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EXPLORING THE EFFECTS OF STITCHING PROCESS ON THE MECHANICAL PROPERTIES OF THREE- DIMENSIONAL (3D) STITCHED UNIDIRECTIONAL COMPOSITES

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Keywords

Stitching, Unidirectional Fabric, Carbon Fiber, Mechanical Tests, Polymer Composites.

Abstract

The stitching process has obvious effects on the out- of- plane mechanical properties of composites such as impact damage mechanism or impact energy absorption. However, the effects on the in- plane mechanical properties of composites have been under discussion and need to be clarified. In the previous studies, tensile, shear and bending behaviors of 3D stitched biaxial woven carbon composite were investigated. The unidirectional carbon woven fabrics constitute the significant part of raw materials in the composite industry. For this reason, the research study was expanded to examine the in- plane mechanics of 3D stitched unidirectional carbon woven composites. In this study, the unstitched and 3D stitched unidirectional woven carbon composites were manufactured and tested under the shear, tensile and bending loads. While the stitching process improved the tensile and shear modulus of composite, it could not create the significant difference in the bending behavior. The highest module and maximum stress values were obtained in the tensile test. The bending and shear test results follow them, respectively. Moreover, it was proven that the fabric architecture of stitched composite layer has the substantial effect on the tensile properties of 3D stitched composite.

DİKİM İŞLEMİNİN ÜÇ BOYUTLU (3B), DİKİLMİŞ TEK EKSENLİ KOMPOZİTLERİN MEKANİK ÖZELLİKLERİNE ETKİLERİNİN İNCELENMESİ

Anahtar Kelimeler

Dikme, Tek Eksenli Kumaş, Karbon Lifi, Mekanik Test, Polimer Kompozit.

Öz

Dikme işlemi kompozitin kalınlığı yönündeki darbe hasar dayanımı ya da darbe enerjisi emilimi gibi mekanik özellikleri üzerine belirlenmiş etkilere sahiptir. Bu duruma karşın dikme işleminin kompozitin düzlemi yönündeki mekanik özellikleri üzerine etkileri hala tartışılmakta ve aydınlatılması ihtiyacı duyulmaktadır. Önceki dönemlerde yapılan çalışmalarda iki eksenli karbon dokuma kumaşların dikilmesi ile üretilmiş 3B kompozitin çekme, düzlemsel kayma ve eğilme özellikleri incelenmiştir. Tek eksenli karbon dokuma kumaşlar kompozit endüstrisinde kullanılan ham maddelerin önemli bir bölümünü temsil etmektedir. Tek eksenli karbon dokuma kumaşların dikilmesi ile üretilmiş olan 3B kompozitin düzlemsel mekanik özelliklerinin incelenmesi amacı ile çalışma genişletilmiştir. Bu çalışmada, tek eksenli karbon dokuma kumaşlar ile dikilmiş ve dikilmemiş kompozitler üretilmiş ve çekme, düzlemsel kayma ve eğilme yükleri altında test edilmişlerdir. Dikme işlemi kompozitin çekme ve düzlemsel kayma modüllerini arttırırken eğilme davranışında önemli bir fark yaratamamıştır. En yüksek modül ve yük değerleri çekme testinde elde edilmiştir. Eğilme ve kayma test sonuçları sırası ile bu değerleri takip etmiştir. Bu sonucun yanı sıra dikilmiş kompozit katmanının sahip olduğu kumaş mimarisinin kompozit çekme özellikleri üzerine önemli bir etkisinin olduğu belirlenmiştir.

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EXPLORING THE EFFECTS OF STITCHING PROCESS ON THE MECHANICAL PROPERTIES OF THREE- DIMENSIONAL (3D) STITCHED UNIDIRECTIONAL COMPOSITES

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Highlights

- The stitching improves the tensile and shear modulus of SUD composites,
- The fabric architecture of composite layer has the substantial effects on the mechanics of SUD,
- The stitching process do not have statistically meaningful effects on the maximum stress values of SUD,

Graphical Abstract

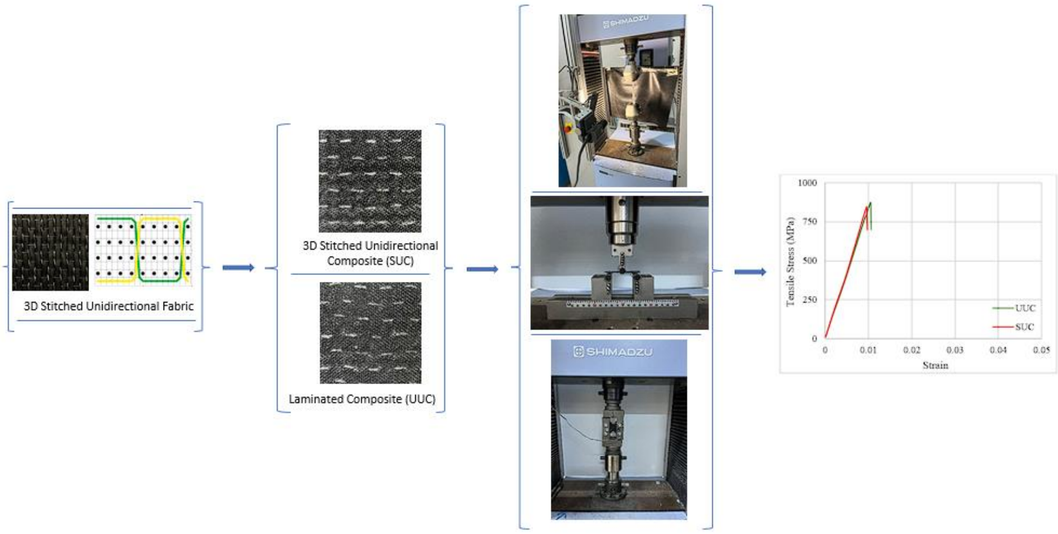

Figure. Investigation The Effects Of Stitching Process On The Mechanical Properties Of 3D Stitched Unidirectional Composite

Purpose and Scope

The effects of stitching process on the in- plane mechanical properties of composites have been under discussion and need to be elucidated for the 3D stitched unidirectional woven composites.

Design/methodology/approach

The 3D stitched unidirectional woven and traditional laminated composites were produced and tested under the shear, tensile and bending loads.

Findings

The maximum tensile, in- plane shear, bending stress and module values of 3D stitched unidirectional woven composites were determined. While the stitching process did not change the maximum stress values of composites, the process improved the tensile and shear module values. In addition, the result proven that the tensile properties of 3D stitch composite are affected by the fabric architecture of composite layer.

Originality

Several studies were carried out to elucidate the effects of stitching process on the in- plane mechanical properties of stitched biaxial woven composites. Because of the multiple effects of stitching process, the contradictory results were obtained from the studies. The unidirectional woven fabrics constitute the significant part of raw materials in the composite industry. Therefore, the effects of stitching process on the 3D unidirectional woven composites were elucidated thanks to this study. Moreover, the results were compared with the previous studies to show the effects of fabric architecture on the composite mechanics.

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1. Introduction

The specific structural properties of three- dimensional (3D) textiles gain outstanding properties to the composites. The separated fiber or yarn group, which is placed in the third direction of fabric, improves the mechanical behaviors in their thickness. The 3D textiles can be obtained by the weaving, knitting, braiding, tufting, stitching or non- woven production methods. Among the production methods, the stitching has special importance thanks to its easy to apply. The 3D stitching process impart the outstanding damage tolerance and acceptable fatigue performance to the polymer composites (Larsson, 1997).

The PRSEUS concept (The Pultruded Rod Stitched Efficient Unitized Structure), which was developed by the NASA, Boeing and the United State Air Force, expanded the awareness and run- up the publications about 3D stitched composites (Velicki and Jegley, 2014). The pattern of stitch, the stitch yarn linear density, the density of stitch, pretension, the type of stitch, the twist of stitch yarn, ply orientation or the raw material of stitch yarn have been under examination to clarify their effect on the mechanical properties of 3D stitched composites. Moreover, the number studies have focused on the effects of stitch yarn linear density (Yalkın et al., 2015; Xu et al., 2015; Tan et al., 2012) and stitch density (Tan et al., 2013; Lascoup et al., 2010; Pingkarawat et al., 2013) because both parameters are strongly related with the mechanical behaviors of composite (Drake et al., 2021).

Reis et al. (2024) produced 3D stitched and laminated composites to investigate their three- point bending, Charpy impact, double cantilever beam and short beam shear properties. The obtained results show that the stitching process improve the fracture toughness of composite. Li et al. (2021) stitched unidirectional carbon fibers with the ultra- thin continues nanotube belts. Afterward, double beam cantilever beam, end notch flexure, tensile and bending tests were carried out. It was concluded that while the stitching did not affect the tensile and bending properties, the process improved mode I and mode II interlaminar toughness of composites. Kaya et al. (2022) produced unreinforced and stitched 3D carbon composites and examined their flexural properties. Although the stitching process reduced the flexural strength and modulus of composites, the process improved the toughness of stitched 3D composite.

The effects of stitching process on the in- plane mechanical properties of composites are not clear and need to be elucidated. For this reason, studies have been conducted to clarify the mechanical behaviors of 3D stitched composites for last decade. For instance, while some studies (Aymerich et al., 2003) were concluded the stitching improves the composites tensile properties, number of studies (Shah Khan and Mouritz, 1996) determined that the stitching degrades the tensile properties. Moreover, the several studies (Larsson, 1997; Kang and Lee, 1994) showed that the process does not change the composites tensile properties. It is possible to extend the contradictory results for other mechanical properties.

The contradictory results of in- plane mechanical properties of stitched composites are originated from the multiple effects of stitching process on the composites. This process can change the thickness of composite, local or total fiber volume fraction of composite, in- plane yarns' crimp ratios, in- plane yarns' orientations or damage the in- plane yarns. This phenomenon makes more complicate the predicting in- plane mechanical behaviors of stitched composites and cause to obtain the contradictory results.

The unidirectional carbon woven fabrics constitute the significant part of raw materials in the composite industry. They are especially demanded by the aerospace industry thanks to their high strength in the fiber direction and easy to model their structure (Heidari-Rarani et al., 2018; Reinforcements, 2024). However, the biaxial woven fabrics were mostly preferred (Kirmasha et al., 2020; Saboktain et al., 2022; Tarfaoui et al., 2019) to constitute the layers of 3D stitched composites. The few numbers of studies (Abdelal and Donaldson, 2018) were conducted to determine the mechanics of 3D stitched unidirectional carbon woven composites (SUC) and need to be elucidated.

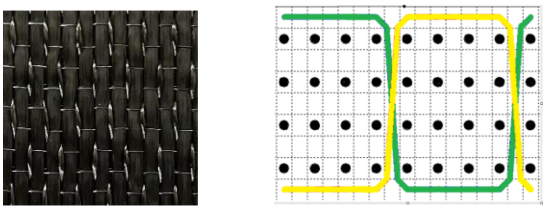
In the previous studies (Korkmaz, 2024; Korkmaz 2023), the tensile, in- plane shear, quasi- static indentation and bending properties of 3D stitched biaxial carbon woven composite (SBC) were investigated. As clarifying the contradictory results in- plane mechanics of stitched composites and observe the effects of fabric architecture, the research was extended and carried out on the SUC. The same stitching conditions, which are the stitch yarn type, the stitch density and stitch length, were applied to obtain the SUC.

In the study, the SUC was produced and applied the shear, tensile and bending load. Moreover, the unstitched unidirectional traditional laminated composite (UUC) was manufactured and characterized to make comparison. Therefore, the effects of stitching process on the in- plane mechanical properties of composite could be clarified under the diversified loads.

2. Material and Method

2.1. 3D Stitched Unidirectional Fabric

The unidirectional woven fabric was used in the study to obtain 3D stitch unidirectional fabric. This kind of woven fabrics include the main yarns at just warp direction. The monofilament glass yarns were placed at the weft direction to keep together the warp yarns and give them the fabric form. Thanks to the low diameter value of monofilament glass yarns, the warp yarns has almost the non- crimp structure. Therefore, they can transfer their strength to the composites with the minimum loss. The unidirectional woven fabric was constituted by the 12k-carbon yarns (800 Tex) and has 200 g/m^2 unit weight. The 3k- carbon yarn (200 Tex) was preferred to apply hand stitch to four layers of fabrics. Density of stitch yarn was 2.5 yarns/ cm and length were 8 mm. Front appearance of SUC and its schematic cross section are presented in Figure 1. In cross-section view, which was created by the WiseTex program (WiseTex suite, 2024), stitch yarns are represented with the green and yellow lines. The weft yarns of unidirectional fabrics, which is monofilament glass yarn, are identified with the black dots. The figure does not include the warp yarns.



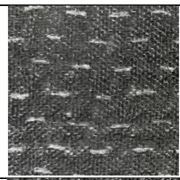
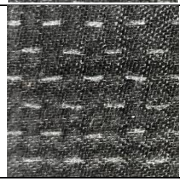
(a) (b)

Figure 1. The 3D Stitched Unidirectional Fabric (A) Front Appearance, (B) The Cross Section

2.2. Production The Composites

In the composite production stage, the VARIM method was preferred and hardener to epoxy proportion was adjusted at 1:3. The matrix had been cured at 80°C for eight hours. Moreover, four layers unidirectional laminated carbon composite was manufactured for comparison. The areal densities of structures are similar and have almost 900 g/m^2. The thickness, density values, fiber volume fractions and surface appearances of composites are shown with their standard deviations (S.D) in Table 1.

Table 1. Properties of Composites

Type of Composite	Fiber volume fraction (%)	S.D	Thickness (mm)	S.D	Density (g/ cm^3)	S.D	Photograph
Unstitched unidirectional composite (UUC)	54.45	0.008	0.83	0.01	1.63	0.06	
3D stitched unidirectional composite (SUC)	57.37	0.008	0.94	0.01	1.51	0.05	

2.3. Test of the Composites

2.3.1 Tensile Test

The composites were tested based on ASTM-D3039/D3039M-14. Shimadzu Autograph AG-X 100 kN testing device was used the tests were applied for just warp direction. The five test samples were prepared for every type of composite at 250 × 25 mm dimensions. Tensile test was carried out with the extensometer to measure displacement values. Tensile modulus and maximum stress values were determined for both composites. Test machine and extensometer equipment are shown in Figure 2(a) and 2(b), respectively.

2.3.2. Bending Test

The bending test was conducted according to ASTM D790 with Shimadzu Autograph AG-X 100 kN. The dept- to-thickness ratio was settled at 32:1. Five specimens, which has 12.5 x 65 mm dimensions, were tested for every type of composite. The bending apparatus is presented in 2(c).

In the test, bending force and deflection values were obtained. Afterward, the bending stress, strain and modulus values were calculated thanks to the equations 1, 2 and 3 (ASTM D790, 2017), respectively.

$$S_f = 3PL/2bd^2 \quad (1)$$
$$e_f = 6Dd/L^2 \quad (2)$$
$$E_B = L^3m/4bd^3 \quad (3)$$

In the equations, S_f is stress in the outer fibers at midpoint (MPa), *P* is load at a given point on the load- deflection curve (N), *L* is support span (mm), *b* is width of beam tested (mm), *d* is the thickness of beam tested (mm), e_f is the strain in the outer surface (mm/ mm), *D* is maximum deflection of the center of the beam (mm), E_B is modulus of elasticity in bending (MPa), and *m* is slope of the tangent to the initial straight-line portion of the force-deflection curve (N/mm).

2.3.3. In- Plane Shear Test

The V-Notched Rail shear test was applied to the composites according to the ASTM-D7078/D7078M-19 standard by the Shimadzu Autograph AG-X 100 kN test machine. The shear apparatus is presented in Figure 2(d).

(a) (b) (c) (d)

Figure 2. Testing Machine and Apparatus (A) Shimadzu Autograph AG-X 100 Kn, (B) Tensile Test With Using Of Extensometer, (C) Bending Apparatus, (D) Shear Apparatus

The strain- gage was used to measure strain values in the test. For every type of composite, the five specimens were prepared. The sizes of shear sample are shown in Figure 3. Shear strength and modulus values of composite were calculated with the equation 4 and 5 (ASTM D7078M-19, 2020), respectively.

$$\tau_{12} = \frac{P}{A} \quad (4)$$

$$G_{12} = \frac{\tau_{12}}{\gamma_{12}} \quad (5)$$

In the equations, τ_{12} is shear stress (MPa), *P* is force (N), *A* is cross section area (mm^2), G_{12} is shear modulus (MPa) and γ_{12} is shear strain.

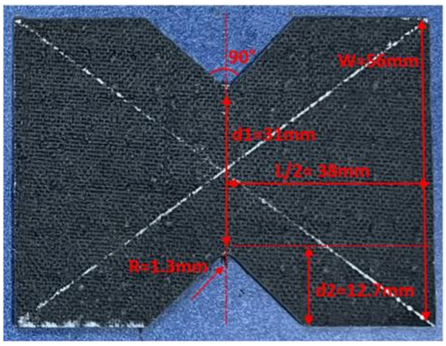


Figure 3. Dimensions Of Shear Test Specimen

3. Results and Discussions

3.1. Tensile Test Results of Composites

The tensile stress- strain graphs of composites are shown in Figure 4. While the red line represents SUC, the UUC is identified with the green line in the figure. In addition, the obtained tensile modulus and maximum tensile stress values of composites are shown in Figure 5. Stitching did not impress maximum tensile stress values of composites. On the other hand, the process enhanced the tensile modulus of composite. It is possible to explain this phenomenon with that the stitching helps the yarns to do not disturb their direction in the composite production stage.

In the previous study (Korkmaz, 2024), stitching process reduce the fiber volume fraction and degrade the tensile module of SBC along the stitching direction. However, the opposite behavior was observed in the SUC and improve the tensile module value. The obtained result proven that the fabric architecture of stitch composite layer has the significant effect on tensile properties of stitched composite.

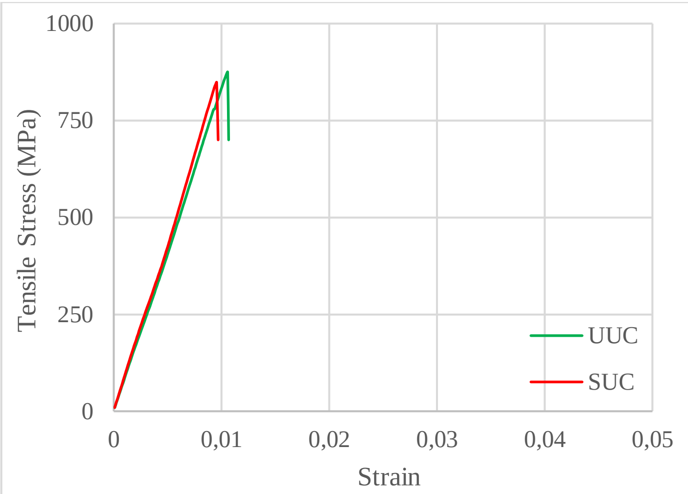
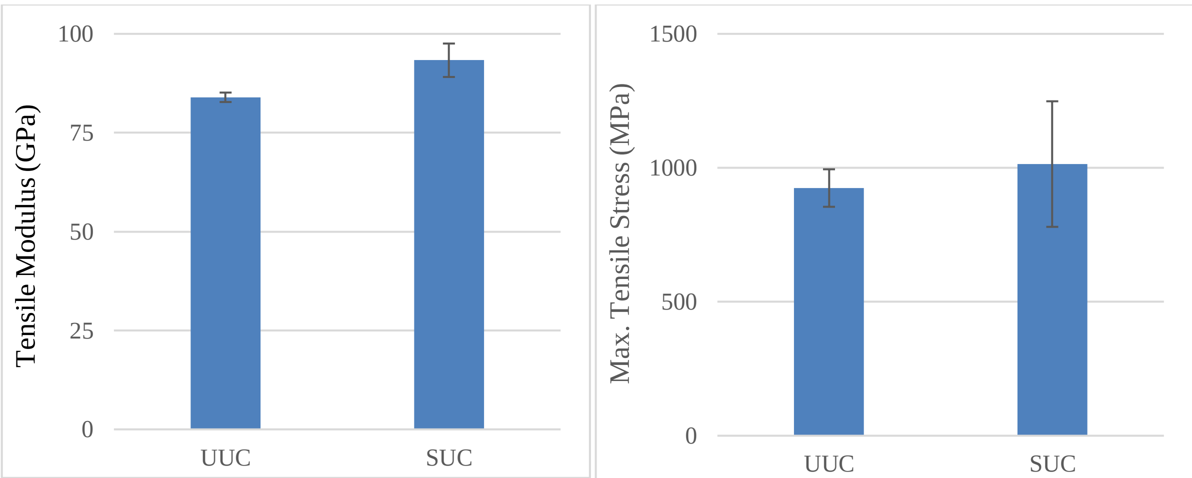


Figure 4. The Stress- Strain Graphs of Composites

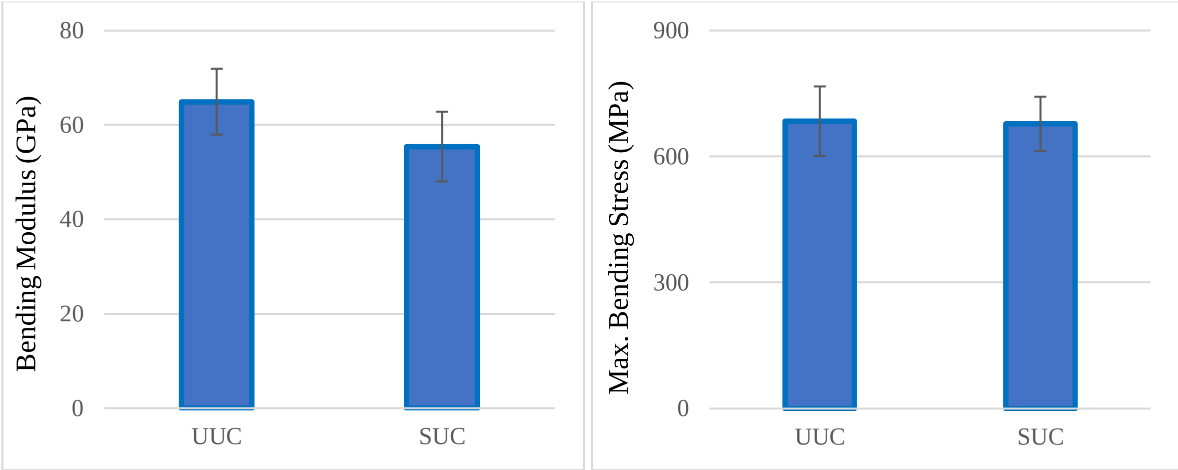


(a) (b)

Figure 5. Tensile Graphs of Composites (A) Tensile Modulus Values, (B) Max. Tensile Stress Values

3.2. Bending Test Results of Composites

Bending modules and maximum bending stress values of composites are presented in Figure 6. The stitching process did not create statistically significant differences in bending module and maximum stress values. In previous study (Korkmaz, 2023), the same behavior was observed in the SBC and the stitching process did not chance the maximum bending stress and bending module of composite.



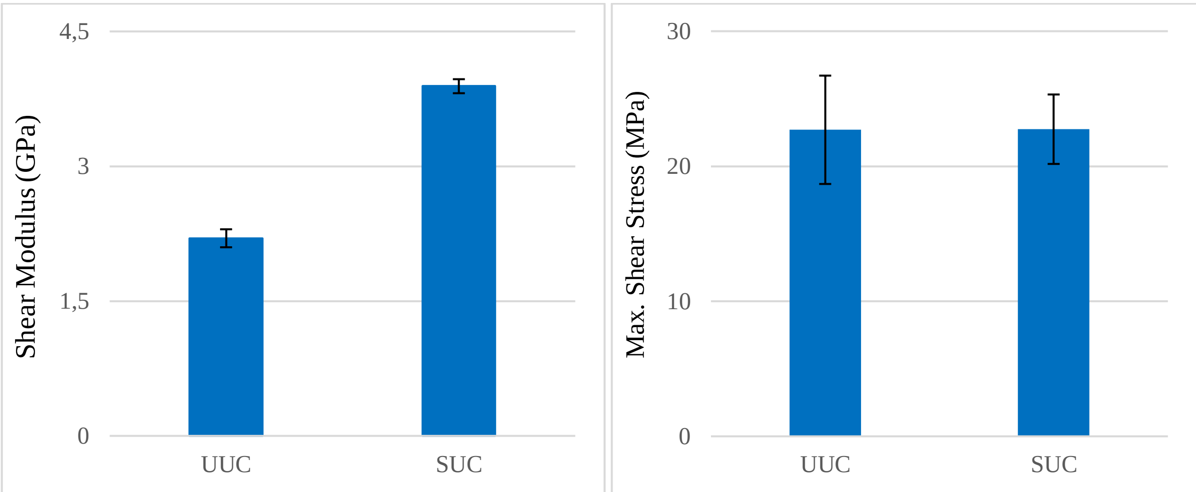
(a) (b)

Figure 6. Bending Graphs of Composites (A) Bending Modulus Values, (B) Max. Bending Stress Values

3.3. In- Plane Shear Test Results of Composites

Shear modules and maximum shear stress values of composites are presented in Figure 7. Although stitching process did not create statistically significant difference in the maximum shear stress values, the shear modulus of composite was increased almost two times.

In the unidirectional woven fabrics, glass monofilament yarn was used as weft yarns. Therefore, unidirectional yarns can gain fabric form and make easier the producers for composite manufacturing. The shear properties of composites are mainly characterized by the intra and inter- layer frictions of fabric layers. Stitching process create interlacement points between in- plane and stitching yarns. As result, the maximum shear stress was not influenced by the process. However, the created interlacement points almost two times improved the shear modulus of composite. In the previous study (Korkmaz, 2024), the same behavior was observed in the SBC. While stitching process improved shear module, process did not change maximum shear stress value of composite.



(a) (b)

Figure 7. Shear Graphs of Composites (A) Shear Modulus Values, (B) Max. Shear Stress Values

4. Conclusions

The 3D stitched unidirectional carbon composite was manufactured and tested under the shear, tensile and bending loads in the study. Moreover, a laminated unstitched carbon composite was manufactured and tested to for comparison. Modulus and maximum stress values of composites were determined for every type of mechanical test.

While stitching process did not change maximum stress values of composites, process improved tensile and shear module values. According to the module and maximum stress values, the highest results were obtained from the tensile test. The results of bending and shear tests follow them, respectively. Moreover, the obtained results were compared with the previous studies, which were carried out on the SBC with the same stitching conditions. Although the stitching decreased the tensile module of SBC, the opposite behavior was observed in the SUC. The result proven that tensile properties of 3D stitch composite is affected by fabric architecture of composite layer.

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Conflict of Interest

No conflict of interest was declared by the author.

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