An Analysis on the Torsional Behaviours of Circular Hollow Composite Shafts with Different Fiber-Reinforcements and at Different Orientation Angles

Haşim Pihtili[1], Hayri Yildirim[2]

[1]Fırat University, Mechanical Engineering Department, Elazığ, Turkey
[2]Dicle University, Diyarbakır Techinical Vocational scholl, Diyarbakır, Turkey.

Abstract: In this study, the torsional stresses of circular hollow shafts manufactured from composite materials were examined at different orientation angles. For circular hollow composite shafts; Glass, Carbon and Kevlar 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 composite shafts were manufactured at θ=45°, 60°, 75°, 80°, 88° orientation angles through the filament winding method. The mechanical torsion tests of circular hollow composite shafts were separately repeated for each sample. The obtained results were evaluated among themselves in terms of the materials used, the length of the shaft, the diameter of the shaft and the orientation angle, after which they were transferred to the graphics.

Keywords: 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 & Kim (1995) 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. Chen & Peng (1998) 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 . Kim et al. (2004) 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. Kim & Lee (1995) 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. Kim et al. (2001) 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. Hahn and Erikson (1977) 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. Soden et al. (1993) 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. Mistry et al. (1992) and Gibson AG, et al (1992) 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. Caroll et al. (1995) presented the rate-dependent behaviour of ±55 filament wound glass/epoxy tubes under biaxial loading. (Swanson et al.,1986; Swanson SR, et al.,1987) 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. (Fujii et al.1991; Amijima S,et al, 1992) 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. Ferry et al.(1999) 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. El-Assal & Khashaba(2007) studied the fatigue behaviour of unidirectional glass fibre reinforced polyester (GFRP) composites under in-phase combined torsion/bending loadin concluding that torsional fatigue strength was significantly lower than pure bending fatigue strength and that the endurance limit of combined torsion/bending fatigue strength was approximately half the fatigue limit of pure bending fatigue strength. (Fawaz & Neale ,1990; Ellyin,et al.1994) proposed a multiaxial model for life prediction, based on the modification of a reference fatigue curve to account for the actual load ratio and multiaxial loading condition. Quaresimin et al. (2010) re-analysed some of the multiaxial fatigue data available in the literature to verify the accuracy of life prediction by Fawaz and Ellyin method and by a polynomial function criterion. Quaresimin & Carraro (2013) studied the biaxial fatigue behaviour of unidirecitonal composites using tubes made of glass/epoxy plies, with the fibres oriented at 90° with respect to the tube's axis and tested under combine tension-torsion loading. The same authors (2014) report an extended study using tubular specimens with three different lay-up ($[90_n]$, $[0_f/90_{u,3}]$ and $[0_f/90_{u,3}/0_f]$) tested under combined tension-torsion loadings showing that yhe presence of shear stress significantly reduces the life spent for initiation of the transverse crack, for a given value of the transverse stress and the crack nuclation resistance of the $[0_f/90_{u,3}/0_f]$ tubes is slightly higher than that of the $[90_{u,4}]$ ones. Quresimin et al. (2014) compare the evolution of fatigue damage in laminates with that measured on tubes tested under tension-torsion loading conditions. Using a designed lay-up of the laminates able to introduce a local multiaxial stress state comparable to that present in the tubes subjected to external multiaxial loading these authors showed that the evolution of fatigue damage in multidirectional laminates tested under uniaxial cyclic loading and tubes tested under external multi-axial (tensio-torsion) loading was basically the same. Schmidt et al.(2012) analysed the damage development in glass fibre winding specimens during biaxial fatigue loading using non-destructive testing methods which reveals that initiation of final failure in the specimens is caused by local fibre waviness . El-Kadi & Ellyin (1994) observed that for a given maximum stress in tension-tension loading the fatigue life increases with the increasing of stress ratio.

2. Materials

Within the scope of this study, glass (600 gr/m^2), carbon (800 gr/m^2), kevlar fiber (316 gr/m^2) were used as the fiber materials, whereas epoxy was used as the matrix material. 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, instead of metal shafts used in all automobiles, research was done on shafts made of composite materials. (Fig. 1).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. 2). Glass, carbon and kevlar fibers in the form of separate rolls were prepared for manufacture. The rollers to be manufactured according to the diameter of each hollow composite shaft in the filament winding machine seen in Fig. 2 were made ready for the process. The outer diameters of these rollers were also equal to the inner diameters of the hollow composite shafts. The circular hollow composite shafts were manufactured by winding the glass, carbon and kevlar fibers separately on the rollers connected to the filament winding machine. There are two types of filament winding methods called wet-winding and dry-winding.

In this study, the circular hollow composite shafts were manufactured through the wet-winding method. In this method, after the glass, carbon and kevlar fibers have been submerged into the epoxy-resin pool, they are wound over the rollers at desired orientation angles. The glass, carbon and kevlar 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 circular hollow composite shafts were designed in given lengths according to ASTM standards and were made available for torsion tests, again, in accordance with ASTM standards.

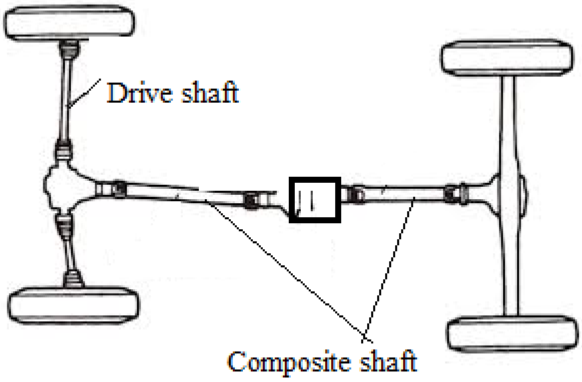

Fig.1: Working condition of shaft used in automobiles

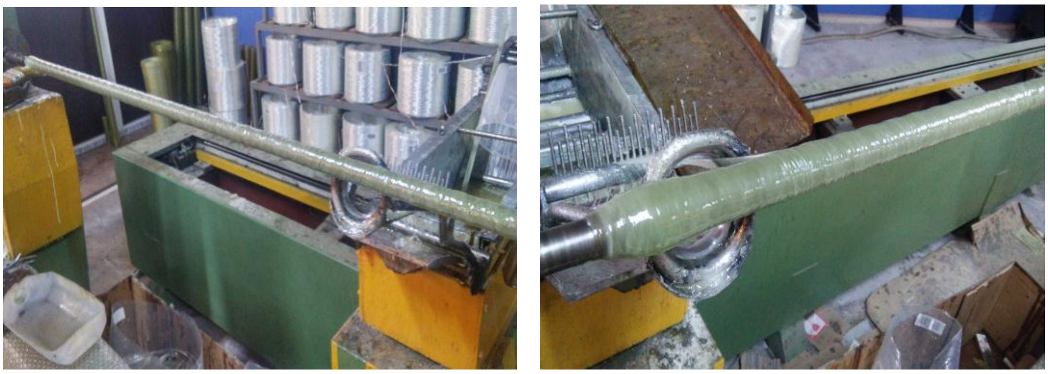

Fig. 2: Filament winding machine

The circular hollow composite shafts manufactured from glass/epoxy, carbon/epoxy and kevlar/epoxy materials of 17mm outer diameter and of 12mm and 13mm inner diameter were cut in 80mm, 200mm and 250mm lengths in order to be used in torsion tests.

a b c

Fig. 3: A test specimens of **a)** glass/Epoxy b) kevlar/Epoxy c) carbon/Epoxy

4. Experimental studies

4.1. Torsion Tests

The circular hollow composite shafts manufactured from 80mm, 200mm and 250mm-long glass/epoxy, carbon/epoxy and kevlar/epoxy materials with D_i =12mm and D_i =13mm inner diameters, 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. The torsion test device operates at the range of 1° - 360° degree/minute (Fig. 4). In general, it was observed in the literatures that torsion tests had been performed at the range of 15° - 20° degree/minute. In this study, the torsion tests were performed at the speed of 20° degree/minute for each sample. In accordance with ASTM standards, all the samples were placed between two jaws in the way that they would be in downright/perpendicular position. A plastic plug material was placed on both ends of the samples so that the sample ends/tips fixed on the jaws would not get damaged, and the jaws could grasp the ends/tips better and the results of the test in particular would prove to be more sensitive during the torsion tests. As the result of the fact that the upper jaw remained fixed and the lower jaw turned/spinned, a torsion torque was applied on the samples, and then the maximum modulus of rupture in torsion was obtained (Fig.5, 6, 7). Thus, the data obtained for each sample were transferred to the graphics and were, then, interpreted.

Fig. 4: Test setup for the torsion test

a b c

Fig. 5: Test numune uçlarının plastik dolgu malzemesi ile takviyelendirilmeleri: a) glass/epoxy b) kevlar/epoxy c) carbon/epoxy

a b

Fig. 6: Specimens of carbon/epoxy a) before torsion, b) after torsion

a b c

Fig. 7: Different steps of specimens under torsion a) glass/epoxy b) kevlar/epoxy c) carbon/epoxy

5. Results and discussions

5.1. Effects of reinforcement materials on torsion stress

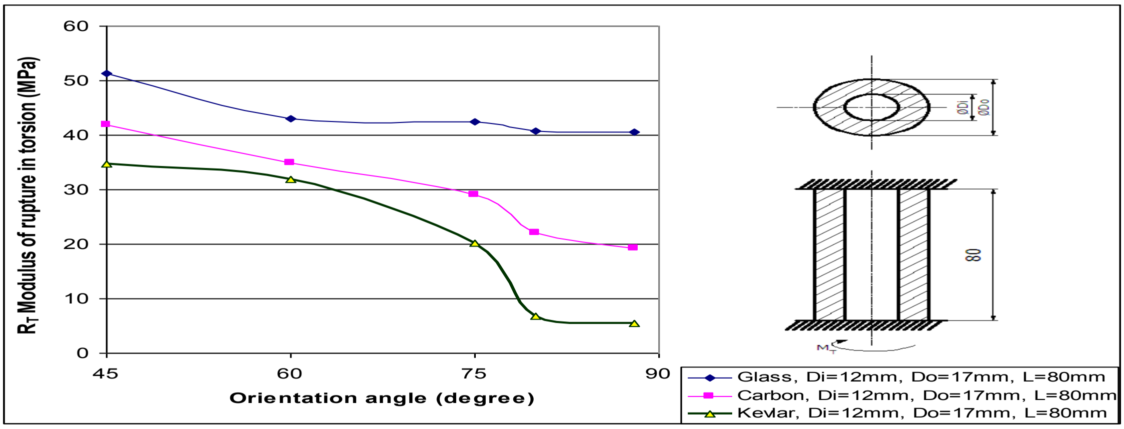

Fig. 8: Torsion stress- orientation angle and length curve of glass, carbon and kevlar for torsion stress

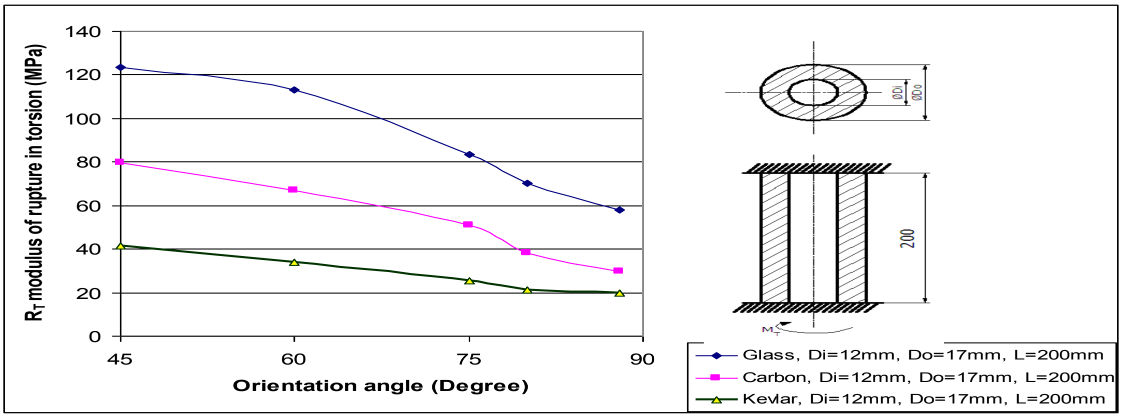

Fig. 9: Torsion stress - orientation angle and length curve of glass, carbon and kevlar for torsion stress

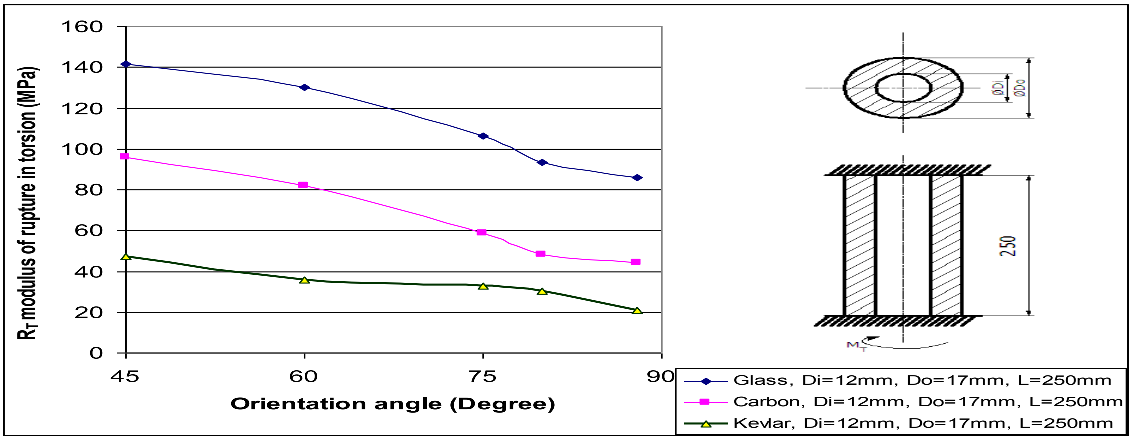

Fig. 10: Torsion stress - orientation angle and length curve of glass, carbon and kevlar for torsion stress

The values of modulus of rupture in torsion of hollow circular glass/epoxy, carbon/epoxy and kevlar/epoxy composite shafts were analyzed according to the reinforcement materials and 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. 8, 9, 10).
- It was seen that the modulus of rupture in torsion in three separate reinforcement materials had reached the maximum value when it was at 45° orientation angle (Fig. 8, 9, 10). 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.
- It was observed that the values of modulus of rupture in torsion pertaining to the composite shafts in three different lengths, which were reinforced by glass/epoxy, had proved to be higher, which, as seen in Fig. 8, 9, 10, were followed by the composite shafts reinforced by carbon/epoxy and kevlar/epoxy, respectively. Nonetheless, the fact that gr/m^2 weights in the course of the manufacturing process proved to be different from one another also brought forth differences in the results. In other words, as the gr/m^2 weight decreases, the mechanical properties of the reinforcement material, such as values of stress and endurance/resistance, increase.
- It was seen that kevlar/epoxy composite shafts had also been exposed to the lowest torsional stresses in all lengths (Fig. 8, 9, 10).
- When the test results of all the circular hollow composite shafts were examined in terms of length, it was seen that the modulus of rupture in torsion pertaining to the glass-reinforced shafts proved to be higher than that of the other samples. That is, as the length increases, the shear stress values of the materials increase, as well. The reason for this is the fact that the torsion angle is in direct proportion to length.

5.2. Effects of wall-thickness on torsion stress

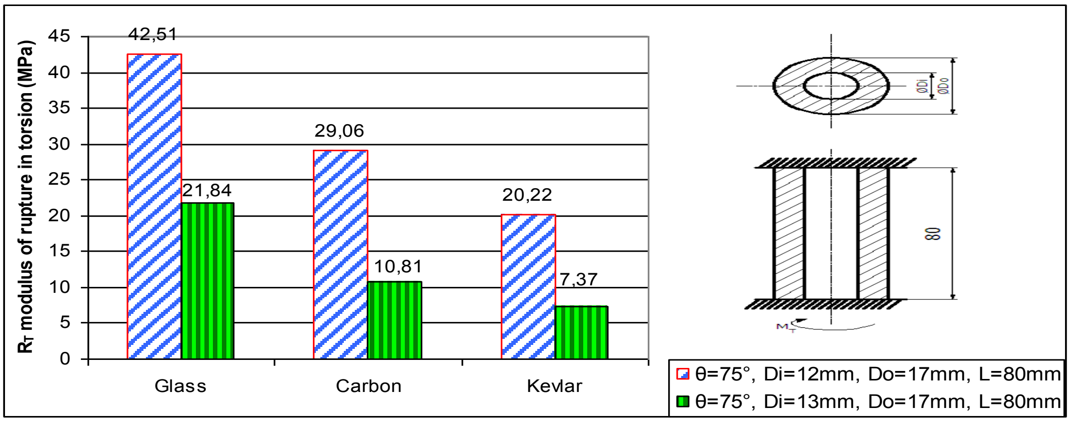

Fig. 11: Effects of wall-thickness for glass, carbon and kevlar on torsion stress

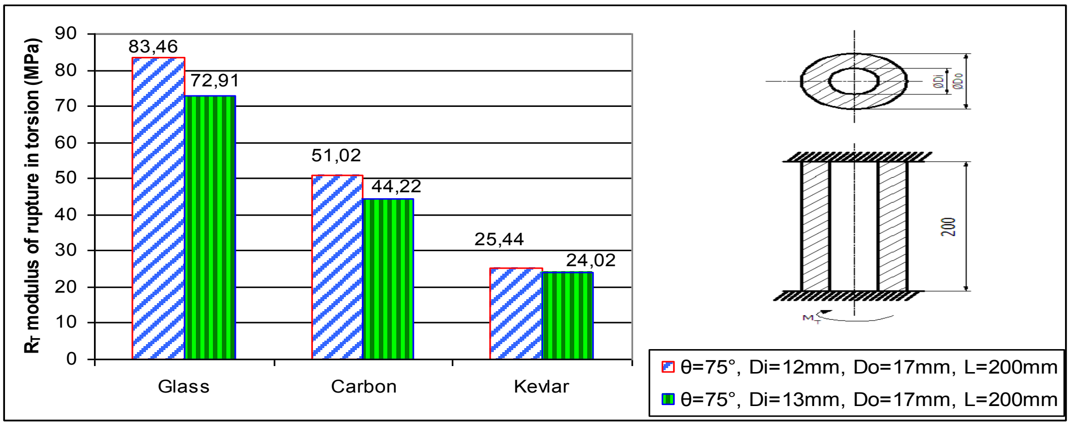

Fig. 12: Effects of wall-thickness for glass, carbon and kevlar on torsion stress

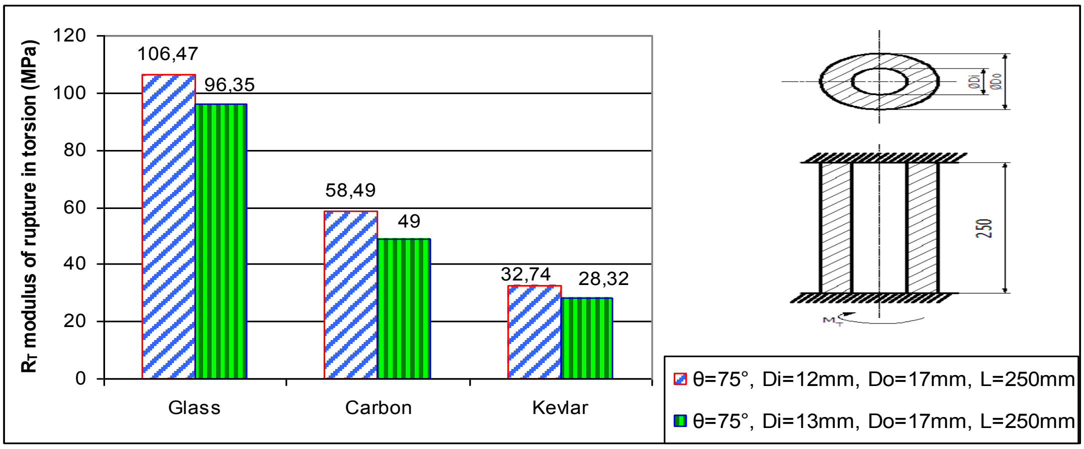

Fig. 13: Effects of wall-thickness for glass, carbon and kevlar on torsion stress

The values of modulus of rupture in torsion of hollow circular glass/epoxy, carbon/epoxy and kevlar/epoxy composite shafts were analyzed according to the wall-thickness. Accordingly;

- It was seen that the values of modulus of rupture in torsion of the circular hollow glass/epoxy, carbon/epoxy and kevlar/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. 11, 12, 13).

- It was also seen that the values of modulus of rupture in torsion of the Glass/Epoxy composite shafts in different lengths and at θ=75° orientation angle, with the inner diameters, D_i=12mm and D_i=13mm, proved to be at the highest level, whereas the values of modulus of rupture in torsion of kevlar/epoxy composite shafts proved to be at the lowest level (Fig. 11, 12, 13).

- It was observed that the values of modulus of rupture in torsion of glass/epoxy composite shafts of 250mm length and at θ=75° orientation angle and with the inner diameter, D_i=12mm, proved to be at the highest level (Fig. 19), whereas the values of modulus of rupture in torsion of kevlar/epoxy composite shafts with L=80mm and D_i=13mm (inner diameter) proved to be at the lowest level (Fig.11).

- It was determined that the values of modulus of rupture in torsion of the glass/epoxy composite shafts of two different wall thicknesses and of three separate lengths were at the highest level, whereas values of modulus of rupture in torsion of the kevlar/epoxy composite shafts were at the lowest level (Fig. 11, 12, 13).

- It was ascertained that the values of modulus of rupture in torsion of the circular hollow composite shafts had also increased as the wall thickness increased (Fig. 11, 12, 13). 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 circular hollow 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.

5.3. Effects of lengths of reinforcement material on torsion stress

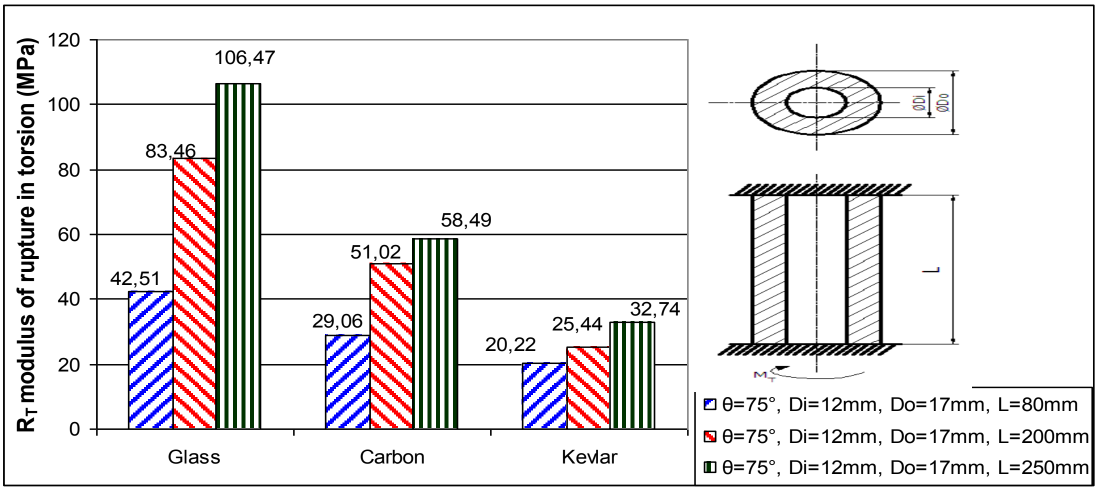

Fig. 14: Effects of length of specimens for glass, carbon and kevlar on torsion stress

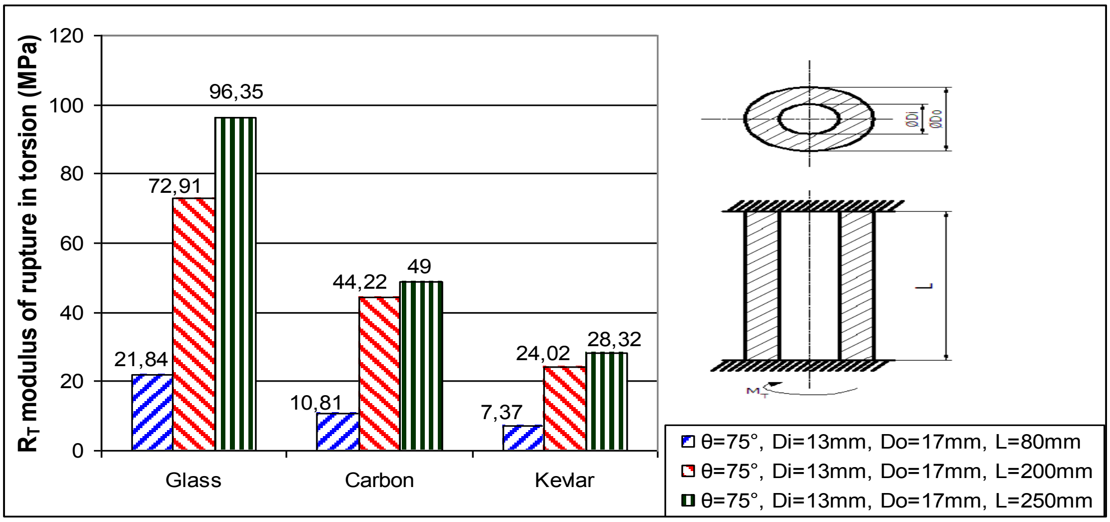

Fig. 15: Effects of length of specimens for glass, carbon and kevlar on torsion stress

The values of modulus of rupture in torsion of hollow circular glass/epoxy, carbon/epoxy and kevlar/epoxy composite shafts were analyzed according to the lengths of the reinforcement materials. Accordingly;

- It was seen that as the lengths of all the circular hollow composite shafts increased, the values of modulus of rupture in torsion also increased (Fig. 14, 15). As the lengths of the circular hollow 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, followed by carbon/epoxy and kevlar/epoxy composite shafts, respectively (Fig. 14, 15).

- The lowest value of modulus of rupture in torsion was determined in the kevlar/epoxy composite shafts of L=80mm-length, at θ=75° orientation angle, and with D_i=13mm-inner diameter (Fig. 15).

- The values of modulus of rupture in torsion pertaining to both D_i=12mm and D_i=13mm-inner diameters as well as L=80mm, 200mm, 250mm-lengths were determined to be at the highest level in glass/epoxy composite shafts but at the lowest level in the kevlar/epoxy composite (Fig. 14, 15).

6. Conclusions

In this study, the torsional stresses of circular hollow shafts manufactured from glass/epoxy, carbon/epoxy and kevlar/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 circular hollow 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 in all the 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 test results of all the circular hollow composite shafts were examined in terms of length, it was seen that the values of the modulus of rupture in torsion of the glass-reinforced shafts proved to be higher than that of the other samples.

It was also observed that there was an increase in the rotational angle and shear stress values of the materials when the lengths of all the circular hollow composite shafts were extended. 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 pertaining to all the circular hollow composite shafts had increased as the wall thickness increased.

The weights in gr/m^2 in the course of the manufacturing process are of great importance. In other words, an increase or a decrease in gr/m^2 weights cause changes in the stress values of the reinforcement materials. The lower the gr/m^2 - weight of a composite material, the better the endurance/resistance and the other mechanical properties of the material.

The shear stresses in all the circular hollow 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.

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