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Biaxial tubular hybrid braided structures with supreme tensile performance: Experimental and statistical assessments

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ABSTRACT

Biaxial tubular braided structures are increasingly being recognized as superior alternatives to traditional materials in structural engineering due to their enhanced tensile properties and durability. In this study, the mechanical characteristics of these structures are examined, focusing on the influence of braiding angle, yarn hybridization, and layer configurations on tensile behavior. Sixteen diverse specimens, crafted from polyester and basalt yarns using a 32-carrier vertical braiding machine, are explored, incorporating variations across four braiding angles, three hybridizations, and both single and dual-layer setups. Each specimen underwent rigorous uniaxial tensile testing, revealing critical insights into the relationships between structural configuration and mechanical performance. It was found that increasing the braiding angle significantly enhances elongation, strain, and energy absorption capacities. Additionally, a higher basalt yarn content was observed to amplify tensile strength, suggesting potential for tailored structural optimization. Notably, dual-layer configurations were found to outperform single layers in tensile efficiency, underscoring the advantage of layered designs in engineering applications. A significant gap in current literature is filled by this study, as a detailed analysis of biaxial tubular hybrid braids is provided, paving the way for their informed application in advanced composite structures.

1. Introduction

Nowadays the use of fiber-reinforced composite materials especially braided composites has increased significantly in different industries. Different types of these materials suggest several advantages over conventional engineering metals such as high strength-to-weight ratio, high durability, stiffness, damping property, flexural strength, and resistance to corrosion, wear, impact, and fire. It should be mentioned that these properties are due to the properties of the reinforcing material in a composite, i.e. braided structure. Therefore, knowing the mechanical properties of a braided structure such as tensile properties is a critical and vital issue [1].

Braiding is a promising method to form continuous fiber-reinforced composite materials that nowadays is very common. Different braided structure types including biaxial and triaxial, with or without core yarn in single or multi-layer shapes are used as the fiber-reinforced materials in a composite structure [1]. A biaxial braided structure is a structure that is formed by two sets of yarns running in opposite directions [2,3].

According to Fig. 1, nowadays these structures are used in a broad range of applications including, but not limited to, medical, sports, and automotive. One of the most important and most usable applications of tubular braided structures in medical applications is used as a pylon in lower limb prosthetics. This expensive and difficult-to-be-available part is usually made from titanium, aluminum, or steel. Therefore, the utilization of a tubular fiber-reinforced composite can be a suitable alternative to this structure. Although tubular braided structures in different forms can be used as three main parts of a lower limb anatomical consists of the thigh, the leg, and the foot [4,5]. Moreover, braided structures are used in construction and building materials such as concrete, arches, and beams [6–8]. For example, Mutlu Kurban et al. used a braided structure to obtain textile-reinforced concretes as a new construction material for increasing the flexural strength and toughness of the reinforcement materials [6]. In recent years, fiber-reinforced polymers have also shown the potential to replace conventional internal steel rebars in the concrete reinforcement because of performance benefits related to their advanced properties, such as corrosion resistance, high tensile strength, etc. [8].

Over the years, researchers have then made efforts to understand

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braided structures' behaviours. For instance, Branchweiler showed that the braiding angle (θ), which is the angle between the longitudinal direction of the braid and the deposited fibres, is a critical parameter that describes the geometry of a braided structure and determines its mechanical properties [9]. Different studies demonstrated that by increasing the braiding angle, the tensile properties of a braid structure will change [10]. Omeroglu investigated the biaxial braided structures produced by polypropylene yarns and found that a proportional increase in the braiding angle can delay the plastic deformation in the braided structure [11]. Dabiryan and Johari evaluated the energy method on the tensile properties of tubular braided structures. They observed that jamming state, a situation in which there is no more space to move the yarns in a braid, affects the tensile properties [12].

Boris et al. [13] investigated the tensile properties of biaxial and triaxial braided structures and figured out that not only does the triaxial braided structure have better tensile properties than the biaxial ones but also the tensile properties of biaxial and triaxial braided structures decrease by increasing the braiding angle from 13 ° to 20 °. Zhang Yujing et al. [14] showed that fluctuating amplitude of the stress distributions in a braided structure is directly dependent on the tensile load of yarns in a braided structure. Using of yarns' combination is another parameter that can affect the tensile properties of the braided structure. Therefore, the use of yarns with higher tensile properties in the braided structure will increase the tensile properties of the braided structure [15,16]. Nowadays, braided structures can be used as a reinforcement in composite materials. Therefore, there are studies about different behaviours of braided composites [17–19]. In all the mentioned studies, the use of fibers with different properties and the same linear density in the

Fig. 1. The applications of biaxial tubular braided structures.

production of biaxial hybrid braids and the use of fibers with different properties and various linear density in the production of triaxial hybrid braids with different fibers in the braid and core have been done. Supposedly, there are lack of sufficient studies on biaxial hybrid ones with different fibers included the various linear density. Ghamkhar et al. [20] investigated the experimental and theoretical tensile modulus of hybrid braided structures. They found that an increase in the braiding angle and the amount of a high-functional yarn leads to a decrease and increase in the tensile modulus, respectively. Moreover, the proposed theoretical model to estimate the tensile modulus in this work was in good agreement with the experimental results. Ghamkhar et al. [21] investigated the tensile modulus of the biaxial and triaxial braided structures in another study and provided a method to predict the tensile modulus of these structures. The braided structures in two mentioned studies were single layer. Saraswat et al. [22] investigated the tensile properties of some multi-layered braided structures which are formed as a result of over-braiding the previously formed braids at the combinations from two different braiding angle 30° and 45° in the inner and outer layers. This work showed that the braid angle in the outer layer has significantly been affected the stress-strain behavior and proposed a simple model for predicting the tensile behavior. A good agreement was observed between the theoretical and experimental values of braid angle, toughness, and stress–strain characteristics of multi-layered braided structures. In the last two years, the use of braided composites has grown to achieve the behavioral performance of composites enhancement. In this regard, Li et al. study used braided structures in composites in order to achieve flexural performance enhancement. They observed increasing flexural strength and effectively restricting the development of cracks [23]. Also, Cai et al. represented that using a braided glued laminated bamboo composite in the construction industry not only has better impact resistance and secondary load capacity but also is a new design idea to help the development the engineering materials [24]. Moreover, Abedi et al. for the first time, devoted the different capabilities including reinforcing, self-sensing, and self-heating to a planar braided composite. They claim that it can be a key step for intelligent cities' advances [25].

The aim of this paper is to rigorously investigate the impact of several braiding parameters—specifically, the braiding angle, yarn combination, number of layers, and carriers' arrangement—on the tensile properties of tubular hybrid biaxial braided structures. This study uniquely evaluates the interplay of these parameters using basalt and polyester yarns, which are known for their distinct tensile properties, to determine the most influential factors in optimizing tensile performance. Notably, this is the second exploration of the tensile properties of biaxial tubular hybrid braids with varied functional yarns in our series of studies, building upon the foundational experimental and theoretical analysis of tensile modulus presented previously [20].

Braided structures, increasingly utilized across diverse industries—from reinforcing composite materials as alternatives to traditional metals to innovative applications in biomedical tissues—demand a thorough understanding of their mechanical behaviors to enhance design reliability and cost-efficiency. The findings from this research are expected to advance the current understanding of hybrid braids' mechanical properties, offering vital insights that could drive innovation in the design and application of these complex materials. This study not only fills a crucial gap by providing comprehensive data on the multifaceted impacts of braiding parameters but also sets the stage for future research in the braided structure development.

2. Materials and methods

2.1. Fabrication of braided structures

To achieve the primary purpose of this study, that is an experimental investigation of the tensile behavior of biaxial hybrid braided structures, the twistless multifilament polyester and basalt yarns were used to fabricate braided specimens. The used polyester and basalt yarns were with a count of 2300 and 7000 denier, respectively. Two-dimensional single-layer and two-layer biaxial tubular braid structures were produced according to Table 1 on a 32-carrier vertical braiding machine.

It should be noticed that denier is a weight-per-unit-length measure of any linear material. Officially, it is the number of unit weights of 0.05 g per 450-meter length. This is numerically equal to the weight in grams of 9000 m of the material. Denier is a direct numbering system in which the lower numbers represent the finer sizes and the higher numbers the coarser sizes. In the U.S., the denier system is used for numbering filament yarns, manufactured fiber staples, and tow. In most countries outside the U.S., the denier system has been replaced by the tex system [2]. Also, the produced braided specimens shown in Fig. 2 are divided into three groups in terms of appearance due to the three kinds of hybridizations.

As can be seen in Table 1, a two-part code is assigned to each braided specimen. The first part shows the braiding angle and includes 28, 33, 37, and 40 degrees. The second part represents the number of layers, hybridization of yarns, and arrangements of each layer. This part has two letters and a number. The first and second letter belongs to the inner layer arrangement and outer layer arrangement, respectively. The letters N, G, and R show single-layer structure, group arrangements of a layer which means first all the basalts and then all of the polyesters, and repetition arrangements which means some basalt carriers and 1 polyester carrier with some repetitions, respectively. Number 1 in part two shows 4 basalt and 28 polyester yarns in a layer that carriers placement in this case in repetition arrangement will 1 basalt and 7 polyesters with 4 repetitions (Fig. 2.a), number 2 shows 16 basalt and 16 polyester yarns in a layer that its repetition arrangement is one by one (Fig. 2.b), and number 3 shows 28 basalt and 4 polyester yarns in a layer of braided structure that repetition arrangement is opposite to number 1 and is 7 basalts and 1 polyester with 4 repetitions (Fig. 2.c). Braided specimens with different braid angles were produced by changing the ratio of angular speed of carriers to the take-up speed of the braiding machine. The sample selection was done so that the each of parameters' effects (braiding angle, hybrid, number of layers, and type of arrangement) can be investigated.

Fig. 3 shows a schematic of how to produce the single-layer and two-layer samples with 28 basalt carriers and 4 polyester carriers and their carrier arrangements. Basalts and Polyester carriers in Fig. 3 are shown with brown and white, respectively. As shown in Fig. 3(a), for producing a two-layer braid, a single-layer braid should be produced at first on the braiding machine. Then, the produced single- layer braid enters the braiding machine as a core, and the second layer is produced on the first layer. Therefore, a single-layer and a two-layer braid have one step production and two-step production, respectively. Although to show the schematic for the two kinds used carrier's arrangements namely grouping and repetition, to figure clarity and suitable understanding from the figure, a 16-carrier braiding machine is depicted in Fig. 3(b). As can be seen, in the grouping arrangement all a group of yarns are placed on the carries side by side at first then, the other group. In other words, all polyester and all basalt are together. While the repetition arrangement is different. It depends on the number of each yarn type, and it is placed one yarn beside the other group of yarns. For example, for 4 polyester yarns and 28 basalt yarns in grouping arrangement 4 polyester yarns are placed on the braiding machine's carries side by side at first then, 28 basalt yarns. In the repetition arrangement, 1 polyester and 7 basalt yarn carries are placed on the braiding machine's carriers, and it is repeated 3 more times.

2.2. Tensile test for determining the tensile properties of the braided structures

To determine the tensile properties of the braided samples, uniaxial tensile testing was performed using Bullard clamps on the 15-ton capacity SANTAM tensile testing machine shown in Fig. 4. The uniaxial tensile test was carried out at 25 ± 2 temperatures °C and 65 ± 5 %

Table 1
Specifications of the tubular biaxial braided structures.

Sample Code	Braiding Angle (°)	Number of layers	The number of basalt carriers of each layer	The number of polyester carriers of each layer	Carriers Arrangement of the inner layer	Carriers Arrangement of the outer layer
28-NG1	28	1	4	28	-	Group
33-NG1	33	1	4	28	-	Group
37-NG1	37	1	4	28	-	Group
40-NG1	40	1	4	28	-	Group
28-NG2	28	1	16	16	-	Group
33-NG2	33	1	16	16	-	Group
37-NG2	37	1	16	16	-	Group
40-NG2	40	1	16	16	-	Group
28-NG3	28	1	28	4	-	Group
33-NG3	33	1	28	4	-	Group
37-NG3	37	1	28	4	-	Group
40-GG3	40	2	28	4	Group	Group
40-GR3	40	2	28	4	Group	Repetition
40-RG3	40	2	28	4	Repetition	Group
40-RR3	40	2	28	4	Repetition	Repetition

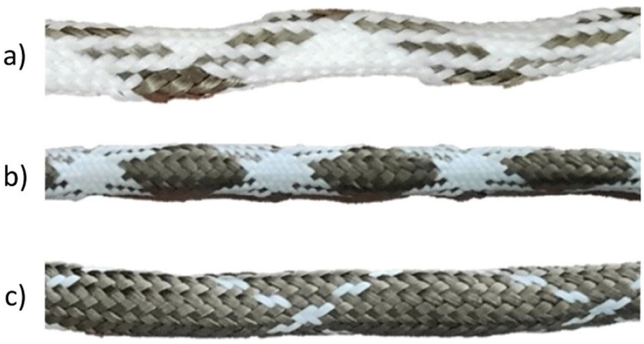

Fig. 2. Three main group of produced braided specimens. a)1: 4 bazalts and 28 polyesters, b)2: 16 bazalts and 16 polyesters, c)3: 28 bazalts and 4 polyesters.

relative and humidity. The test speed and the gauge length were 75 mm/min and 250 mm, respectively. This is carried out according to the standard ISO 2062. braid

Bllard clamps are used today to perform the tensile test of braids because the jaws that were used before them had some defects. For example, a very high percentage of braids break at the point of contact with the jaws which prevents an acceptable comparison of the force of the braids. The other is increasing the percentage of the braid breaking by increasing the pressure between the two jaws to increase friction and prevent the braid from sliding. These two defects were the most important reasons to design suitable jaws. The design and use of Bllard clamps, not only deleted the mentioned defects but also eliminated the human factor in controlling the pressure intensity between the jaws, prevented the slip of the braid samples in the place of the jaws, and recognized the actual length of the braided structure at the moment of rupture [6].

Each braided specimen was tested in 5 repetitions, and the mean values of 5 measurements from each tensile property were reported as the final value. A total of 80 specimens were tested.

3. Results and discussion

Experimental and statistical investigations of the samples help to evaluate the samples to optimize ones and then use them in biomedical composites and prostheses, such as the pylons in the lower limbs. To investigate the effect of different braid parameters on tensile properties the samples were divided into some different comparable groups. The classification of the samples and the parameters to be compared in each group are listed in Table 2.

3.1. *Investigating the tensile behavior of the tubular braided structures*

The result of each tensile test and force-extension curve according to Fig. 5(a) are accessible for any specimen, separately. As mentioned in the last paragraph of Section 2 the mean value result of 5 repetitions will be compared. For a better analysis of tensile properties and understanding of the tensile modulus, the force-elongation curve should be turned into the stress-strain curve (Fig. 5(b)).

As can be seen in Fig. 5, the behavior of a tubular hybrid biaxial braided structure under a uniaxial tensile test can be expressed as follows:

At first, no force is applied to the braid, so there is no value for the braid’s stress or strain. By gradually applying the tensile force to the braid, the elongation increase also occurs in this structure. Point S is the start of applying force to the braid and causing elongation, because of which the force-elongation and stress-strain curves begin to move away from the axes. This curve continues with a very low constant slope up to point S and suddenly the slope of the curve increases at this point. The reason for this is that at the beginning of applying tensile force to the braided structure, the direction of the yarns in the structure changes. Therefore, the slope in this part is very low. The geometry of the braid changes due to the change in the direction of the yarns until the jamming condition is reached, so that at the jamming moment, the most geometrical changes have occurred in the braid structure. By passing this point and applying more tensile force, the yarns forming the braid will be stretched, bent, and compressed. This causes the elastic modulus to increase. The dashed line marked in Fig. 5(b) defines the jamming point. The value of the slope on the left side of this dashed line is indicated by α, which represents the initial modulus. As it was said, the initial modulus (E1) is the slope of the first linear region in the stress-strain curve, which is affected by the geometric changes in the braid structure due to the change in the direction of the yarns. After reaching the jamming, by increasing the force again, the slope is fixed so that a tensile in the braid structure occurs due to the increase of force at point B. In the case of single-layer braids, this part has several peaks due to the occurrence of multiple tears, but there is one point as the peak of the tear force in this diagram, which is point B. This is discussed in another study [20]. In this part of the diagram, the properties of yarns are important. The value of the slope of the graph on the right side of the dashed line marked in Fig. 5(b), which is indicated by β, is called the secondary modulus or the effective modulus. The secondary modulus or the effective modulus (E2) is the slope of the second linear region in the stress-strain diagram, which is affected by the mechanical properties of the threads and the structural parameters of the rib and determines the final use of a rib structure. Therefore, after tearing at point B, a sudden drop in force occurs in the braid structure (point Q) because of the yarn tearing. This leads to break up the structure temporarily which can still

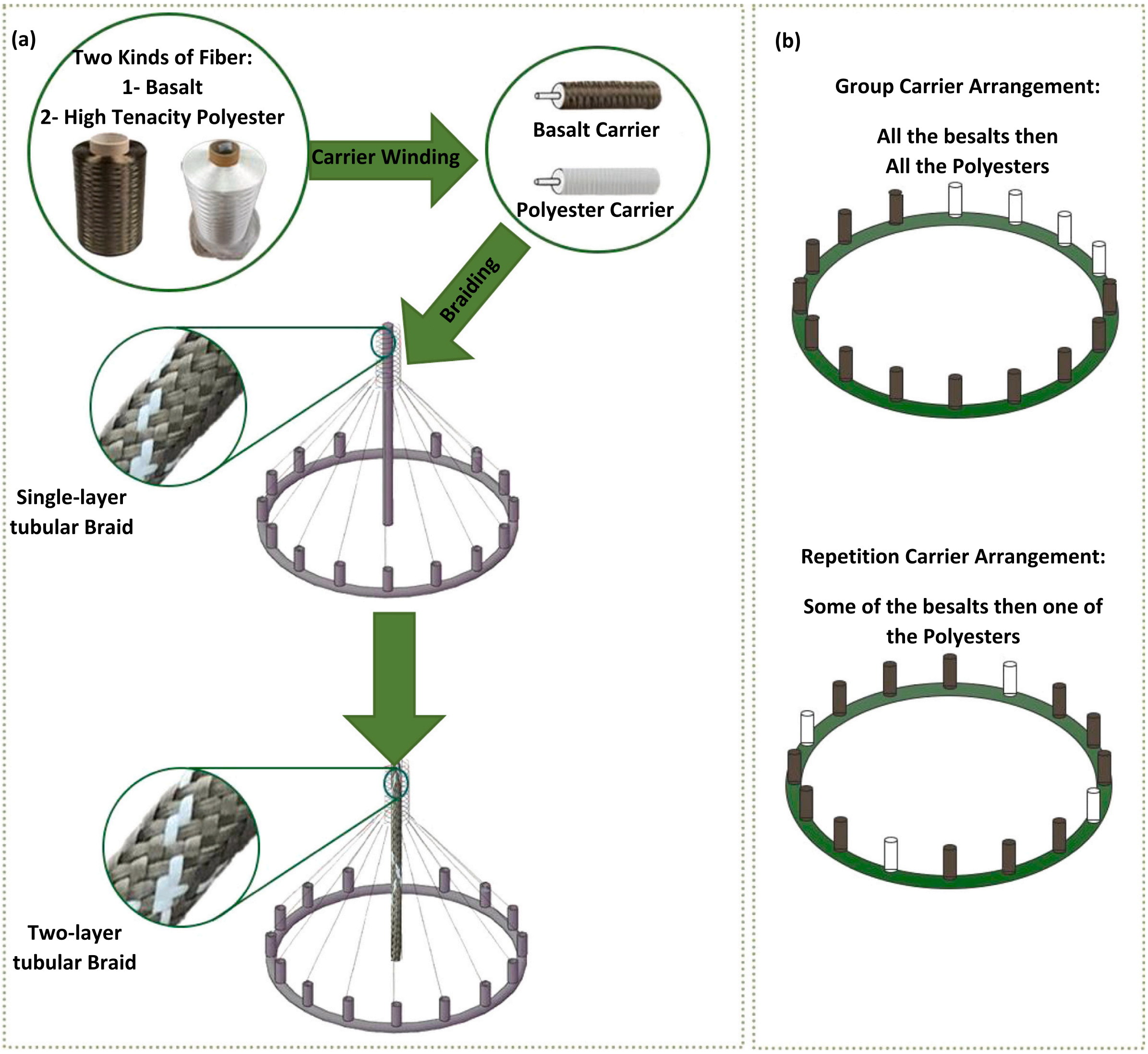

Fig. 3. The schematics: a) How to produce a single layer and two-layer examined samples, b) Two carrier arrangements for the samples consisting of grouping and repetition.

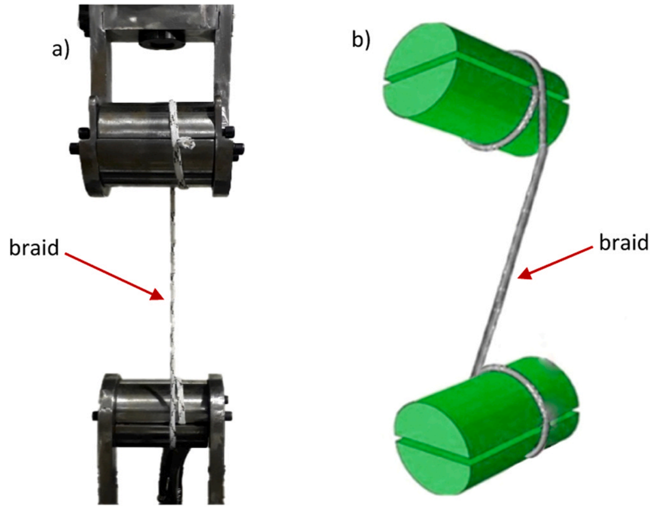

Fig. 4. Tensile test of braid structure, (a) a clamped braided specimen in the Bllard clamps on the SANTAM tensile testing machine, (b) schematic of how to pass a braid through a Bllard clamp.

Table 2
Classifications of samples for comparison.

Group	Sample Code	Comparative parameters	Factors
1	28-NG1 33-NG1 37-NG1 40-NG1 28-NG2 33-NG2 37-NG2 40-NG2 28-NG3 33-NG3 37-NG3 40-NG3	Hybridization from Polyester/ Bazalt ratio: 87.5/12.5,50/50, 12.5/87.5 Braid angle: 28,33,37,40	Hybridization from Polyester/Bazalt ratio Braid angle
2	40-NG3 40-GG3	Number of layers: Single layer, Two-layer	Number of layers
3	40-GG3 40-GR3 40-RG3 40-RR3	Carriers Arrangements: Group, Repetition	Carriers Arrangements

According to Table 2, It is expected that the 12 samples of group 1 will have the same results in examining the effect of braiding angle and hybridization.

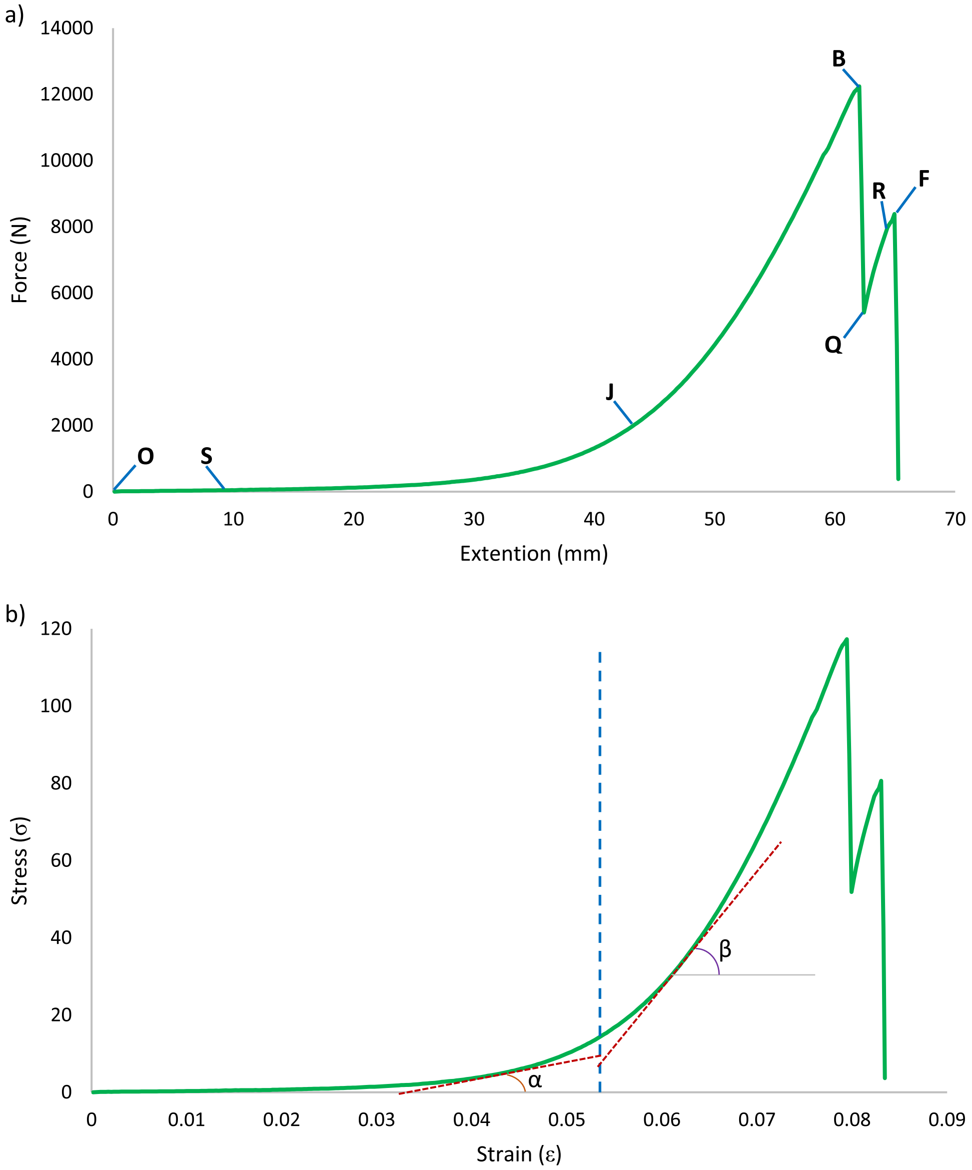

Fig. 5. a) The force-elongation curve for a biaxial hybrid braided sample containing 32 carriers. b) The stress-strain curve for a biaxial hybrid braided sample containing 32 carriers.

resist the tensile force and failure with the help of other healthy yarns that have no rupture. In other words, point Q is the reconstruction point with new conditions where the braided structure regenerates itself. It is due to the presence of more resistant yarns or other layers that prevent the complete tear of the braid, the slope increases again with the value Beta occurs and the braid travels along the QR path with a constant slope. There is a bit of slope change in point R due to the rupture of the yarn bunch tearing. Almost all the yarns' threads except for one or two yarns are torn at this point, which are also torn in a very short time, and the braided structure fails at point F. As mentioned, the path of RF is followed until reaching the final failure of the braid, and the braid structure is completely broken at point F. Therefore, the tensile behavior of this structure can be divided into different areas in the force-elongation curve or stress-strain curve like the other studies such as Brunnschweiler or Boris studies [6,10]. These arears are explained as follows:

1. OS: In this part, the force applied to the braided structure is zero.
2. SJ: The part of the curve that starts to separate from the zero force axis and continues until the jamming condition.
3. JB: The linear part of the curve until the break happens along which Young's modulus is constant. This part can continue with some breaking points.
4. QR: The linear part of the curve until the failure happens along which Young's modulus is constant similar to JB.
5. RF: The final short and flat part of the curve that goes towards the failure point. It should be noted that this part is usually very small and is ignored.

3.2. The experimental investigation of the different parameters on tensile behavior of the braided structures

A material's behavior is described using mechanical characteristics such as Young's modulus, fatigue limit, viscosity, shear modulus malleability, compressibility, and bulk modulus. Uniaxial tensile behavior is one of the most important mechanical characteristics describing a material's behavior under actual tensile behavior and mechanical stress [26]. To investigate the experimental parameters on the tensile behavior of the braided structures, the results of the tensile characteristics for the braided specimens are shown in Fig. 6. The

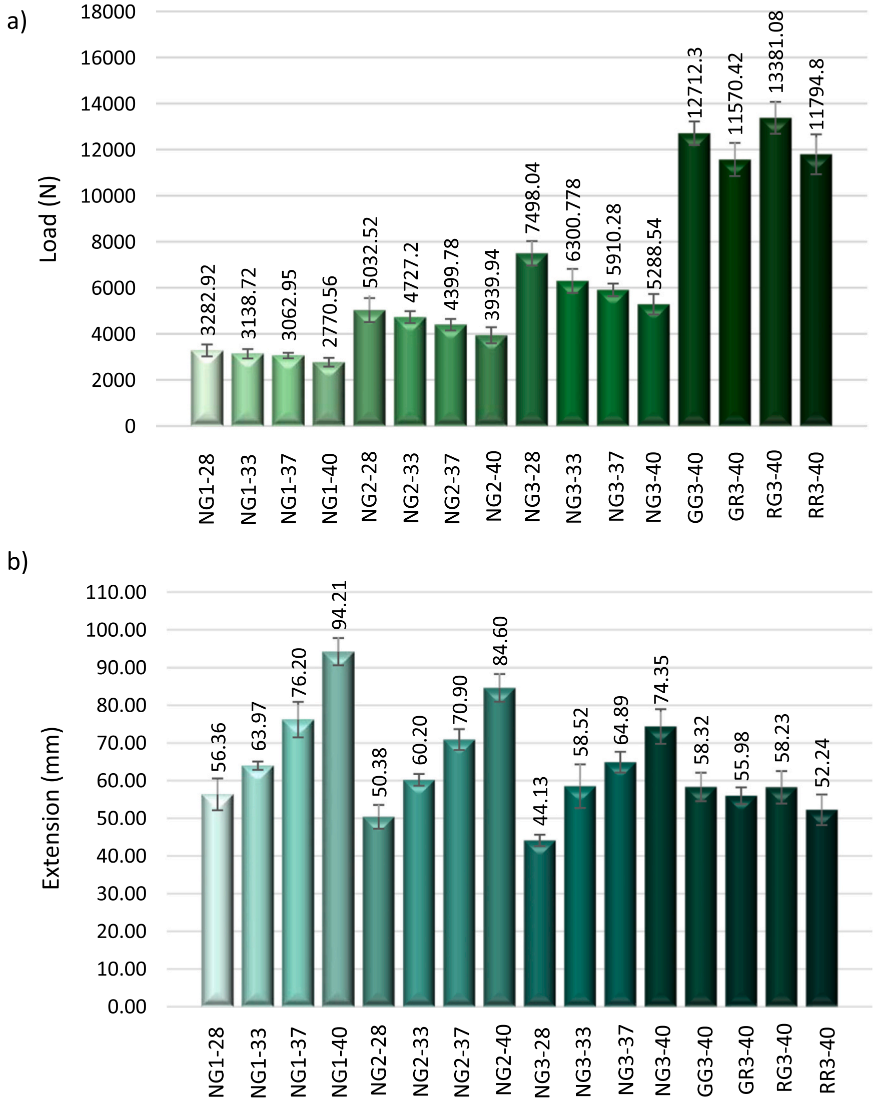

Fig. 6. The results of (a) The ultimate tensile load. (b) Tensile extension. (c) Tensile elongation. (d) Tensile energy.

ultimate tensile loading, the tensile extension, the tensile elongation, and the tensile energy are present in Fig. 6(a), (b), (c), and (d), respectively. These parameters are reported by the device during the tensile test. For example, the ultimate tensile is the point B in Fig. 5(a).

It should be noted that the most important tensile parameters to investigate a structure include tensile stress, tensile strain, and tensile modulus. Therefore, investigating the tensile properties of biaxial hybrid braided structures needs to determine these three parameters. It is enough to calculate the slope of the linear region of the stress-strain diagram to determine the experimental elastic modulus. Therefore, the force-elongation diagram obtained from tests done experimentally should convert into a stress-strain diagram.

Since the braid structures are complex, therefore it is impossible to determine accurately and experimentally the effective cross-sectional area of a braided structure, and the engineering stress values are calculated by dividing the force values by the linear density of the braid structure in terms of the Tex unit. The value of a linear density in terms of Tex is the weight in grams of 1000 m from the material. On the other hand, the cross-sectional area of a braided structure changes during tension, and this causes a difference in the braiding angle and strain values. Therefore, it is necessary to convert the engineering stress and strain values into true values using Eqs. (1) and (2), respectively.

$$\sigma_T = \left(\frac{F}{L_D}\right) * \left(\varepsilon + 1\right) \tag{1}$$

$$\varepsilon_T = \ln(\varepsilon + 1) \tag{2}$$

In these equations, σ_T, ε_T, F, L_D, ε are true stress, true strain, force in terms of cN, linear density in terms of Tex, and strain, respectively.

Fig. 7 shows the result of the three most important tensile parameters that are true stress, true strain, and true modulus that they are in terms of centi-newton(cN) per Tex, percentage (%), and centi-newton(cN) per Tex, respectively.

3.2.1. *Effect of Breading Angle and Hebraization on the single layer braided structures*

As can be seen in Fig. 6, in general, an increase in braiding angle leads to a decrease in the tensile load. On the other side, it increases extension, elongation, and energy. The reason is that the distance from the braiding axis increases by increasing the braiding angle and requires less tensile force and more extension, elongation, and energy for failure. While an increase in the number of basalt carriers causes an increase in the tensile load and energy and a decrease in the extension and elongation of the braided specimens, respectively. It is necessary to mention

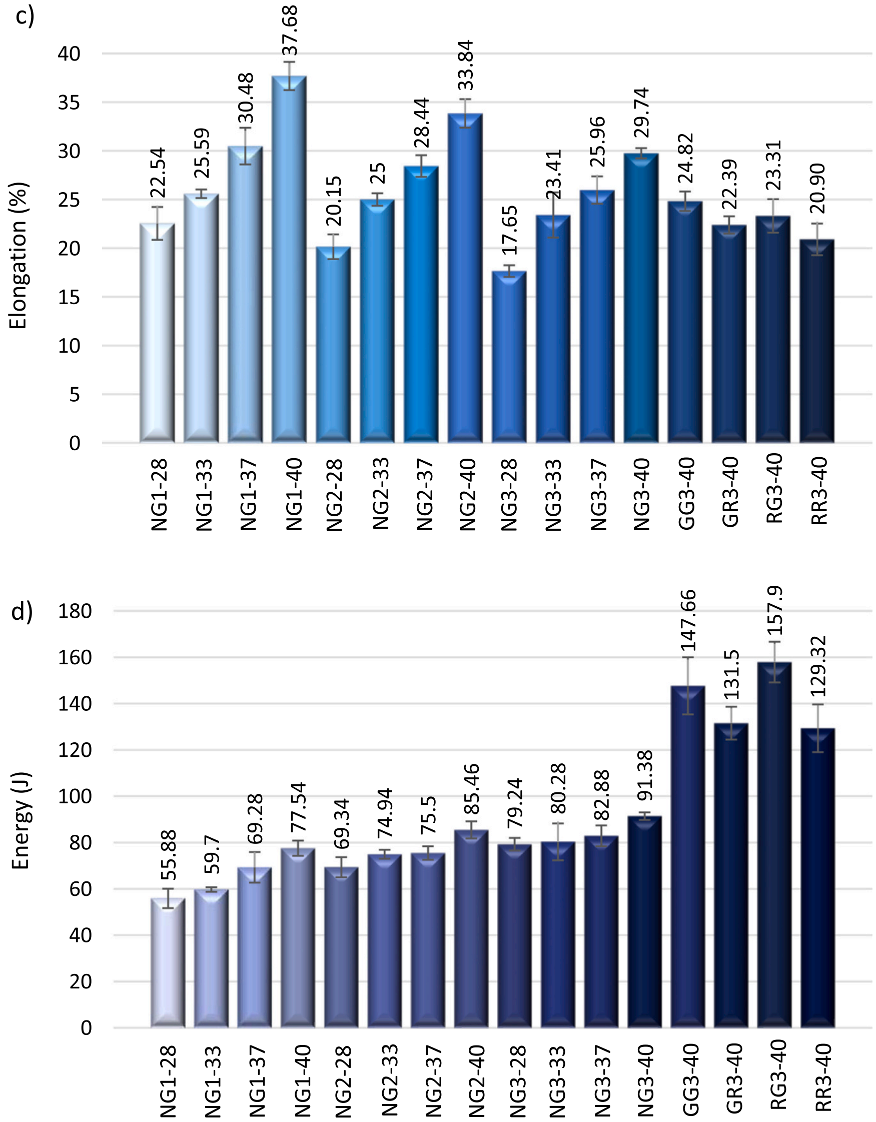

Fig. 6. (*continued*).

that basalt yarn has a higher tensile load than polyester yarn. Therefore, it is clear that an increase in the number of basalt yarn in the tubular hybrid braided structures leads to an increase in the tensile load and energy. On the other side, the polyester yarn has a higher extension than basalt yarn, then the braided structure with a higher amount of basalt will have no high extension and elongation. Moreover, as can be seen in Fig. 7, there is a direct relation between true tensile stress, tensile modulus, and braiding angle, while there is an indirect relation between the true tensile strain and the braiding angle. It means that the increment in the braiding angle leads to an increase in the true tensile stress and tensile modulus and a decrease in true tensile strain. Basalt is a high-function fibre because of its properties such as high tensile load, high modulus, high energy, and low elongation. Obviously, an increase in the number of basalt carriers leads to an increase in the true tensile stress and tensile modulus. On the other hand, this causes a decrease in the true tensile strain.

3.2.2. *Effect of number of layers*

As can be observed in Figs. 6 and 7, two-layer braided structures have more tensile load and energy, and much more tensile stress and tensile modulus than single-layer ones in a same braiding angle. However, two-layer braided structures endure less elongation, extension, and true strain than single-layer braided structures. They are acceptable because of fibres used to produce the braided structures. The results show that in cases where a small increase in elongation, extension, or strain is needed, it can be achieved by using single-layer braids. But in cases where high tensile loads, energy, tensile stress, or tensile modulus are needed, the use of two-layer braided structures can be very ideal and favourable.

3.2.3. *Effect of arrangements or placement type of carriers on two-layers braided structures*

As can be found in Figs. 6 and 7, the most and the least values of tensile properties belong to GG or RG samples and RR or GR samples, respectively. The two-layer braided structures with the same internal structures regardless of the type arrangement grouped or repetition show the results close to each other. Also, the two-layer braided structures with similar external structures and the grouped internal structure have more values. Moreover, similar values in extension, elongation, and strain in two-layer braids can be obtained in single-layer ones at different braiding angles.

3.3. *The statistical investigation on the tensile behaviour of the braided structures*

Statistics is a crucial process behind how we make discoveries in

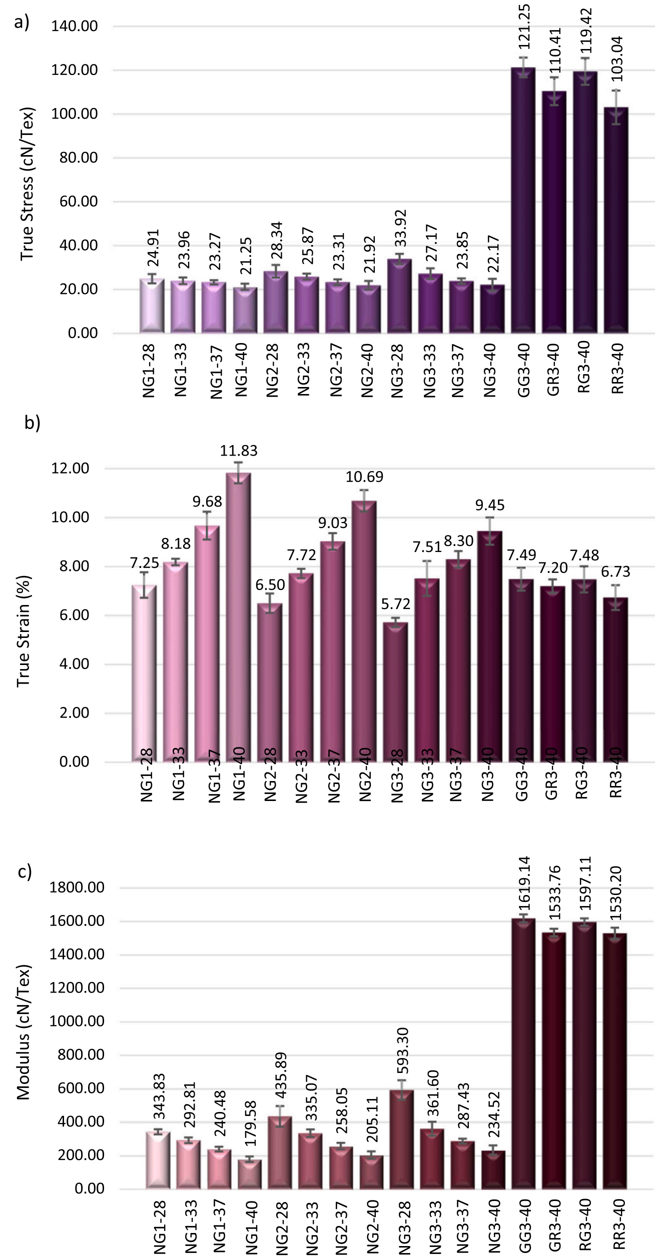

Fig. 7. The three most important tensile parameters. (a) True tensile stress. (b) True tensile strain. (c) True Tensile modulus.

science, make decisions based on data, and make predictions. Therefore, ranking the samples to determine their tensile function is necessary in this step. Given that the tensile modulus is affected by all the tensile properties a one-way analysis of variance with a 95 % confidence level is performed for the experimental results of tensile modulus. Then, assortment and grouping the tensile modulus based on the calculated main parameters using an SNK method. The results of the statistical analysis are listed in Table 3 to Table 6. This statistical analysis determines whether there is a significant difference between the variables. Although the one-way analysis of variance with a 95 % confidence level can be performed on all the properties separately. Therefore, this statistical analysis can be used on all tensile properties of the braided structures.

The statistical results illustrated in Table 3 indicate that the braiding angle, the hybridization, and layer arrangement (number of layers and carriers' arrangements) have a significant difference in the tensile modulus and at least one group is different from the other groups of each of these parameters. The tabulated results in Table 4 to Table 6 indicate the braiding angles cause the tensile test results of the specimens to have no full overlap with each other. Also, the hybrids and the layer arrangement used to produce the braided structures have no full overlap with each other and they are grouped in more than one group. All these parameters are statistically significant.

Table 3
The one-way analysis of variance with a 95 % confidence level for the tubular biaxial braided structures.

Source	Df	Some of Squares	Mean Square	F
Braiding angle	3	476422.525	158807.508	17.974
Hybrid	2	230001.157	115000.578	13.016
Layer Arrangement	4	7064235.189	1766058.797	199.886
Braiding angle* Hybrid	6	53545.242	8924.207	1.010
Braiding angle*Layer Arrangement	0	.000		
Hybrid*Layer Arrangement	0	.000		
Braiding angle*Hybrid*Layer Arrangement	0	.000		
Error	64	565460.669		
Total	79	27010073.35		

As said before, to evaluate the performance of the braiding angle, hybridization, and layer arrangement parameters more accurately on the tensile properties of the hybrid braided structures, it is necessary to rank them. Therefore, the statistical analysis was continued by grouping the specimens with the SNK method for all tensile properties to ranking the braided structures according to their tensile performance. The obtained results are listed as follows:

Tensile Loading: 40-NG1,37-NG1,33-NG1,28-NG1<40-NG2,37-NG2<37-NG2,33-NG2,28-NG2<33-NG2, 28-NG2,40-NG3<37-NG3,33-NG3<28-NG3<40-GR3,40-RR3<40-GG3,40-RG3

Tensile Extension: 28-NG3<28-NG2,40-RR3,40-GR3,28-NG1<40-RR3,40-GR3,28-NG1,40-RG3,40-GG3,33-NG3<40-GR3,28-NG1, 40-RG3,40-GG3,33-NG3,33-NG2<40-RG3,40-GG3,33-NG3,33-NG2, 33-NG1,37-NG3<37-NG2,40-NG3, 37-NG1<40-NG2<40-NG1

Tensile Elongation: 28-NG3<28-NG2,40-RR3<40-RR3,40-GR3,28-NG1,40-RG3,33-NG3<40-GR3,28-NG1, 40-RG3,33-NG3,40-GG3,33-NG2<40-RG3,33-NG3,40-GG3,33-NG2,33-NG1<40-GG3,33-NG2, 33-NG1,37-NG3<37-NG2,40-NG3, 37-NG1<40-NG2<40-NG1

Tensile Energy: 28-NG1, 33-NG1<33-NG1,37-NG1,28-NG2<37-NG1, 28-NG2,33-NG2,37-NG2,28-NG3< 28-NG2,33-NG2,37-NG2,28-NG3,33-NG3< 33-NG2,37-NG2,28-NG3,33-NG3,37-NG3,40-NG2,40-NG1<40-NG2, 40-NG1,40-NG3<40-RR3, 40-GR3<40-GG3, 40-RG3

True Tensile Stress: 40-NG2, 40-NG1, 37-NG1,37-NG2, 33-NG1,37-NG3,28-NG1,33-NG2,28-NG2,40-NG3<37-NG1,37-NG2,33-NG1,37-NG3,28-NG1,33-NG2,28-NG2,40-NG3,33-NG3,28-NG3<40-GR3,40-RR3<40-GG3, 40-RG3

True Tensile Strain: 28-NG3, 28-NG2,28-NG1,33-NG3,33-NG2, 33-NG1,37-NG3,37-NG2,40-NG3,37-NG1,40-NG2, 40-NG1<40-RR3<40-GR3, 40-RG3,40-GG3

Tensile Modulus: 40-NG1,40-NG2, 37-NG1,7,37-NG3, 33-NG1,40-NG3,33-NG2,28-NG1<7,37-NG3,33-NG1,40-NG3,33-NG2,28-NG1,28-NG2<37-NG3,33-NG1,40-NG3,33-NG2,28-NG1,28-NG2,33-NG3<28-NG3<40-GR3,40-GG3, 40-RR3<40-GG3, 40-RR3, 40-RG3

Table 4
Grouping the tensile modulus based on the braiding angle.

Braiding angle	N	1	2	3	4
37	15	263.8197			
33	15		358.3487		
28	15			458.8996	
40	35				1032.3376

Table 5
Grouping the tensile modulus based on the hybrid.

Hybrid	N	1	2
1	20	264.4326	
2	20	307.1267	
3	40		1022.9162

Table 6
Grouping the tensile modulus based on the layer arrengements.

layer arrengements	N	1	2	3
1	60	327.7889		
2	5		1531.7507	
3	5		1622.6858	1622.6858
4	5			1667.0796
5	5			1714.5838

Table 7
Specifications of the tubular biaxial braided structures.

Sample Code	True Tensile Stress	True Tensile Strain	Tensile Modulus	Total	Rank
28-NG1	8	5	9	22	10
33-NG1	7	10	7	24	8
37-NG1	4	14	4	22	10
40-NG1	1	16	1	18	12
28-NG2	11	2	11	24	8
33-NG2	9	9	8	26	6
37-NG2	5	12	5	22	10
40-NG2	2	15	2	19	11
28-NG3	12	1	12	25	7
33-NG3	10	8	10	28	5
37-NG3	6	11	6	23	9
40-GG3	16	7	16	39	1
40-GR3	14	4	14	32	3
40-RG3	15	6	15	36	2
40-RR3	13	3	13	29	4

For a more accurate diagnosis, in the next step, a concession is assigned to each appraised three tensile parameters including true tensile stress, true tensile strain, and tensile modulus to determine the most satisfactory hybrid braided specimen at tensile characteristics. These are tabulated in Table 7.

The assigned scores present that the two-layer braided structures have significantly the highest tensile characteristics. The sample with 40-GG3 code and 40-NG1 code have the highest and lowest tensile characteristics, respectively. Therefore, it can be concluded that the main issue for using fibers in hybrid braided structures, is the design of materials and structures. As can be seen, some of the braided structures samples have the same total score or rank. These structures have the same function. High-functional fibres have a high cost, and they are not proper for use as a braid yarn. Therefore, the changing in the braiding angle, hybridization, and layers arrangement (number of layers and carriers' arrangement) at the same time can lead to the same tensile function of a biaxial hybrid braid structure. In the conditions that the cost of production is important, this issue will be helpful.

4. Conclusion

This study has comprehensively examined the effects of braiding angle, hybridization, and layer arrangement on the tensile properties of tubular biaxial hybrid braided structures. Through experimental and statistical analyses, the influence of these parameters on the mechanical performance of sixteen distinct braided configurations was investigated, each crafted using combinations of polyester and basalt yarns. The findings confirm that both the braiding angle and the presence of basalt fibers significantly modify the tensile load, energy absorption, and modulus of the braided structures, with notable differences observed between single and dual-layer configurations. Specific findings from this study are as follows:

1) Braiding Angle and Material Effects: Increasing the braiding angle consistently resulted in decreased tensile load but increased tensile energy, true stress, and modulus, particularly when basalt fibers were used. The presence of basalt, known for its superior mechanical strength compared to polyester, prominently enhanced the tensile properties of the braids.
2) Elongation and Strain: Correspondingly, a higher braiding angle and the inclusion of more basalt fibers led to increased elongation and extension, but reduced true strain. This indicates that while braids become more extensible, their ability to withstand deformation without permanent change (strain) decreases.
3) Layer Configuration: Structures with dual layers demonstrated significantly better performance in terms of tensile loading, energy, stress, and modulus compared to their single-layer counterparts. This suggests that multi-layering in hybrid braided structures could be a crucial factor in enhancing mechanical resilience and load-bearing capabilities.
4) Cost-Effectiveness and Material Use: The study also highlighted that modifying the braiding angle in single-layer structures can achieve mechanical properties comparable to those of dual-layer structures, potentially reducing material usage and cost.

These insights underscore the critical influence of structural parameters on the performance of hybrid braided structures and suggest avenues for optimizing design to meet specific mechanical requirements. The detailed understanding of how each parameter affects the mechanical outcomes provides a valuable basis for the engineering of more efficient, cost-effective, and high-performance composite materials suitable for diverse applications, including automotive, aerospace, and biomedical engineering.

CRediT authorship contribution statement

Ghazal Ghamkhar: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Mahdi Bodaghi:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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