Journal of Textiles and Polymers
Vol. 11, No. 3, 11-17, June 2023
https://www.itast.ir
DOI: 10.48302/jtp.2024.426763.1278

Experimental study on the effect of braiding angle on the fracture behavior of 2D braided composite cylinders

Maryam Zeynivand Mojarrad[1], Hadi Dabiryan[*1], Ali Akbar Gharehaghaji[1], Amir Masoud Rezadoust[2]
[1]Textile Engineering Department, Amirkabir University of Technology (Tehran Polytechnic), Tehran, Iran.
[2] Iran Polymer and Petrochemical Institute, Tehran, Iran.

Article Information

Article history:

Received: 2023-11-24

Accepted: 2024-02-21

***Keywords*:**

2D braided composite cylinders, Fracture modes, Braiding angle, Tensile strength.

Abstract

This research aims to study the fracture mechanism of two-dimensional (2D) braided glass/epoxy composite cylinders under axial tensile load. For this purpose, three types of composite cylinders were fabricated using braids with three braiding angles, i.e., 30°, 45°, and 60° to find out the role of braid angle on the fracture mechanism of composites. Novel fixtures (jaws) were designed and produced for tensile testing of composite cylinders. Composite cylinders were subjected to the tensile test by applying a SANTAM static tensile machine. Macroscopic damage morphologies of the samples were provided after the tensile test by using an optical microscope. The results indicated that different fracture modes occurred in the braided cylindrical composites. Fiber fracture, matrix fracture, and de-bonding were the dominant fracture modes observed in the braided composite cylinders proportional to the angle of braids. Fiber fracture was the main mode of fracture in the composite cylinders reinforced with braids having an angle of 30°, while the dominant fracture mode in the composite cylinder reinforced with braids having an angle of 60° was matrix fracture. In samples with a 45° braiding angle, a combination of fracture modes was observed. In summary, the results indicated that the braiding angle has a significant influence on the fracture behavior of composite cylinders.

1 INTRODUCTION

Braiding is the interlacing of yarns at a specific angle named braiding angle between the longitudinal axes of the structure and the yarns in an expected structure. Relying on a series of superior performance benefits such as high stiffness, modulus, and strength-to-weight ratios, braided composite tubes have demonstrated great potential in various engineering fields such as aerospace, automobile, sports, and marine industries[1, 2]. Tubular braided composites consist of braided yarns embedded in a matrix and are fabricated by using a Radial braider or Maypole braider. These superior structures are produced with different braiding patterns including Diamond (1/1), Regular (2/2), Hercules (3/3), and tri-axial (Diamond or Regular with axial yarns) [3-5]. To find out the influence of the braided structures on the mechanical performance of tubular braided composites, several studies have been done to numerically simulate the braiding process [6-10]. Braiding angle was proved to have a significant influence on the mechanical properties of tubular braided composites [11-14]. Studies on tubular braided composites under tension loadings have been investigated by several researchers[5] [15-17]. Melenka and Carey[5] studied the tensile and torsional behavior of 1/1 and 2/2 braided Kevlar fiber/epoxy composite tubes with braid angles of 35°, 45° and 55°. The results indicated that tensile strength and Young modulus decrease with the increase of braid angle for both 1/1 and 2/2 braid patterns, although no distinct trend for the torsional/shear properties across different braid architectures was demonstrated. Gautam et.al [18] studied the influence of braid angle and several axial tow insertions on the mechanical performance of flattened tubular braided carbon fiber/epoxy composites. They studied two types of braids i.e., bi-axial and tri-axial, for three braid angles (35°, 45°, and 55°). The results showed that for the bi-axial braids, an increase in the braid angle led to a decrease in the strength, axial modulus, and specific energy absorption, increasing the strain to failure. Xun et al [19] studied the torsional crack development in the 3D braided composite tubes with 3D digital image correlation (3D-DIC) and micro-computed tomography (micro-CT) techniques. They reported that the torsional damage propagates along the helix of the braided strand in the torsion direction and inhibits in the vertical direction within repeated braid units. The bundles were subjected to axial tension in the torsion direction and axial compression in the vertical direction. This led to the slippage and cross-section deformation in the braided yarns at the intersection points. The results showed that the interface cracks were the main damage

* Corresponding Author: dabiryan@aut.ac.ir

modes and induced final torsional failure both after yarn and resin damages. Gideon et.al [20] studied the consequent energy absorption and quasi-static axial compression behavior of three different types of carbon/epoxy braided composite tubes. They investigated the influence of sample length and braiding angle on the failure mechanism and energy absorption of the braided composite tubes. They concluded that the length of the sample increased, the peak load decreased and the energy absorption of the braided tubes at 45° braiding angle was significantly higher than that of other braiding angles of 25° and 35°. The failure modes included fiber breakage, matrix crack along the braiding angle, and bulging and de-bonding between yarns. Many attempts have been made to analyse the fracture mechanism of braided composites under different loads. Harte and Fleck[15] claimed that for tubular braided composites fiber fracture was the main cause of failure in small braid angles, while in the larger braid angles it was mainly due to the neck propagation. They also studied a regular fiberglass tubular braided composite to investigate the failure modes for various braid angles under different types of loadings with a minor focus on combined tension–torsion loading. They used common strain gauges to carry out strain measurements without any discussion on strain distribution over the braid. Reported works have also demonstrated that the braiding angle in braided composite cylinders has a significant effect on the fracture behavior and failure modes created under different loadings [21-24]. Gu et.al [2] evaluated the torsion progressive damage and failure mechanism of two-dimensional (2D) braided carbon/epoxy composite cylinders with four braiding angles including 30°, 45°, 55°, and 60°. They utilized three-dimensional digital image correlation to monitor the progressive torsional strain and crack propagation. Results indicated that the braiding angle has a significant influence on the torsional mechanical behavior of composite cylinders. In addition, they concluded that the damage modes of 30° and 60° composite samples were mainly influenced by cumulative matrix damage, while those of 45° and 50° were largely dominated by the fiber breakage. Wu et. al [25] investigated the deformation behavior of single-layer braided fabric and its effect on the failure modes of composite tubes under quasi-static axial compression. The results showed that braiding structures with larger braiding angles and more interlacing points between yarns provided more resistance to prevent yarns separating from the composite tubes and caused a folding fracture mode. Whereas, a splaying fracture mode happened in the braided fabrics with smaller angles. Tate et.al [26] studied the effect of braiding angle on fatigue performance and in-plane mechanical properties of biaxial braided composites. In their research, carbon/epoxy braided composite specimens were manufactured applying low cost vacuum assisted resin transfer moulding including (VARTM) with different braid angles of 25°, 30° and45°. The results showed that as braid angle increases the tensile modulus, strength and Poisson's ratio were decreased considerably. They also concluded that braided composites irrespective of the braid angle, did not demonstrate any evident matrix cracks either at the surface or at the edges and/or delamination of plies until 90% of the fatigue life, when tested at 10 Hz frequency.

Therefore, the braid angle does not have a significant effect on the failure mechanism under fatigue loading.

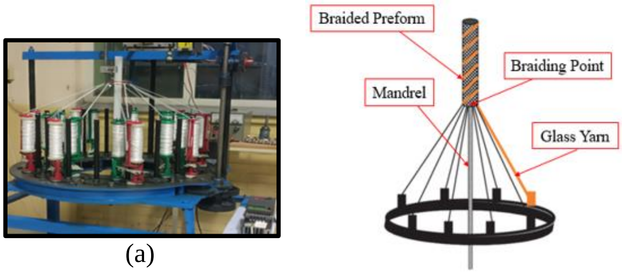
This study aims to investigate the effect of braiding angle on the damage behavior of glass/epoxy braided composite cylinders under tensile loading. 2D braided composite cylinders with three different braiding angles are prepared. The specimens are subjected to a tensile test, and the tensile properties are evaluated and analyzed. An optical microscope is utilized to observe and study the failure mechanisms and multi-scale damage modes of 2D braided composite cylinders under tensile loading.

2 EXPERIMENTAL

2-1 Materials and Specimen Preparation

2-1-1 Reinforcement Production

To study the influence of braiding angle on the fracture mechanism of 2D braided composite cylinders under tensile load, braided preforms were produced on the 18-carrier braiding machine (9 carriers moving clockwise and 9 carriers moving counter-clockwise). Fig. 1 shows the applied braiding machine in this research. A Glass yarn count of 1200 Tex was used to produce tubular braids. The tubular braided preforms were produced in three different braiding angles (30°, 45°, and 60°).



(a)

(b)

Fig. 1 Braiding Machine: (a) Real view and (b) Schematic view

A Polyethylene rod with a diameter of 24.4 mm was applied as a mandrel to form the tubular braids. The braiding angle was measured by using Image J 1.8.0-172 software. Easily remove the mandrel, the surface of the polyethylene mandrel was polished with silicon spray and epoxy wax. The tubular braid produced on the mandrel is shown in Fig. 2.

Fig. 2 Produced tubular braids

Fig. 3 shows the method of measuring the braiding angle by Image J software.

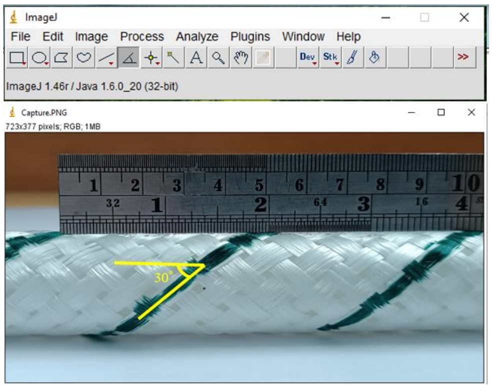


Fig. 3 Image J software and measuring the braid angle

The measured angles by Image J software are shown in Fig. 4.

Fig. 4 Measured braid angles by Image J software

2-1-2 Composite Fabrication

The epoxy resin and braided preforms were applied as matrix and reinforcement of composites, respectively. For this purpose, the resin (epoxy LR 620) and hardener (EPH 620) were mixed in a weight ratio of 100:20 in a vacuum mixer. Table 1 shows the properties of C-glass fiber.

Table 1 C-Glass fiber and Epoxy resin properties

	C-Glass[27]	Epoxy
Density (g/cm^3)	2.48	1.15
Tensile strength (MPa)	3300	2788
Elastic modulus (MPa)	69000	2788
Shear modulus (MPa)	27000	-
Flexural modulus (MPa)	-	2500
Flexural strength (MPa)	-	100
viscosity $(MPa \cdot s)$		1000
Elongation-at-break (%)	4.8	5.00
Poisson's ratio	0.276	-

To calculate the mechanical properties of C-glass yarns, the tensile test was performed on the samples. The prepared glass yarn is shown in Fig.5. The Tensile test was performed according to the ASTM D2524 standard method using the INSTRON machine.

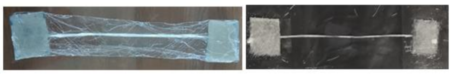


Fig. 5 Prepared C-glass yarn for tensile test

The stress-strain curves for epoxy resin and glass yarns for different counts are indicated in Fig.6 and Fig.7, respectively.

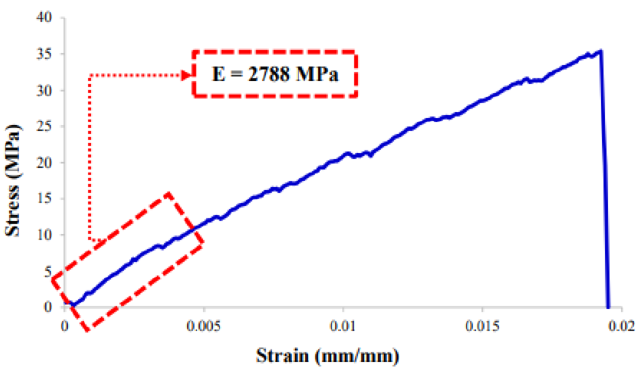


Fig. 6 Stress-strain curve for epoxy matrix from experiment

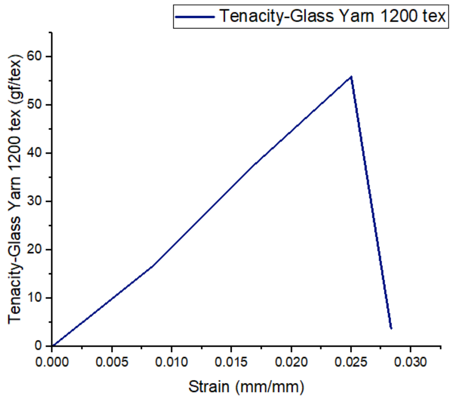


Fig. 7 Stress-strain curve for C-glass yarns from experiment

The composite cylinders were fabricated by the Hand Lay-up method. Then, a filament winding machine was used for wrapping tape on a rotating mandrel. The process of composite production is shown in Fig.8. Afterwards, the composites were cured for 24 hours at room temperature, and the post-cure process was carried out at 80 ºC for 2 hours. Composite cylinders were cut into 200 mm specimens and used for tensile test.

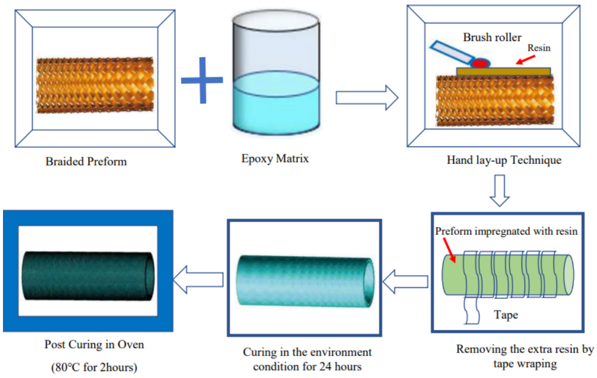


Fig. 8 Schematic of composite fabrication process

The final 2D braided composite cylinders are shown in Fig. 9.

Fig. 9 2D braided composite cylinders

The structural parameters of 2D braided composites are indicated in Table 2.

2-2 Tensile Test

The tensile test was performed on the specimens to find out the influence of braiding angle on the fracture modes of composite cylinders. For this purpose, a new jaw was designed and manufactured to hold the cylindrical composites during the tensile test. Fig. 10 shows a prepared set-up that was applied to evaluate the tensile test of samples.

Table 2 Structural parameters of 2d braided composite cylinders

Sample's code	Inner diameter (mm)	Outer diameter (mm)	Wall thickness (mm)	length (mm)	Fiber volume fraction (%)	Fiber weight fraction (%)
A-30	24.5	25.5	0.5	200	54.3	62.5
B-45	24.4	25.5	0.55	200	44.7	59.1
C-60	24.4	25.6	0.6	200	42.6	57.7

Fig. 10 Tensile test equipment

As shown in Fig. 10, the tensile test equipment includes two metal cylinders made of CK 45 steel with an outer diameter of 4.5 cm, an inner diameter of 3.7 cm, and a height of 8 cm. The groove with a diameter of 1 cm in the lower part of each cylinder was created. Two steel pins with a diameter of 1 cm and a length of 12 cm were used to connect the prepared mold to the jaws of the tension device. Also, inside the steel cylinder, a column with a height of 2 cm and equal to the inner diameter of the cylinder (24.5 mm) was created to keep the cylinder straight inside the mold. To connect the composite cylinders to the prepared mold, LR 620 epoxy resin was used along with hardener, chopped glass fibers, and calcium carbonate as filler in the amount of 30% by weight of resin and hardener. The composition of resin with calcium carbonate was prepared in the amount of 50 grams for each mold and poured into the cylindrical molds. The composite cylinder was placed in the resin and kept in the oven at 80°C for 30 min for fast curing, after which the sample was firmly placed inside the mold. 50 grams of the prepared mixture was poured into the second mold and the other end of the composite cylinder was placed inside it. The prepared part was placed in the oven at 80°C for two hours so that the post-curing stage could be done to further ensure the strength and complete connection of the resin to the steel jaws. Finally, the sample was removed from the oven and used to perform the tensile test. Fig. 11 shows the prepared specimens for the tensile test. The composite cylinders were subjected to tensile tests by applying a SANTAM testing machine. The length of specimens under the tensile test was 100 mm. The specimens were subjected to a tensile load with a speed of 5 mm/min according to ASTM D638-14 Standard. The number of 6 samples was tested for each composite specimen. The composite cylinder under tensile loading is shown in Fig. 12.

Fig. 11 Final prepared specimen for the tensile test

Fig. 12 Braided composite cylinder under tension

Fig. 13 Braided composite cylinders after tensile test; Angles of (a) 30°, (b) 45°, (c) 60°

3 RESULTS AND DISCUSSIONS

3-1 The Tensile Behavior of Braided Composite Cylinders

Fig. 14 shows the stress-strain curve of samples A-30, B-45 and C-60. As can be seen, all curves can be divided into two main regions. After an almost linear region at the beginning of the stress-strain curves, a nonlinear part is observed continuing to the peak of the diagram. Different slopes of the first region of curves indicate the different elastic modulus. The nonlinear region is attributed to crack propagation in the structure of composites, which occurs in different failure mechanisms such as fiber fracture, matrix fracture, or debonding. According to Fig. 14, the braided composite cylinder reinforced with 30° braid performance has the highest tensile strength.

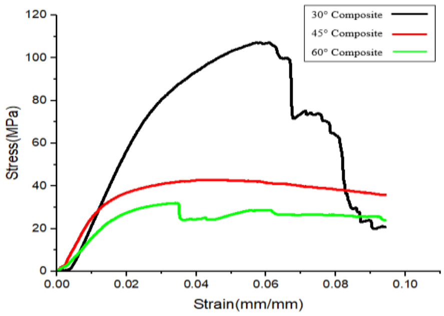


Fig. 14 The stress-strain behavior of composite cylinders

As can be seen in Fig. 14, the ultimate strength of the A-30 sample is significantly higher than that of the B-45 and C-60 samples. The higher ultimate stress of the A-30 sample is attributed to the braiding angle which increases the fiber portion in the direction of applied tensile force to the composites. On the other hand, the smaller the braiding angle, the shorter the fiber path in the structure of composites.

3-2 The Effect of Braiding Angle on the Fracture Modes of Cylinders

It is well known that fracture in fiber-reinforced composites occurs due to fiber fracture, matrix cracking, fiber/matrix de-bonding, or/and separation of bonded plies (delamination). However, damage in composites can be caused by multiple fiber-bridged matrix cracking in a unidirectional composite, multiple intra-laminar cracking in a laminate, local delamination distributed in an inter-laminar plane, and fiber/matrix interfacial slip associated with multiple matrix cracking. The final macroscopic failure modes of cylindrical composites are shown in Fig. 15 - 17. Images were taken using an optical microscope with 200x magnification. The photos showed that the fracture modes of the composites are fiber breakage, cracks in matrix and matrix fragmentation, fiber/matrix debonds, and/or separation of bonded plies. As shown in Fig. 15 - 17, the different composites revealed different failure modes under the tensile loading, and different aspects of fracture and damage occurred, so the damage modes of the A-30 sample differed from those of the B-45 and C-60. The fiber failure and fiber pull-out are the dominant phenomena in the A-30 sample. In the other samples, especially in the C-60, matrix fragmentation was more observed. Since the braiding angle determines the fiber path, it can be concluded that the fiber path in the structure of composites has a significant influence on the fracture of composite cylinders.

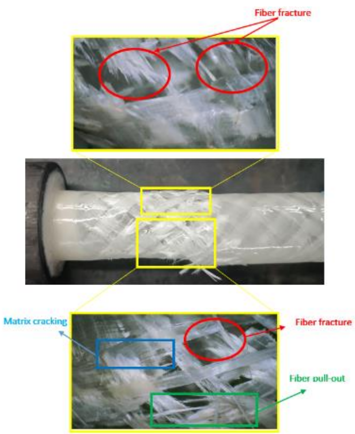


Fig. 15 Macroscopic tensile damage morphologies of A-30

Fig.15-17, showed that the macro failure modes mainly are splitting and breakage of fibers, cracking and fragmentation of the matrix, and de-bonding. In comparison, fiber fracture is most prevalent in A-30. Whereas, matrix cracking and matrix fragmentation are found to be more severe in B-45 and C-60 samples. In the A-30 sample, the braid yarns have a smaller angle with the direction of the axial tensile load. In other words, the 30° braiding angle allows glass fiber braided yarns with superior axial performance to withstand the tensile loads, thus this structure is mainly dominated by fiber failure. In addition, the de-bonding between the fibers and matrix was observed in all the braided composite cylinders. The mechanism by which damage begins in different samples was different. The first cracks in the A-30 sample were the result of fiber cracking. By contrast, the first damage that appeared in B-45 and especially in C-60 samples was matrix cracking.

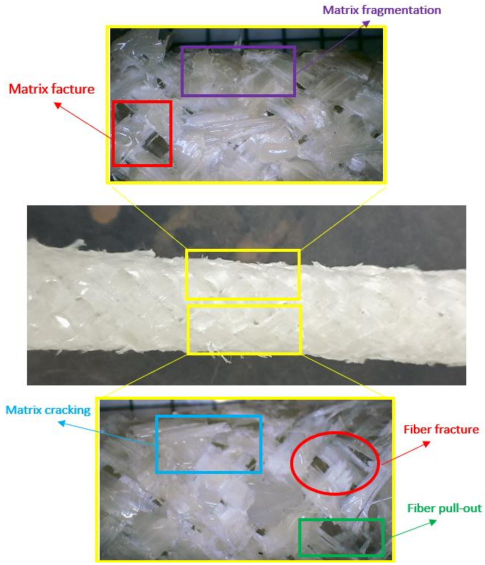


Fig. 16 Macroscopic tensile damage morphologies of B-45

Based on the optical images, the damage distribution of all three kinds of composites is in the form of damages spread along the fiber bundle braiding path. It should be noted that the matrix damages would not cause structural failure while resulting in further dominant damages including fiber breakage and separation and interfacial damage. As the stress increases, the matrix cracks begin to expand, and the interface debonding occurs. For the A-30 sample, the fibers have more interlacing points in the circumferential direction, so matrix cracks are easily confined by the fibers during circumferential propagation. However, the fiber strands of the 45° and 60° specimens have fewer interlaced points in the circumferential direction, which leads to the matrix cracks that propagate in the circumferential direction, hence the circumferential cracks are longer. In all the cylindrical composites under tensile loading, braiding yarns are subjected to a multi-axial stress state, including axial tensile stress and also an in-plane shear stress. Stress concentration intensified at the resin-rich area of yarn cross-over points and the resin cracks were created and caused intra-yarns debonding. These cracks rapidly expanded and also caused debonding between the fiber and matrix.

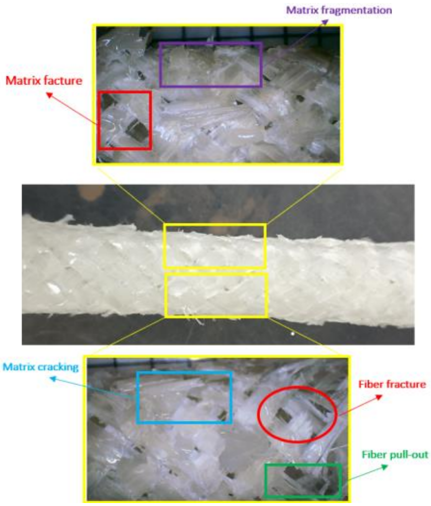


Fig. 17 Macroscopic tensile damage morphologies of C-60

4 CONCLUSIONS

In the present research, the effect of the braiding angle on the fracture behavior of the 2D-braided composite cylinders under tensile loads was studied. The braided composite cylinders were fabricated on the braiding machine at three different braiding angles 30°, 45°, and 60°. The tensile test was carried out on the prepared samples. Macrograph photos were taken from damaged areas of cylindrical composites. The macrographs showed different fracture modes including fiber breakage, matrix fragmentation, and fiber/matrix interface de-bonding on the composites. The fracture modes of composites reinforced with braids having angles of 45° and 60° are mainly matrix fractures, while the failure of cylindrical composites reinforced with braids having angles of 30° often occurs due to the fiber fracture. De-bonding between the braid and matrix was observed in all composites reinforced with braids with different braiding angles.

REFERENCES

[1] Z. Huang, W. Ma, C. Jia, X. Lei, and Z. Zhang, "Thermal stress distribution of multi-layered composite tubes affected by braiding angle," *J. Eng. Fiber. Fabr.*, vol. 17, Jan. 2022.

[2] Y. Gu *et al.*, "Torsion damage mechanisms analysis of two-dimensional braided composite tubes with digital image correction and X-ray micro-computed tomography," *Compos. Struct.*, vol. 256, Jan. 2021.

[3] G. W. Melenka and J. P. Carey, "Development of a generalized analytical model for tubular braided-architecture composites," *J. Compos. Mater.*, vol. 51, no. 28, pp. 3861–3875, Dec. 2017.

[4] G. W. Melenka and J. P. Carey, "Braid CAM: Braided composite analytical model," *SoftwareX*, vol. 7, pp. 23–27, Jan. 2018.

[5] G. W. Melenka and J. P. Carey, "Experimental analysis of diamond and regular tubular braided composites using three-dimensional digital image correlation," *J. Compos. Mater.*, vol. 51, no. 28, pp. 3887–3907, Dec. 2017.

[6] A. Gholami and G. W. Melenka, "Finite element analysis of 2-D tubular braided composite based on geometrical models to study mechanical performances," *Mech. Adv. Mater. Struct.*, vol. 29, no. 28, pp. 7542–7558, 2022.

[7] T. Liu, X. Wu, B. Sun, W. Fan, W. Han, and H. Yi, "Investigations of defect effect on dynamic compressive failure of 3D circular braided composite tubes with numerical simulation method," *Thin-Walled Struct.*, vol. 160, Mar. 2021.

[8] H. Zhou, W. Zhang, T. Liu, B. Gu, and B. Sun, "Finite element analyses on transverse impact behaviors of 3-D circular braided composite tubes with different braiding angles," *Compos. Part A Appl. Sci. Manuf.*, vol. 79, pp. 52–62, Dec. 2015.

[9] L. Shi, Z. Wu, X. Cheng, Z. Pan, and Y. Yuan, "Transverse impact response of hybrid biaxial/uniaxial braided composite tubes," *Eng. Struct.*, vol. 244, Oct. 2021.

[10] Y. Jin, Z. Wu, Z. Pan, L. Peng, and X. Hu, "Numerical and experimental study on effect of braiding angle on low-velocity transverse punch response of braided composite tube," *Int. J. Damage Mech.*, vol. 29, no. 4, pp. 667–686, Apr. 2020.

[11] A. Armanfard and G. W. Melenka, "Experimental evaluation of carbon fibre, fibreglass and aramid tubular braided composites under combined tension–torsion loading," *Compos. Struct.*, vol. 269, Aug. 2021.

[12] H. Zhou, C. Li, L. Zhang, B. Crawford, A. S. Milani, and F. K. Ko, "Micro-XCT analysis of damage mechanisms in 3D circular braided composite tubes under transverse impact," *Compos. Sci. Technol.*, vol. 155, pp. 91–99, Feb. 2018.

[13] Z. Wu, Q. Zhang, B. Li, Y. Liu, and Z. Pan, "Transverse impact response and residual flexure characteristics of braided composite tubes: Effect of stacking sequence," *Thin-Walled Struct.*, vol. 155, Oct. 2020.

[14] W. Wang, H. Wang, and H. Fan, "Fabrication and crushing behaviors of braided-textile reinforced tubular structures," *Mater. Today Commun.*, vol. 28, Sep. 2021..

[15] A.-M. Harte and N. A. Fleck, "On the mechanics of braided composites in tension," 2000.

[16] C. K. Leung, G. W. Melenka, D. S. Nobes, and J. P. Carey, "The effect on elastic modulus of rigid-matrix tubular composite braid radius and braid angle change under tensile loading," *Compos. Struct.*, vol. 100, pp. 135–143, Jun. 2013.

[17] A.-M. Harte and N. A. Fleck, "Deformation and failure mechanisms of braided composite tubes in compression and torsion." [Online]. Available: www.elsevier.com/locate/actamat.

[18] M. Gautam, S. Sivakumar, A. Barnett, S. Barbour, S. L. Ogin, and P. Potluri, "On the behaviour of flattened tubular Bi-axial and Tri-axial braided composites in tension," *Compos. Struct.*, vol. 261, Apr. 2021.

[19] L. Xun, S. Huang, B. Sun, and B. Gu, “Torsional cracks development in carbon-fiber 3-D braided composite tubes,” *Thin-Walled Struct.*, vol. 184, no. September 2022, p. 110477, 2023.

[20] N. M. Barkoula, B. Alcock, N. O. Cabrera, and T. Peijs, “Flame-Retardancy Properties of Intumescent Ammonium Poly(Phosphate) and Mineral Filler Magnesium Hydroxide in Combination with Graphene,” *Polym. Polym. Compos.*, vol. 16, no. 2, pp. 101–113, 2008.

[21] L. Shi, Z. Wu, X. Cheng, Z. Pan, and Y. Yuan, “The hybridization effect and damage sequence investigation of biaxial/unidirectional braided composite tubes by micro-CT method,” *Journal of Industrial Textiles*, vol. 52. SAGE Publications Ltd, Jan. 01, 2022.

[22] Y. Chen *et al.*, “Crack initiation and propagation in braided SiC/SiC composite tubes: Effect of braiding angle,” *J. Eur. Ceram. Soc.*, vol. 40, no. 13, pp. 4403–4418, Oct. 2020.

[23] Z. Pan, F. Qiao, M. Wang, Z. Wu, and Z. Ying, “A novel damage mechanism analysis of integrally braided CFRP and CFRP/Aluminum hybrid composite tube subjected to transverse impact,” *Mater. Des.*, vol. 206, Aug. 2021.

[24] Z. Wu, L. Shi, Z. Pan, Z. Xiang, and Y. Yuan, “Damage assessment of braided composite tube subjected to repeated transverse impact,” *Thin-Walled Struct.*, vol. 156, Nov. 2020.

[25] Z. Wu, H. Ding, Z. Ying, Y. Yuan, and X. Hu, “Influence of braided fabric on the fracture modes of a composite tube under quasi-static compression,” *J. Reinf. Plast. Compos.*, vol. 36, no. 10, pp. 766–779, 2017.

[26] J. S. Tate, A. D. Kelkar, and J. D. Whitcomb, “Effect of braid angle on fatigue performance of biaxial braided composites,” Int. J. Fatigue, vol. 28, no. 10 SPEC. ISS., pp. 1239–1247, 2006.

[27] F. Hasanalizadeh, and H. Dabiryan, “A New Approach to Characterize the Low-Velocity Impact Behavior of Sandwich-Structured Composite Reinforced with Weft-Knitted Spacer Fabric,” *Journal of Textiles and Polymers*, Vol. 10, No. 3, 35-41, July 2022.