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Effect of Twist Level on the Mechanical Performance of S-Glass Yarns and Non-crimp Cross-ply Composites

Abstract

High modulus/high strength continuous fibres are used extensively for manufacturing textile preforms, as a reinforcement, for composites due to their excellent specific properties. However, their brittle behaviour and tendency to separate easily into individual filaments or bundles can lead to damages during manufacturing processes such as weaving and braiding. Thus, the critical step in the development of an optimal yarn for textile-reinforced composites is to find an optimum twist, which results in a minimum loss of properties of the composite laminates, while maintaining good processability and sufficient strength for textile and/or composite manufacturing. In this study, twist level has been varied to improve the handling and mechanical properties of S-glass yarns (i.e. tensile strength). Varying levels of yarn twist (15-40 twists metre^{-1}) were employed to study its impact on the mechanical properties (i.e. tensile strength, modulus, elongation at break etc.). Furthermore, the effect of twist on the mechanical properties of non-crimp cross-ply composites produced via vacuum infusion process was studied. It was observed that mechanical performance (i.e. tensile strength properties) of twisted yarns is improved up to 30 twists metre^{-1} while it is deteriorated at 40 twists metre^{-1}. At yarn level, the experimental results were compared with theoretical estimations utilizing existing models for twisted yarns properties. Discrepancies were observed between experimental and theoretical results especially for high level of twist. The tensile strength and elongation of S-glass cross-ply composites at all levels of twist were higher compared to the composite laminates manufactured by using non-twisted yarns. At composite level, the experimental results were also computed employing rule of mixture and good agreement was observed between experimental and predicted results.

Key words: Twisted yarns, Mechanical properties of yarns, Twist angle, S-glass yarns, Tensile strength of yarns, and Textile reinforcement.

1 Introduction

There is a growing interest in the use of textile structures i.e. woven (2D and 3D), braided, knitted and UD/cross-ply preforms as reinforcement for composites due to their higher stiffness and strength in the through-thickness direction and their potential to mitigate delamination initiation [1, 2]. In cross-ply preform, fibres or plied yarns are positioned alternately in the 0° and 90°orientations as shown in Figure 1. Such an elaborate configuration of layers is required to endure a more complex stress state [3, 4]. Cross-ply composites offer higher resistance to delamination and also present higher compressive strength than woven fabric composites owing to the greatly reduced waviness in the non-crimp cross-ply composites [5].

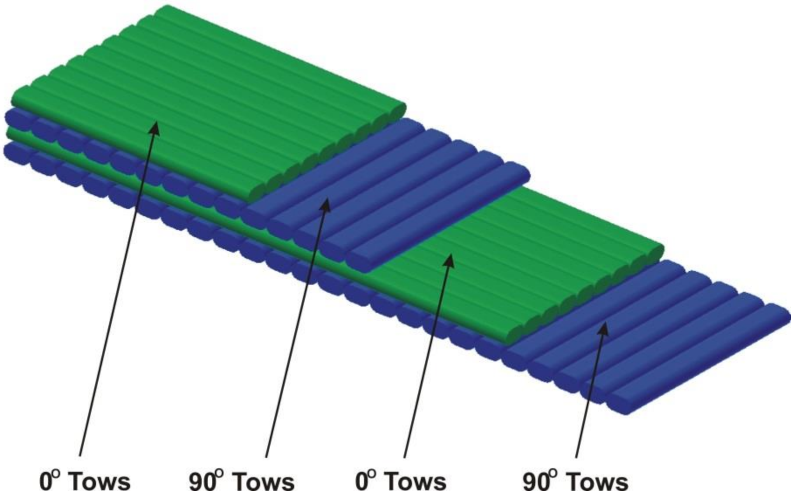

Figure 1 Cross-ply preform structure [4]

Generally, most of the reinforcements for textile composites are made from multifilament yarns with little to no lateral cohesion. These filaments do not possess uniform properties and the strength of the composite is dependent upon the weak spot in the filament i.e. broken filament in strand [6-8]. These assemblies of filaments can separate easily into individual filaments or bundles resulting in damage during manufacturing process [9]. The use of sizing agents is prevalent to enhance the cohesion forces between filaments of brittle strands [10, 11]. However, the resulting properties are not still sufficient enough and the processing cost is higher [12]. Twisting is an important process, which induce lateral cohesion between filaments of twisted yarns and improve their processability during preform fabrication [8, 13], Twisting also help to localise the micro-damages in the yarn [14, 15]. The mechanical properties of yarns (tensile strength and modulus) are also influenced by twisting. In general, the tensile strength and modulus of yarn are increased when the yarn is slightly twisted [16]. However, the strength, stiffness and permeability of yarns can be reduced when higher twist is applied due to the increased difficulties of resin impregnation and fibre obliquity [17-20]. Clearly, the influence of twist can transfer to composite laminates. The tensile strength of high twisted yarn composites is dropped up to 70% when compared to low twist yarn composites [21].

Many inter-dependent structural parameters i.e. single filament diameter d_f, the total yarn diameter d_y, the total number of filaments inside the yarns N, the packing fibre density and geometry inside the yarn cross section; the degree of twist, which can be controlled either by the surface angle θ_s or by the number of twist per specific length T. All these parameters can play role in deciding the properties of yarns during twisting [19]. The addition of twist to the yarns can strongly influence the twist angle and diameter of these yarns [6, 22] and can result in excessive deformation in their cross-section [23]. Hence, the level of twist is an important parameter, which can significantly influence the mechanical properties of the yarns as well as composite laminates and need to be studied carefully to facilitate the manufacturing of textile reinforcements and optimize the mechanical performance of yarns and textile reinforced composite materials.

Many researchers have tried to establish relations of the twist angle with modulus. However, these relations are restricted to application to an embedded fabric in a resin system because the fibre deformation in the matrix is considerably smaller [24]. Additionally, Hearle et al [25] and Morton et al [26] found the ideal helix assumption for twisted yarns is not valid for those textile composites with twisted yarns in which the migration and the micro-buckling are formed during the fabrication process. However, some observations suggested that over short lengths of yam, the ideal helical structure appeared to be a good approximation to reality. Researchers [27-30] have suggested an analytical model for twisted impregnated yarns considering the micro-buckling, migration and twist angle of twisted yarns. Further, Naik et al [31] concluded that the transverse tensile strength of the impregnated twisted yarns has been improved compared to with those of the corresponding impregnated strands.

Several researchers have studied the effect of twist on mechanical performance of yarns, textile reinforced composites [32-34], and their findings have been illustrated that the sufficient mechanical performance of yarns (i.e. tensile strength) can be achieved via applying a certain values of twisting to these yarns. The S-glass yarns have high strength and modulus and are an ideal candidate for aerospace applications [35, 36]. Extensive research work has been published on mechanical properties of textile composites manufactured by incorporating S-glass yarns [37-39]. But literature on effect of twist on mechanical properties (i.e. longitudinal tensile strength) of S-glass yarn and subsequently on composites manufactured by this high strength yarn is scant. As already mentioned, twist level not only facilitate the textile reinforcement manufacturing process by making the yarn uniform but also enhance the mechanical strength of yarn and composites when optimum twist is applied. However, the mechanical properties (i.e. longitudinal tensile strength) of yarns are generally deteriorated beyond an optimum level of twist. So in the present work, S-glass yarns were manufactured with varying twist levels and subsequently cross-ply composites from these yarns. The effect of varying twist at multi-scale i.e. on properties of yarns (strength, modulus, and breaking extension of the yarns) and composite (strength, modulus and strain to failure) was studied to identify the optimum twist levels for enhanced mechanical performance. Theoretical estimations of strength have also been made by utilizing existing yarn models and rule of mixture at yarn and composite levels respectively.

2 Experimental work

2.1 Materials and Yarns preparation

In this study, S-glass yarn, which has linear density 33 tex (g/ km), supplied by AGY industries was used to produce the twisted S-glass yarn combined from 18 individual yarns. Yarn specifications are given in Table 1. In order to manufacture these yarns, a novel variation of the setup of the twisting machinery has been developed and used to introduce a variety of twisting angles into yarns. A schematic diagram showing this setup is illustrated in Figure 2.

Table 1 The properties of the S-glass yarn

Yarn type	Liner density (tex)	Fibre diameter (µm)	Filament count	Yarn tenacity (cN/tex)	Elongation (%)
S-glass	33	9	207	79.3 ± 19.8	3.8 ± 0.2

The untwisted glass yarns with approximately 624 tex linear density (i.e. 18 S-glass yarns), are supplied from yarn packages which are mounted on the holder in conjunction with an electric motor (Part A in Figure 2), pass through a tensioner (Part B in Figure 2). The tensioner is used to optimize the yarn tension and prevent entanglement of the filaments. The holder, which connected directly with electric motor (Part A in Figure 2), is rotated at an appropriate speed to provide the required twist on the yarns axis. Once the yarns emerge from the tensioner, they are passed through profiled driven rollers (Part C in Figure 2), which supply and control the linear velocity of the yarns along the machine. When the first rotation is applied to the yarns, the twist insertion actually happened and filaments deformed in a helical form, and each additional rotation increased the number of turns of twist and twist angle respectively. Then, the twisted yarns are wound with a constant tension onto a package that is placed on a yarn winder in a warping unit to avoid entanglement.

Thus, the general formula for the suitable twist which can impart to filaments is given by equation 1[40]

$$T = \frac{N_s}{V_d} \tag{1}$$

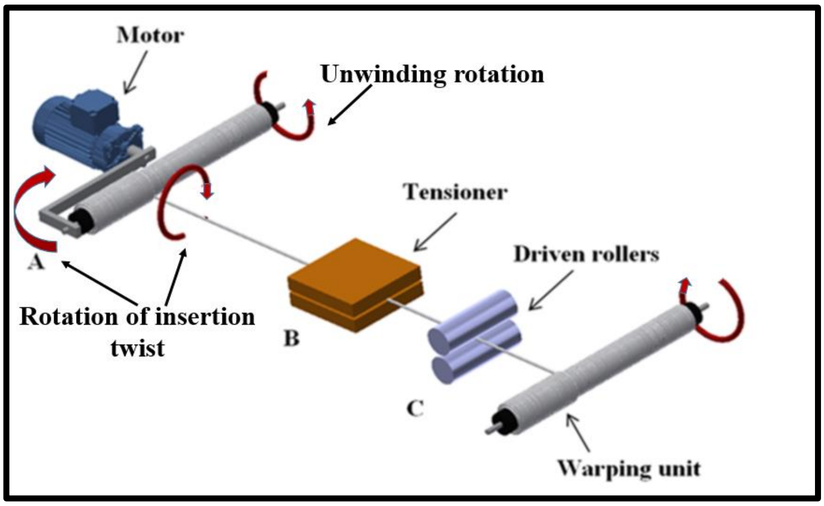

Figure 2 Schematic of twisting process

Where, T is additional twist (Turn per metre), N_s is rotational speed of the twisting tool (e.g. revolution per minutes provides by electric motor), and V_d is linear velocity of driven rollers (metre /minute), and represented the linear speed of yarn. Therefore, if the rotational speed of twisting device (electric motor) and speed of driven rollers are 180 r.p.m and 6 m/min respectively, the twist inserted into the filaments is 30 Turn per metre. In this study, different values of twisting levels are inserted to yarns in order to find the optimal twist and yarn shape to reduce their damage during weaving. The key parameter can play an important role in the properties of the twisted yarns. The twist angle is shown in Figure 3a and can be measured by using equation 2 [41]. In addition, the cross-section of twisted yarns presented in Figure 3b.

$$\tan\theta = \frac{\pi d}{h} \tag{2}$$

Where, $\theta(\,degree), d(mm),$ and $h(mm)$ are twist angle, diameter of the twisted yarn, and length of the yarn in one turn. In addition, there is a strong connection between the twist angle at the surface of yarns (θ) and additional twist level as given in equation 3 [42]

$$\tan\theta = T\pi d \tag{3}$$

In this study, six types of yarns are made with twisting levels ranging from 15 to 40 T/m and these yarns are used to weave non-crimp cross-ply preform (Figure 4) using robotic tow placement machine with 8 yarns per cm in both warp and weft directions.

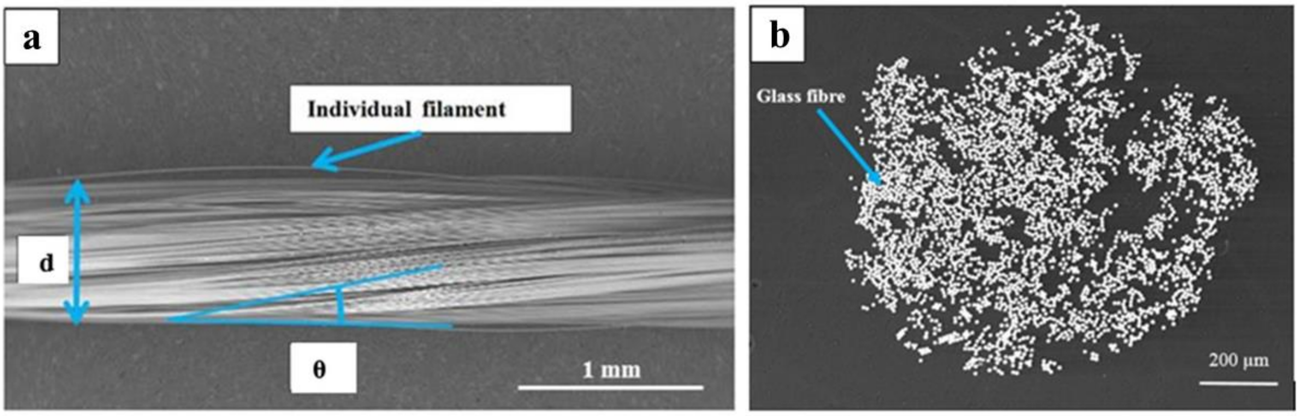

Figure 3 Geometry of twisted yarns and twist angle (a), and cross-section of twisted yarns (b).

In this study, a Z- direction of twist has been selected. While twisting levels 15 and 20 turn per meter (T/m) are classified as low twist (LT), twisting levels 25 and 30 T/m are classified as medium twist (MT) and twisting levels 35 and 40 T/m are classified as high twist (HT).

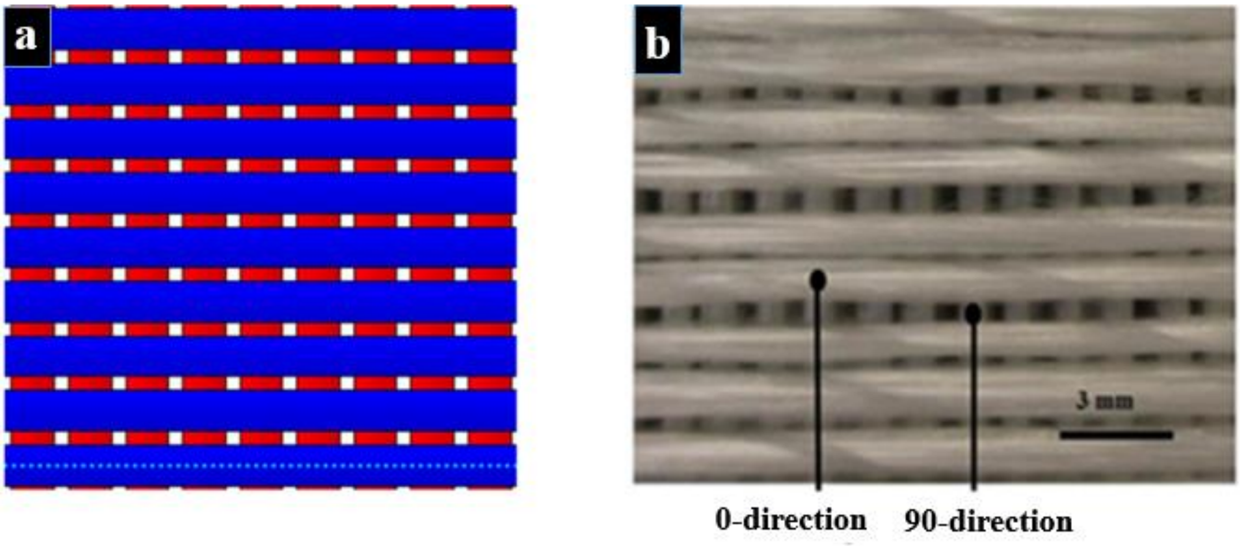

Figure 4 Image of Cross-ply preform, TexGen software image (a), scanned preform image (b)

2.2 Fabrication of composite samples

Composite laminates were manufactured using non-crimp cross-ply preform. In order to manufacture these laminates, $[0, 90]_4$ layups were used resulting into 8 plies of cross-ply structure as can be seen in Figure 5. Vacuum assisted resin infusion method was adopted to manufacture these composites. Epoxy resin with a low viscosity Araldite LY 564 and hardener Ardur 2954 with a ratio of 100:35 by weigh were mixed and degassed before infusion. The recommend cure cycle of 120 minutes at 80 °C followed by 8 hours at 140 °C was adopted. After curing, the composite laminate panels were machined with aiding water-jet diamond cutter to produce the test specimens of required dimensions.

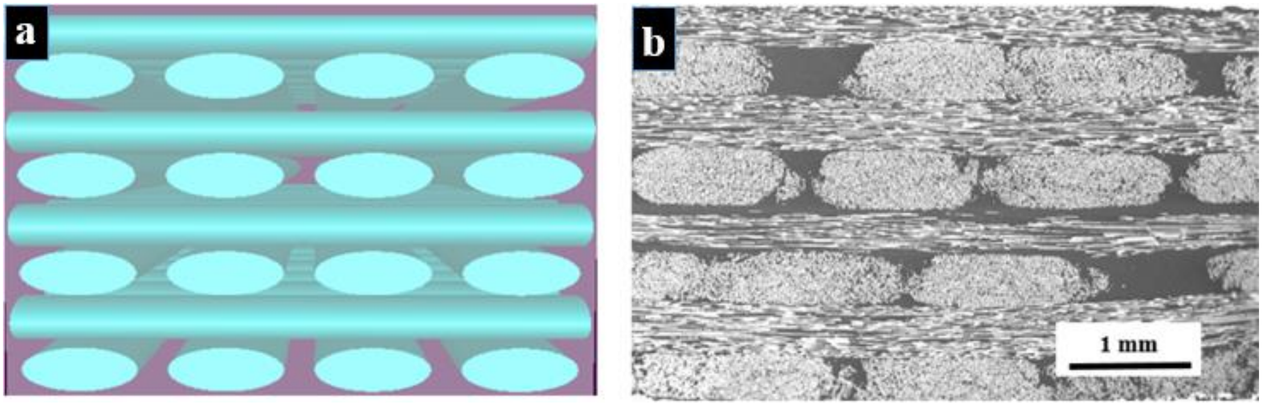

Figure 5 Image of 8 layer cross-ply composite, ideal geometry created by Texgen (a) and a cross-section used in present study (b)

Five types of composite samples were made and their specification are presented in Table 2. The density and volume fractions of composite laminates were measured by using the immersion and burning methods according to BS EN ISO 1183-1 and BS EN ISO 1172 standards, respectively. It is interesting to note that the volume fraction of S-glass fibre composites increased with increasing twisting levels and this because of the increasing of yarn packing fraction of the yarns [43].

2.3 Models of twisted yarns

The theoretical modeling of yarn properties can be a useful tool to prepare right-first-time yarns for the intended application. In an industrial setting, new types of yarns can be developed more quickly using models by adjusting the design of a yarn already in production or designing a completely new yarn. So that, the risk, time and designing costs of a yarn can be reduced significantly by modelling prior to yarn production [44], The main properties, which are influenced by the addition of twist to a yarn under loading, are the stiffness and strength of this yarn. This is because of the orientation of individual filaments increase in eccentricity to the longitudinal direction with increasing twist level. Thus, a loss of longitudinal stiffness occur due to this off-axis eccentricity. One of the earliest model, which took into consideration the changes in fibre orientation as main reason for variation of yarns properties, is known as either $\cos\theta$ model or as

Gegauff's classic model [16]. In this model, the stiffness of the twisted yarns is calculated from the following equation 4:

$$E_y = E_f \times cos^2\theta \tag{4}$$

Where E_y, E_f, and θ are the yarn modulus in the longitudinal direction, the elastic modulus of the filament, and the surface yarn twist angle respectively. In addition, the tensile strength of the twisted yarns is significantly influenced by twisting as observed from Hearle's equation [45]. According to this equation, the prediction of tensile strength of twisted yarns can be considered as a function of the twist angle according to the relationships described in following equation 5:

$$\sigma_{yarn} = \sigma_f \times cos^2\theta \tag{5}$$

Where σ_{yarn} and σ_f are the tensile strength of the yarns and the filaments respectively.

The yarn strain can also be varied by changing the twisting levels or varying the path of filaments in yarn along the yarn axis. By considering the Poisson's effect, the strain on the yarn can be modified from Hearl's equation [6] and the strain to failure of twisted yarns can be determined from following equation [46]

$$\epsilon_f = \epsilon_y(cos^2\theta - \nu\, sin^2\theta) \tag{6}$$

Where ϵ_y, ϵ_f, and ν are the yarn strain, fibres strains and the Poisson‘s ratio of the yarn respectively.

2.4 Mechanical testing

To elucidate the effect of twist on the mechanical properties of the yarns i.e. tensile strength, modulus of elasticity and elongation, tests were conducted following ASTM D2256-2, with a gauge length of 250 mm and a rate of 0.2 mm/s on the yarns (Instron 4411, n=10). Optical microscope was used to measure the diameters of twisted yarns. The diameter of yarn was not perfectly round and the change in the yarn diameter along the yarn axis was small at the same twisting level, so that, the mean values were adopted as the diameter of the twisted yarns in this study. The yarn twist angles were estimated employing image processing software, ImageJ. The linear density of twisted yarns was obtained by weighting 500 mm of the twisted yarns on Mettlo Toledo analytical semi microbalance machine. The tensile strength of the un-twisted and twisted yarns was measured by dividing the breaking force over the cross-sectional area of the yarns. In addition, the elastic modulus of the yarns was calculated from the slope of the linear region of the stress-strain curves.

Meanwhile, the toughness of yarns was determined by integrating the area under the stress-strain curve.

To characterize the effect of twisted yarns on the mechanical properties of composite laminates, tensile strength tests were performed in accordance with ASTM D3039M 2008 (250 mm × 25 mm rectangular samples were tested displacement rate of 2.0 mm/min using Instron testing machine 5982). (Instron 5982, n=5). The strains were recorded along the specimen length and width directions using a video extensometer monitoring a gauge length of 50 mm.

3 Results and Discussion

3.1 Effect of twist variation on mechanical properties of yarn

The effect of level of twist on the mechanical properties of yarn is characterized using twist or helix angle made by the fibre bundle with respect to yarn axil direction or by the measurement of changes in the diameter of yarn. The twist direction denoted by the letter ''S'' or ''Z'', which represents the orientation of the filaments on the surface of the yarn with respect to the yarn when placed in a vertical position.

Figure 6 shows the optical microscopy images of glass yarns that are subjected to range of twisting levels from 15 to 40 Turn per meter to induce varying twist angles. Ideally yarn cross-sections should be measured to capture the changes in yarn cross-sectional area which in turn can also give idea about yarn packing fraction and intra-tow voids for resin flow. As this is not focus of the present study, so only yarn diameters from microscopic images are calculated to estimate the change in diameters of yarns with varying twist levels. In future study, we plan to measure the yarn cross-sectional areas at each twist level, which will help to study the change in yarn packing fraction and intra-tow voids for resin flow. Coming to Figure 6, it is observed that the fibre-twisting angle (θ) increase with increase in number of twisting level (T), while there is a decrease in the yarn diameter (d). As an example, 15 T/m corresponds to a fibre twisting angle of 5.90 ° and equivalent diameter of yarn 1.043 mm, while 40 T/m corresponds to $\theta = 12.23°$ and d=0.67 mm. and that is because of filaments inside the yarns become more tightly configured with increasing twisting level.

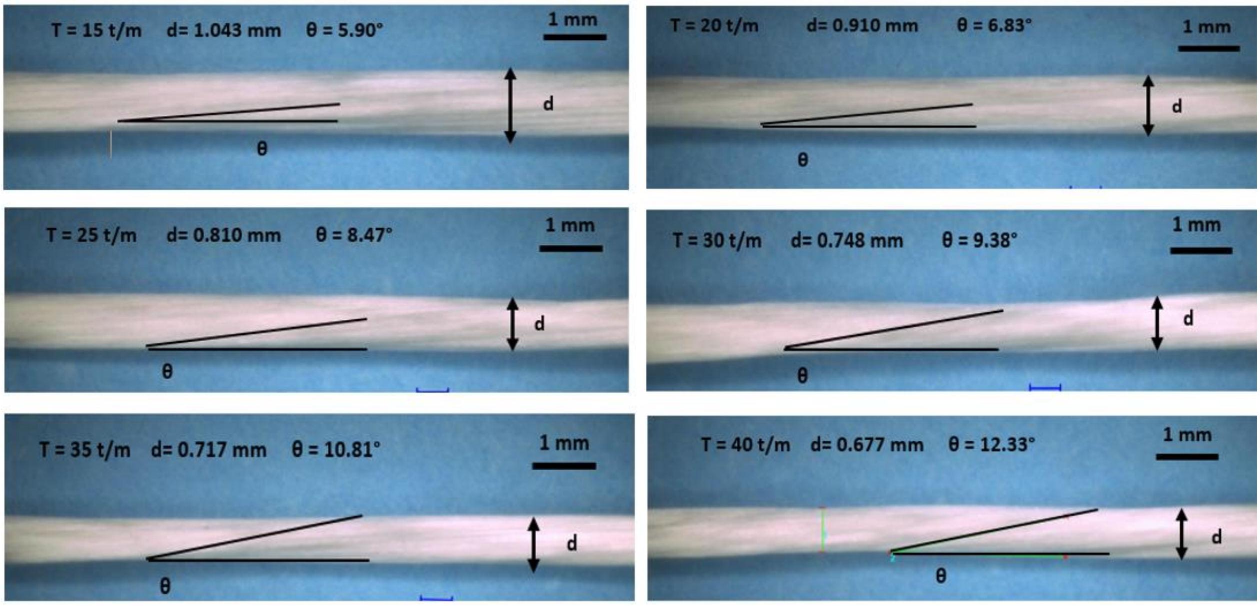

Figure 6 Optical images of glass yarns at various twist levels

Figure 7 and Table 2 present the strength properties of glass yarn at various twist levels. Figure 7a shows the tensile strength - strain plots for twisted glass yarns. Specifically, the low twisting levels (i.e. 15 and 20 T/m) results in small increase in the tensile strength of twisted yarns compared to non-twisted yarns. Then, with increasing twist levels up to 30 T/m, the maximum tensile strength of twisted yarns is achieved. However, beyond this twisting level, additional twist has been illustrated to reduce twisted yarn strength. The small increase of tensile strength at lower twisting levels can be attributed to the orientation of the filaments in straight path as most of filaments are oriented in a straight path with the longitudinal axis of the yarn producing low interfacial contact and these straight yarns fail under shear amount of slippage. On further twist increase, the inter-friction of filaments increase leading to higher yarn packing density. The increase of packing density means that more filaments are connecting together along the yarn direction improving their resistance to slippage through friction. Moreover, with increasing twist to high levels (i.e. 35 and 40 T/m), the binding of filaments continue until they start to interlock. The interlocking of filaments occur due to converting the tensile stress to transverse stress during the tensile deformation as result of high twist action.

When stress is continuously built up in the twisted yarns under tension, the interlocking of filaments can prevent the inter-fibres shear motion or slippage, and consequently the strength of twisted yarns is improved. Thus, it is noticed that during the tensile loading of the twisted yarns, the apparent stress-strain curves behave as a short linear region because of slippage of filaments inside the yarns followed by nonlinearity with considerable extension while the filaments continue to slip and finally failure occur.

Table 2 Tensile strength properties of S-glass yarns at different level of twist

Level of Twist (T/m)	Angle of Twist (°)	Tensile Strength (MPa)	Yarn Tenacity (cN/tex)	Modulus of Elasticity (GPa)	Strain to Failure
0	**0**	**2353 ±6.30**	**94.3 ±0.25**	**59.60 ±0.60**	**4.17 ±0.06**
15	**5.9**	**2362 ±7.20**	**94.64 ±0.29**	**59.04 ±0.70**	**4.33 ±0.07**
20	**6.83**	**2375 ±6.00**	**95.16 ±0.24**	**59.10 ±0.72**	**4.50 ±0.04**
25	**8.47**	**2391 ±4.20**	**95.80 ±0.17**	**58.50 ±0.53**	**4.53 ±0.04**
30	**9.38**	**2431 ±4.00**	**97.40 ± 0.16**	**58.54 ±0.91**	**4.56 ±0.07**
35	**10.81**	**2352 ±7.50**	**94.24 ± 0.30**	**57.53 ±0.70**	**4.70 ±0.05**
40	**12.33**	**2332 ±5.00**	**93.44±0.20**	**57.40 ±1.06**	**4.83 ±0.03**

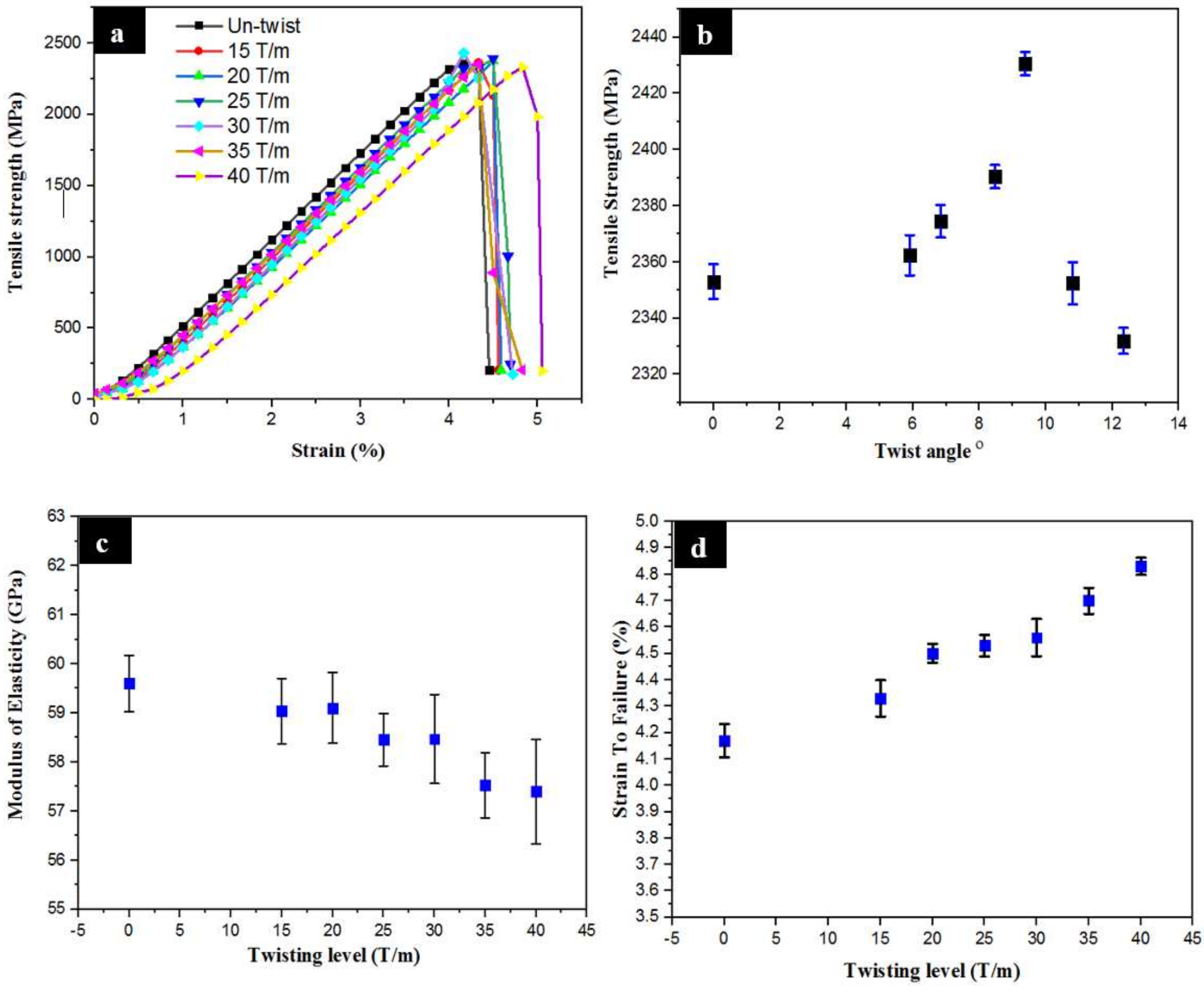

Figure 7 a) Tensile strength-strain curves for various twist levels, b) Tensile strength with various twist levels, c) Modulus of Elasticity for different twist levels, and d) Strain to failure for various twist levels (±1 SD)

As noticed in Figures 7a and 7b, the tensile strength of glass yarns increase at medium twisting levels (i.e. 25 and 30 T/m), which is considered optimum level. Beyond this levels, the filaments are oriented far away from the yarn axis making the contribution of filaments strength to the glass yarns strength less effective and hence reduce the overall yarn strength. Hence two phenomenon are observed here. First, the increase in strength with twist is associated with increase in cohesion of filaments under twist, while the second is decrease of strength with twist, which is associated with filaments obliquity under high twist leading to reduction of the contribution of filaments strength to that of yarns. These behaviours are in agreement with the conventional understanding of relationship between strength and twist in the textile yarns [46, 47]. The relation between the stiffness (i.e. Young modulus) of yarns and twisting levels are also shown in Figure 7 c. As can be seen, the Young modulus values for six types of twisted yarns are generally lower than the Young modulus of the non-twisted yarns; they varied between (59 GPa and 57 GPa), while the value of 59.60 GPa is found for the non-twisted glass yarns. The reduction in the Young's modulus of twisted yarns at lower twisting levels can be attributed to the twist contraction. The length of most filaments is longer than the length of yarn due to helical structure of the yarn. Consequently, as the load direction and the filament orientation are not the same, the filament strength is not fully translated to the strength of the yarn and results in the comparatively low modulus of twisted yarns compared to the non-twisted yarns [16, 48].

Elongation and strain to failure of yarns-twist relation are presented in Figure 7d. It is observed that the elongation of the yarns increased with increasing twist levels. The strain of the yarns strongly depends on the strain of the individual filaments, which can sustain while they are subjected to tensile loading. So that, the twisted filaments have extra length between jaws and are stretched more compared to untwisted filaments and the tension load become more concentrated towards the yarns core. This extension in the filaments increase their lateral pressure and compaction, resultantly yarns become more dense and coherent to strain. Thus, at low twisting levels, the individual filaments can intercept higher loads leading to slight improvement in the elongation compared to untwisted ones. On increase of twist levels, higher elongation has been achieved as the coherent forces in the yarns stop the filaments from absorbing all the tension load consequently avoiding early breakage.

The relation of toughness with yarn twist is presented in Figure 8. The toughness value are measured from integrated area under stress-strain curves. It can be seen from Figure 8 that unlike strength measurements, the high value of toughness ($\sim 5.8\ kJ\ m^{-3}$) has been achieved at high level of twist (i.e. 40 T/m), followed by medium twist (i.e. 30 T/m) with value ($\sim 5.5\ kJ\ m^{-3}$) and lastly the lowest values have been obtained at low twist (i.e. 15 T/m it has value $\sim 5.1\ kJ\ m^{-3}$). Although, the medium level of twist illustrate the highest value of strength, their low strain (4.56%) compared to (4.83%) strain of high level of twist, satisfy lower toughness than the high level of twist. The improved toughness of glass yarns with twist is strongly attributed to the alignment of filaments in the axial direction and enhancement in their coherency. Therefore, it is expected that with increased coherency of filaments, the degree of yarn packing also increase resulting into higher toughness. The improvement in toughness of twisted yarns can be challenging, this is because of difficulty to create very strong yarns that can carry significant amount of strain. Meanwhile increasing the twist can help with elongation; large stress at high twist decreases the tensile strength. However, the medium twisted yarns show the highest tensile strength compared to low and high twist yarn, respectively. In particular, a medium twisted glass yarn appear higher absorbing elastic energy and therefore, provide better resistance to elastic and plastic deformations. Depending on such benefits of improvement in mechanical properties (i.e. longitudinal tensile performances and modulus of elasticity), medium twisted glass yarns are mechanically suitable for extreme environmental conditions including impact, shock and vibrations and stretchable smart textiles [33]

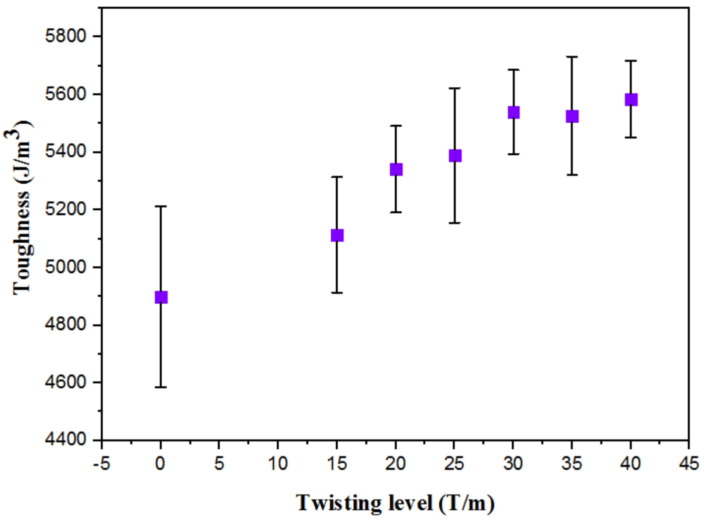

Figure 8 Toughness of yarns at various levels of twisting

The obtained experimental results of yarn mechanical properties are also compared with theoretical estimations from existing models of yarn to verify the validity of these models. Thus, the tensile strength, modulus of elasticity, and strain to failure for all twisted yarns obtained experimentally at various twisting levels (15 - 40 T/m) are plotted against the theoretical results, which are extracted from the equations 4, 5 and 6 for verification. The values of σ_f ,E_f and ϵ_f are extracted experimentally from tensile strength tests of S-glass fibres, also the Poisson ratio of glass yarns, ν equal to 0.22. The experimentally measured and predicted tensile strength, modulus of elasticity, and elongation for twisted S-glass yarns are shown in Figure 9. As can be seen from Figure 9a, the model gives a good prediction for the tensile strength compared to the experimental results at low levels of twist while, the plots shows the difference between experimental and numerical values . This most likely due to the lack of damage that occurred in the filaments and the model could not capture it at higher twist levels.

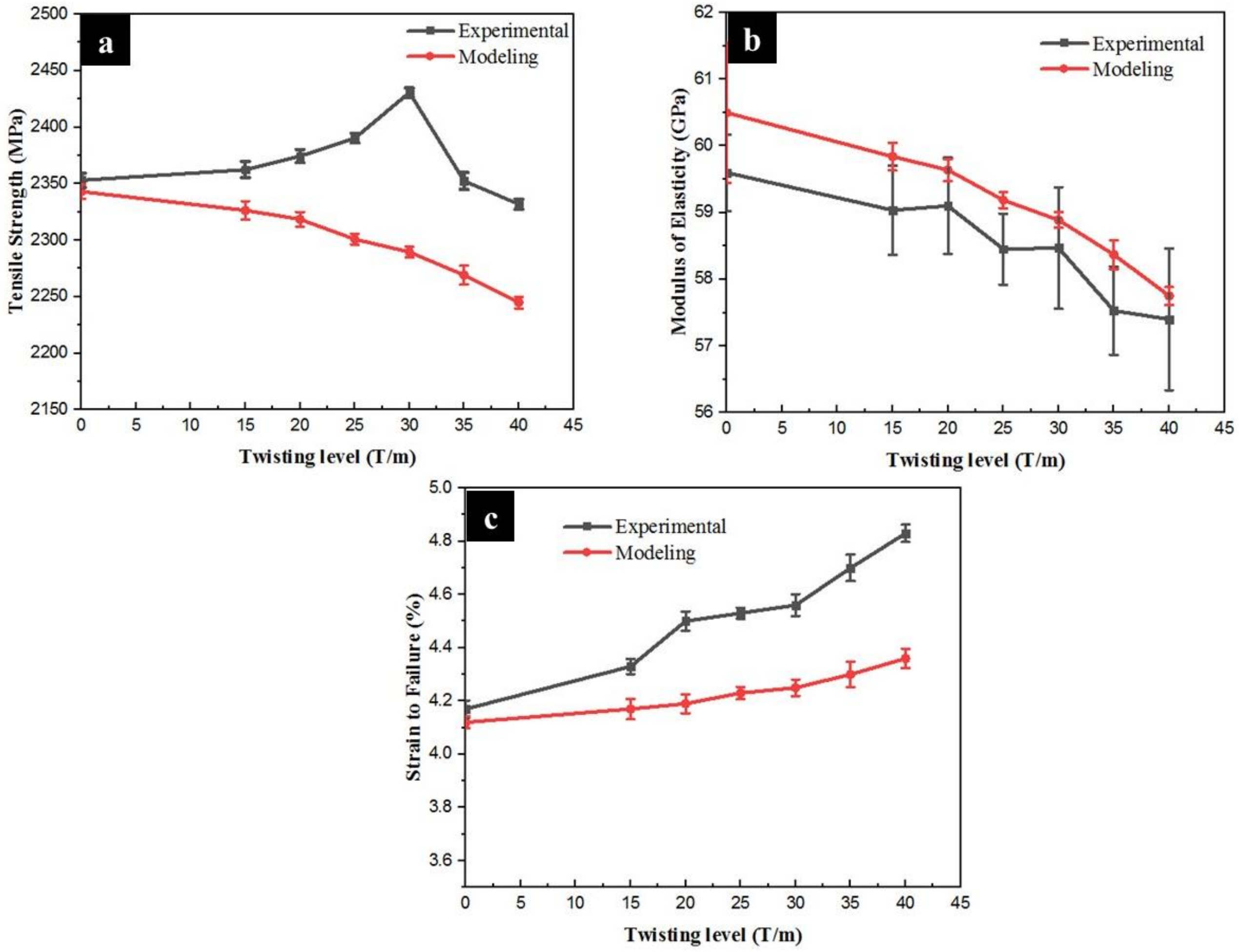

Figure 9 Comparison of predicted and experimental of a) Tensile strength, b) Modulus of Elasticity and, c) Strain to failure for twisted yarns at various twist levels

Unlike the tensile strength results, the model over-predicts the modulus of elasticity (Figure 9b). Additionally, the difference between model values and experimental observations is smaller than 10% for all levels of twist, which implies that the theoretical model can predict a relatively accurate value of the modulus of elasticity.

The elongation behavior of twisted S-glass yarns in both experimental and theoretical observation are also shown in Figure 9c. The range of experimental data generally lied with range of model at low and medium levels of twist but there is difference in values at high levels of twist which could be due to the model equation doesn’t take into account the fibre length and their migration with increasing of twisting levels.

3.3 Composite mechanical properties

The specification of composite laminates, which made from the S-glass composites at different levels of twist, is illustrated in Table 3. Further, the mechanical behaviour of representative S-glass composites at different levels of twist is presented in Table 4 and Figure 10. It can be noticed from the composite stress-strain curves in Figure 10a that for all twist levels, composite samples appeared a non-linear stress-strain response which is typically associated with the cross-ply composite structures [49]. In cross-ply laminates, 0^0 plies are loaded along the reinforcement fibres while 90^0 plies are loaded in transverse direction. Polymer matrix is weakest in the composite and on application of load, the matrix cracking of 90^0 plies starts followed by transverse ply failure in the early stages, which can be noticed as non-linear behaviour of stress-strain curves. On application of further load, the 0^0 plies start cracking laterally and finally these plies fail due to fibre breakage. The fibre breakage of 0^0 plies can be seen in Figure 13. Interestingly, increasing twisting levels exaggerates the non-linear stress-strain response. This behaviour can be attributed to the addition of twisting of the S-glass yarns due to which most filaments are helically wound around the axis of the yarns [50].

Table 3 Specification of composite laminates

Composite Code	Thickness (mm)	Glass fibre volume fraction V_f %	Density(g/cm^3)
0 T/m	3.01 (±0.01)	44.42 (±0.711)	1.87 (±0.017)
15 T/m	3.03 (±0.04)	44.83 (±0.520)	1.88 (±0.019)
20 T/m	3.02 (±0.10)	45.05 (±0.602)	1.89 (±0.029)
25 T/m	3.04(±0.20)	45.89 (±0.370)	1.85 (±0.031)
30 T/m	3.05 (±0.01)	45.88 (±0.771)	1.76 (±0.011)
35 T/m	3.00 (±0.05)	46.88 (±0.672)	1.77 (±0.021)
40 T/m	2.89 (±0.03)	47.33 (±0.631)	1.78 (±0.032)

Hence, most of filaments are not completely aligned but rather are off-axis to the yarns direction. It is expected that this additional non-linear elastic response could be due to the rotation of these filaments upon load application and subsequent stretching of rotating filaments. Thus, uncoiling and reorientation of filaments in the twisted yarns during tensile loading [29] can also be reason for the non-linear stress-strain behaviour in the twisted S-glass composites. It is found from the results of Hao Ma et al [51], that the increasing of the twisting level of sisal composite can increase the displacement of failure.

Table 4 Tensile strength properties of composite laminates at different level of Twist

Level of Twist (T/m)	Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Strain to Failure
0	**566 ±23**	**22.20 ± 1.50**	**3.11 ±0.22**
15	**643 ±11**	**24.25 ±1.00**	**3.30 ±0.35**
20	**649 ±21**	**25.40 ± 1.40**	**3.45 ±0.23**
25	**668 ±13**	**26.73 ±2.10**	**3.40 ±0.32**
30	**674 ±26**	**21.24 ±2.00**	**3.50 ±0.27**
35	**618 ±24**	**20.62 ±2.11**	**3.65 ±0.32**
40	**608 ±10**	**20.80 ±1.30**	**3.70 ±0.45**

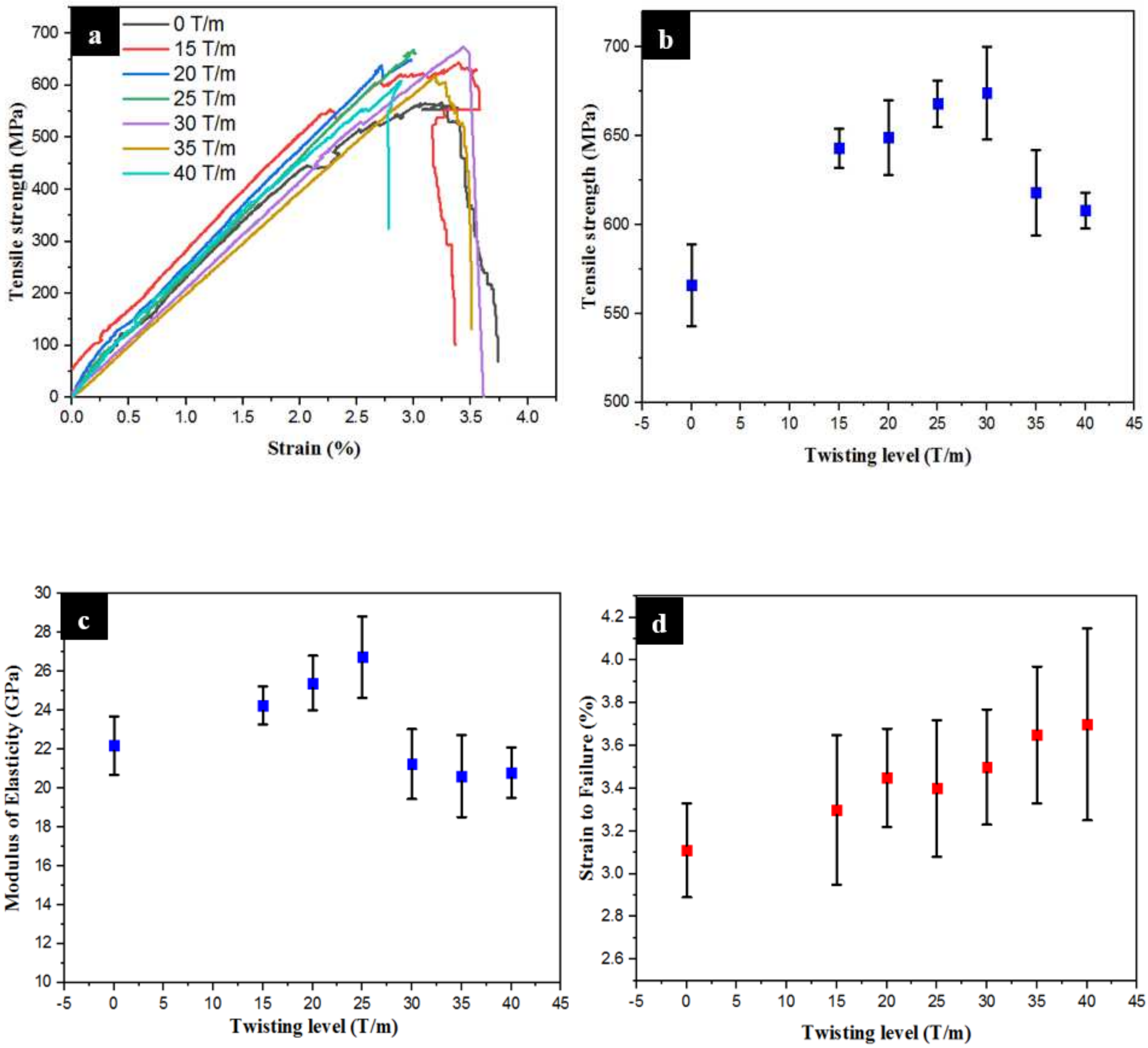

Figure 10 Effect of twist on the a) Tensile strength-strain plots and b) Tensile strength, c) Modulus of Elasticity, and d) Strain to Failure verse twisting level of composites

The tensile strength properties of glass yarns composites at different twist levels are presented in Figure 10b. It can be observed that with increase in twist of the yarns up to 30 T/m, the tensile strength of composite increases and then there is slight decrease in strength on application of further twist. The higher strength at 30 T/m can be attributed to the better interfacial adhesion of twisted filament and epoxy, which provide better lateral cohesion between filaments and the bonding shear strength between the filaments and epoxy, respectively. Similar behaviour has been reported in the literature [8, 52]. The decrease in the strength of composites with higher twist levels may be attributed to the obliquity of the filaments and inability of resin infiltration in highly twisted yarn due to decrease in the cross-sectional area of twisted tows resulting in low inter-filament gaps [51].

From the stress-strain response of composite laminates at the different twist levels, the Young's modulus is also determined using the initial tangent modulus in the strain range of 0.025 -0.100% (Figure 10c). Figure 10 c clearly shows that the modulus of composites increase up to 25 T/m then there is immediate drop after this level of twist. This can be attributed to the increase of obliquity, the deviation of the filaments axis from the yarn axis resulting in a number of slack filaments from their position leads to drop of E-moduls. These results confirmed with investigation of Rask et al, [53], which showed that with increasing twisting until an optimum level, the tensile modulus of fibre composite laminates increased. Then, the tensile modulus of composite laminates started to decrease beyond an optimum level of twist. The strain to failure of composites laminates, which corresponds to the effective strain at tensile failure of yarns is presented in Figure 10d and it can be seen that failure strain increase with increasing levels of twist. By the increasing of twisting level, possible micro damages of filaments in the yarns can be localized, leading to possible increase in the failure strength of the yarns and consequently composites. In addition the results of investigation of Cheung et al [54] showed that the strain to failure for Kevlar 49 twisted tubular braided composites was increase with increasing level of twist. Similar behaviour has been reported in the literature [51].

In addition, the experimental tensile strength of composite laminates values are compared with theoretical tensile strength values and shown in Figure 11

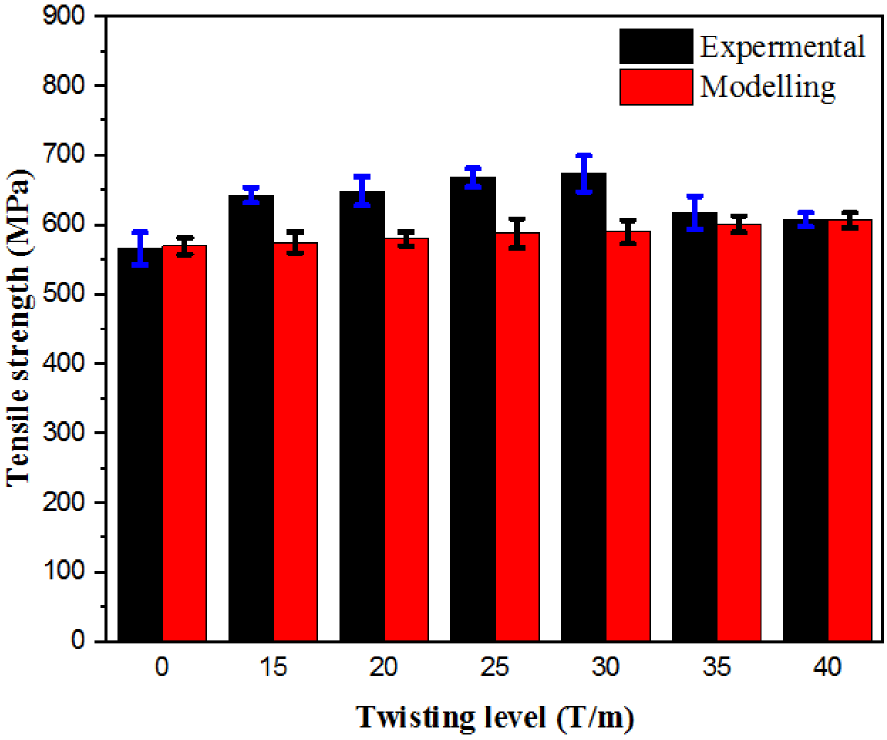

Figure 11 Comparison of experimental and predication tensile strength of non-crimp composite laminates ate different level of twist.

The tensile strength of non-crimp cross-ply laminate theoretically comes from the longitudinal and transverse tensile strengths of laminas of this composite as shown in Figure 12.

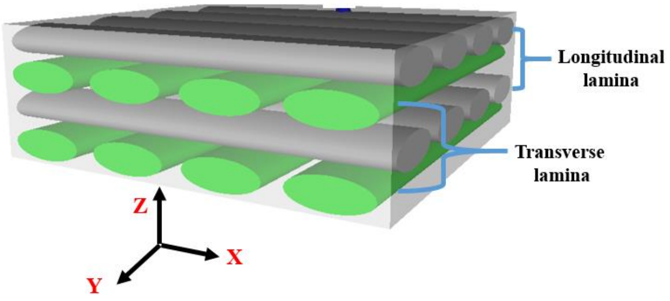

Figure 12 Configuration of non-crimp composite laminate

So that, the rule of mixture can be applied to calculate the tensile strength of this composite while both longitudinal and transverse directions are 50% in the $[0, 90]_4$ configuration. The longitudinal tensile strength of the unidirectional lamina is calculated from the following equation [55].

$$\sigma_c^L = \sigma_f V_f + \sigma_m V_m \tag{7}$$

Where, σ_f, σ_m, V_m and V_f are the the tensile strength of fibre , the tensile strength of matrix , volume fraction of matrix and volume fraction of fibre respectively

The transverse strength of unidirectional lamina is also calculated using following equation [55]

$$\sigma_c^T = E_2[\frac{d}{s}\frac{E_m}{E_f} + \left(1 - \frac{d}{s}\right)]\epsilon_m^T \qquad 8$$

Where, σ_c^T, E_2, (d/s), E_m, E_f, and ϵ_m^T are the transverse tensile strength of lamina (Eq. 9), diameter to fibre spacing ratio (Eq. 10), matrix Young's modulus, fibre Young's modulus , and ultimate strain of matrix (Eq.11)

$$\frac{1}{E_2} = \frac{V_f}{E_f} + \frac{V_m}{E_m} \qquad 9$$

$$\frac{d}{s} = \sqrt{1 - \frac{4V_f}{\pi}} \qquad 10$$

$$\epsilon_m^T = \frac{\sigma_m}{E_m} \qquad 11$$

In this study, we calculated the theoretical tensile strength of non-crimp cross-ply composite laminates measured from σ_c^L and σ_c^T respectively by dividing the values by factor 2. The values of σ_f ,σ_m, E_f, $E_m$are achieved experimentally and presented in the Table 5.

Table 5 Mechanical properties of S-glass fibre and Epoxy resin

Property	S-glass	Epoxy
Young's Modulus (GPa)	60.20	3
Ultimate tensile strength (MPa)	2400	78

As can be seen from Figure 11, the theoretical results are capturing the trend very well. In addition, the tendency of the predication results show good agreement with experimental results at high level of twist illustrating reduction in tensile strength of composite at high level of twist. This is due to the poor impregnation between epoxy and S-glass yarns, which occur at the high level of twisting leading to the reduction in the tensile strength.

The fracture surface of the tensile test specimen also give insight into the effect of twist on how damage failure occur. It can be seen that for the non-twisted S-glass yarns (Figure 13 a) a more serrated and uneven fracture occur and the composite failure is fibre controlled. In addition, the fracture path is longer and starts running along the length of filaments. Meanwhile, in the twisted S-glass yarns composite at 30 T/m (Figure 13 b), the tensile fracture is macroscopically brittle with flat fracture surface and the composite failure seems to be matrix controlled

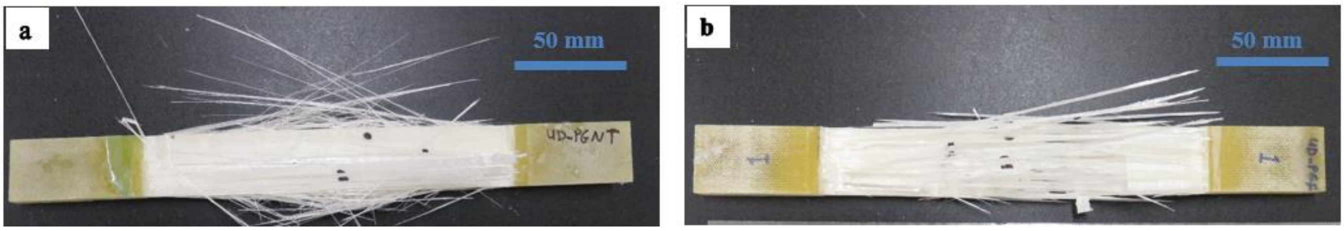

Figure 13 Fracture of tensile specimens a) Non-twist S-glass composite b) Twisted S-glass yarns at 30 T/m

4 Conclusion

The optimization of the yarns to facilitate the manufacturing process for textile reinforcements and improvement in the mechanical performance of resulting textile-reinforced composites is a key challenge for materials scientists and engineers. The current work aims to balance between processability and the mechanical properties of high–performance fibres (i.e. S-glass yarns) and cross-ply composites.

Introduction of twist to yarns can improve the processability of the yarn but it can also affect the mechanical properties of yarn and resulting composites. Here, in this study, different levels of twist were applied to S-glass yarns and non-crimp cross-ply composites were manufactured with these yarns. Effect of twist was studied on the tensile properties of both yarns and cross-ply composites and an optimum level of twist was studied to enhance the mechanical performance of yarns as well as textile reinforced composites. Existing theoretical models were employed to calculate the tensile properties of the yarn in order to investigate the validity of these models with obtained experimental results. Furthermore, tensile properties of the composites were estimated by utilizing modified rule of mixture for cross-ply composites. Expectedly, the mechanical properties (i.e. longitudinal tensile strength) of the twisted S-glass yarn increased with increasing level of twist up to an optimum point before it starts to deteriorate. For instance, the tensile strength of twisted S-glass yarns improved by increasing the level of twist up to 30 T/m. The theoretical models for yarns were able to capture the trend of the modulus of elasticity but there were discrepancies between the experimental and theoretical results for strength and stiffness of twisted glass yarns, especially at higher twist levels.

It was noticed that twist can enhance the mechanical performance of the twisted S-glass yarns composites in term of strength and stiffness to a certain level of twist. However, the degradation in tensile properties started after optimum level of twist.

A modified rule of mixture was also employed to calculate the modulus of cross-ply composites numerically and good agreement was observed between numerical and experimental results.

As observed in this work, an optimum twist can effectively achieve a balance between handling and mechanical performance of high strength fibres. In addition, as a general outlook, the favorable properties such as higher strength and improved toughness for composite laminates can be satisfied by the optimization of the twist levels for glass yarns. In future work, authors will try to improve the theoretical models for better estimation of tensile properties of yarns, which in turn can be utilised for determination of mechanical properties of textile reinforced composites. In future study, we plan to measure the yarn cross-sectional areas at each twist level, which will help to study the change in yarn packing fraction and intra-tow voids for resin flow

Declaration of conflicting interests

The authors declare no potential conflict of interests with respect to the research, author-ship, and /or publication of this article.

References

[1] J.-H. Byun, J. W. Gillespie Jr, and T.-W. Chou, "Mode I delamination of a three-dimensional fabric composite," *Journal of Composite Materials,* vol. 24, pp. 497-518, 1990.

[2] H.-K. Hur, J. Park, and R. Kapania, "Mechanical Characteristics of Helically Twisted Composite Strands Using Sub-unit Cell Geometry," in *50th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference 17th AIAA/ASME/AHS Adaptive Structures Conference 11th AIAA No*, 2009, p. 2479.

[3] J.-M. Berthelot, "Transverse cracking and delamination in cross-ply glass-fiber and carbon-fiber reinforced plastic laminates: static and fatigue loading," *Appl. Mech. Rev.,* vol. 56, pp. 111-147, 2003.

[4] L. M. Ferreira, E. Graciani, and F. París, "Modelling the waviness of the fibres in non-crimp fabric composites using 3D finite element models with straight tows," *Composite Structures,* vol. 107, pp. 79-87, 2014.

[5] L. Zhao, N. Warrior, and A. Long, "Finite element modelling of damage progression in non-crimp fabric reinforced composites," *Composites Science and Technology,* vol. 66, pp. 36-50, 2006.

[6] J. W. Hearle, P. Grosberg, and S. Backer, "Structural mechanics of fibers, yarns, and fabrics," 1969.

[7] N. Naik and R. Kuchibhotla, "Analytical study of strength and failure behaviour of plain weave fabric composites made of twisted yarns," *Composites Part A: Applied Science and Manufacturing,* vol. 33, pp. 697-708, 2002.

[8] A. J. Rajwin, V. Giridev, and M. Renukadevi, "Effect of yarn twist on mechanical properties of glass fibre reinforced composite rods," 2012.

[9] J. Byun and T. Chou, "Elastic properties of three-dimensional angle-interlock fabric composites," *J. Text. Inst,* vol. 81, pp. 538-548, 1990.

[10] D. Shah, P. J. Schubel, M. J. Clifford, and P. Licence, "Mechanical characterization of vacuum infused thermoset matrix composites reinforced with aligned hydroxyethylcellulose sized plant bast fibre yarns," in *4th international conference on sustainable materials, polymers and composites*, 2011, pp. 6-7.

[11] B. C. Goswami, R. D. Anandjiwala, and D. Hall, *Textile sizing*: CRC press, 2004.

[12] K. Potter, *Introduction to composite products: design, development and manufacture*: Springer Science & Business Media, 1996.

[13] B. K. Cheung and J. P. Carey, "Characterizing and modeling of low twist yarn mechanics," *Journal of Engineered Fibers and Fabrics,* vol. 14, p. 1558925019866945, 2019.

[14] J. H. Byun and T. Chou, "Effect of yarn twist on the elastic property of composites," in *Proc. ICCM*, 1995, pp. 293-299.

[15] N. Naik, I. Mudzingwa, and M. Singh, "Effect of twisting on tensile failure of impregnated yarns with broken filaments," *Journal of Composites, Technology and Research,* vol. 23, pp. 225-234, 2001.

[16] Y. Rao and R. J. Farris, "A modeling and experimental study of the influence of twist on the mechanical properties of high-performance fiber yarns," *Journal of applied polymer science,* vol. 77, pp. 1938-1949, 2000.

[17] B. Song and W.-Y. Lu, "Effect of twist on transverse impact response of ballistic fiber yarns," *International Journal of Impact Engineering,* vol. 85, pp. 1-4, 2015.

[18] S. Goutianos, T. Peijs, B. Nystrom, and M. Skrifvars, "Development of flax fibre based textile reinforcements for composite applications," *Applied composite materials,* vol. 13, pp. 199-215, 2006.

[19] X. Sui, E. Wiesel, and H. D. Wagner, "Mechanical properties of electrospun PMMA micro-yarns: Effects of NaCl mediation and yarn twist," *Polymer,* vol. 53, pp. 5037-5044, 2012.

[20] J. Im, P. Percha, and D. Yeakle, "Some physical and mechanical properties of PBO fiber," *MRS Online Proceedings Library Archive,* vol. 134, 1988.

[21] S. Goutianos and T. Peijs, "The optimisation of flax fibre yarns for the development of high-performance natural fibre composites," *Advanced Composites Letters,* vol. 12, p. 096369350301200602, 2003.

[22] A. Weinberg and P. Schwartz, "Effect of fibre volume fraction on the strength of Kevlar-29/epoxy strands," *Journal of materials science letters,* vol. 6, pp. 183-184, 1987.

[23] R. Mirzaeifar, Z. Qin, and M. J. Buehler, "Mesoscale mechanics of twisting carbon nanotube yarns," *Nanoscale,* vol. 7, pp. 5435-5445, 2015.

[24] L. Treloar and G. Riding, "16—A theory of the Stress–Strain properties of continuous-filament yarns," *Journal of the Textile Institute Transactions,* vol. 54, pp. T156-T170, 1963.

[25] J. Hearle, H. El-Behery, and V. Thakur, "15—The Mechanics of Twisted Yarns: Theoretical Developments," *Journal of the Textile Institute Transactions,* vol. 52, pp. T197-T220, 1961.

[26] W. Morton, "The arrangement of fibers in single yarns," *Textile Research Journal,* vol. 26, pp. 325-331, 1956.

[27] N. Naik and V. Madhavan, "Twisted impregnated yarns: elastic properties," *The Journal of Strain Analysis for Engineering Design,* vol. 35, pp. 83-91, 2000.

[28] J. M. Whitney, "Geometrical effects of filament twist on the modulus and strength of graphite fiber-reinforced composites," *Textile Research Journal,* vol. 36, pp. 765-770, 1966.

[29] S. L. Phoenix, "Statistical theory for the strength of twisted fiber bundles with applications to yarns and cables," *Textile Research Journal,* vol. 49, pp. 407-423, 1979.

[30] W. Kilby, "53—The mechanical properties of twisted continuous-filament yarns," *Journal of the Textile Institute Transactions,* vol. 55, pp. T589-T632, 1964.

[31] N. Naik and M. Singh, "Twisted impregnated yarns: transverse tensile strength," *The Journal of Strain Analysis for Engineering Design,* vol. 36, pp. 347-357, 2001.

[32] D. U. Shah, P. J. Schubel, P. Licence, and M. J. Clifford, "Determining the minimum, critical and maximum fibre content for twisted yarn reinforced plant fibre composites," *Composites Science and Technology,* vol. 72, pp. 1909-1917, 2012.

[33] B. M. Zaidi, J. Zhang, K. Magniez, H. Gu, and M. Miao, "Optimizing twisted yarn structure for natural fiber-reinforced polymeric composites," *Journal of Composite Materials,* vol. 52, pp. 373-381, 2018.

[34] H. Gu and M. Miao, "Optimising fibre alignment in twisted yarns for natural fibre composites," *Journal of Composite Materials,* vol. 48, pp. 2993-3002, 2014.

[35] M. Mukhopadhyay, *Mechanics of composite materials and structures*: Universities press, 2005.

[36] S. Adanur, *Wellington Sears handbook of industrial textiles*: CRC Press, 1995.

[37] E. Selver, P. Potluri, C. Soutis, and P. Hogg, "Healing potential of hybrid materials for structural composites," *Composite Structures,* vol. 122, pp. 57-66, 2015.

[38] H. Dalfi, K. B. Katnam, and P. Potluri, "Intra-laminar toughening mechanisms to enhance impact damage tolerance of 2D woven composite laminates via yarn-level fiber hybridization and fiber architecture," *Polymer Composites,* vol. 40, pp. 4573-4587, 2019.

[39] K. Katnam, H. Dalfi, and P. Potluri, "Towards balancing in-plane mechanical properties and impact damage tolerance of composite laminates using quasi-UD woven fabrics with hybrid warp yarns," *Composite Structures,* vol. 225, p. 111083, 2019.

[40] S. Anand and A. R. Horrocks, *Handbook of technical textiles*: CRC Press/Woodhead Pub., 2000.

[41] N. Naik and V. Madhavan, "ELASTIC BEHAVIOUR OF TWISTED YARNS."

[42] Y. A. Ozkaya, M. Acar, and M. R. Jackson, "Yarn twist measurement using digital imaging," *The Journal of The Textile Institute,* vol. 101, pp. 91-100, 2010.

[43] N. Pan, "Theoretical determination of the optimal fiber volume fraction and fiber-matrix property compatibility of short fiber composites," *Polymer composites,* vol. 14, pp. 85-93, 1993.

[44] D. Petrulis, "The influence of fabric construction and fibre type on textile durability: woven, knitted and nonwoven fabrics," *Understanding and Improving the Durability of Textiles,* p. 1, 2012.

[45] J. Hearle, "Theoretical analysis of the mechanics of twisted staple fiber yarns," *Textile Research Journal,* vol. 35, pp. 1060-1071, 1965.

[46] N. Pan, T. Hua, and Y. Qiu, "Relationship between fiber and yarn strength," *Textile Research Journal,* vol. 71, pp. 960-964, 2001.

[47] G. Haddad and J. Sutton, "Application of the Law of Composites to Twisted Continuous-Filament Glass/Nylon Blended Yarns," *Textile Research Journal,* vol. 42, pp. 452-459, 1972.

[48] W. Huang, T. Fu, Y. Zhang, and J. Wang, "An approach to predict the tensile strength of a two-ply yarn from single filament yarn," *The Journal of The Textile Institute,* vol. 108, pp. 412-417, 2017.

[49] D. Mattsson, "Mechanical performance of NCF composites," Luleå tekniska universitet, 2005.

[50] B. Madsen, P. Hoffmeyer, A. B. Thomsen, and H. Lilholt, "Hemp yarn reinforced composites–I. Yarn characteristics," *Composites Part A: Applied Science and Manufacturing,* vol. 38, pp. 2194-2203, 2007.

[51] H. Ma, Y. Li, and D. Wang, "Investigations of fiber twist on the mechanical properties of sisal fiber yarns and their composites," *Journal of Reinforced Plastics and Composites,* vol. 33, pp. 687-696, 2014.

[52] O. Demircan, T. Kosui, S. Ashibe, and A. Nakai, "Effect of surface treatment and twisting on tensile and bending properties of aramid unidirectional composites," *Composite Interfaces,* vol. 21, pp. 287-299, 2014.

[53] M. Rask and B. Madsen, "Twisting of fibres in yarns for natural fibre composites," in *18th International Conference on Composite Materials*, 2011.

[54] B. K. Cheung and J. P. Carey, "Improving two-dimensional braided composite tensile properties by including low angle yarn twist: Production, experimental verification, and modeling," *Journal of Engineered Fibers and Fabrics,* vol. 15, p. 1558925020946449, 2020.

[55] A. K. Kaw, *Mechanics of composite materials*: CRC press, 2005.