 8. Effects of length of specimens for carbon on torsion stress

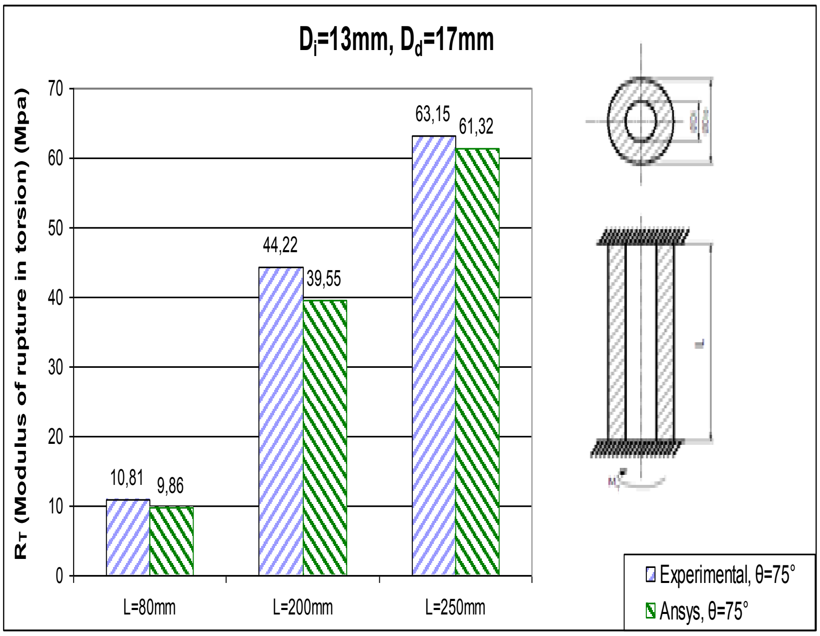

Figure 9. Effects of length of specimens for carbon on torsion stress

The values of modulus of rupture in torsion (R_T) of hollow circular carbon /epoxy composite shafts were analyzed both experimental and ansys according to the lengths of the reinforcement materials. Accordingly;

It was seen that as the lengths of all the hollow circular composite shafts increased, the values of modulus of rupture in torsion also increased (Fig. 8, 9). As the lengths of the hollow circular composite shafts increase, the degree of the rotational angle increases, as well. Hence, the endurance/resistance values increase as the shaft length increases.

It was observed that the glass/epoxy composite shaft of L=250mm-length, at θ=75° orientation angle, and with D_i=12mm-inner diameter had reached the highest values of modulus of rupture in torsion (Fig. 8).

when the lengths of the hollow circular composite shafts were increased the values of modulus of rupture in torsion also increased. The reason for this is the fact that the torsion angle is in direct proportion to length.

As will be seen in the graphics; the experimental and numerical analysis results were found to be close to each other.

6. Conclusions

In this study, the torsional stresses of hollow circular shafts manufactured from carbon/epoxy composite materials were examined at different orientation angles. Composite shafts of different lengths and different inner diameters were used. The hollow composite shafts were manufactured by being wound on the rollers at θ=45°, 60°, 75°, 80°, 88° orientation angles through the use of the filament winding method. Each hollow circular composite shaft that was manufactured was subjected to torsion tests. The significant results obtained from the torsion tests were mentioned below.

The torsional stress values drop down due to the fact that the number of translocations among the fibers will increase as the orientation angle extends. It was seen that the modulus of rupture in torsion of the glass/epoxy composite shafts has reached the maximum value at 45° orientation angle.

It was determined that as the orientation angle of the fiber extended, the modulus of rupture in torsion pertaining to each of the reinforcement material declined.

when the lengths of the hollow circular carbon /epoxy composite shafts were increased the values of modulus of rupture in torsion also increased. The reason for this is the fact that the torsion angle is in direct proportion to length.

It was determined that the modulus of rupture in torsion of the hollow circular composite shafts had increased as the wall thickness increased.

The shear stresses in hollow circular composite shafts increase in a linear way, starting from the inner diameter of the shafts towards the outer surface of the shaft; in other words, the shear stresses take ‘zero’ value at the center of the shafts but reach the maximum value as they move towards the outer surface.

As will be seen in the graphics; the experimental and numerical analysis results were found to be close to each other.

7. Acknowledgement

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