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Influence of Stitching Parameters on Tensile Strength of Aramid/Vinyl Ester Composites

Mehmet KARAHAN [1] *, Yusuf ULCAY [2], Nevin KARAHAN [1], Abdil KUŞ [3]

[1] *Textile Department, Vocational School of Technical Sciences, Uludag University, 16059, Gorukle- Bursa, Turkey*
[2] *Textile Department, Engineering and Architecture Faculty, Uludag University, 16059, Gorukle- Bursa, Turkey*
[3] *Mechanical Department, Vocational School of Technical Sciences, Uludag University, 16059, Gorukle- Bursa, Turkey*

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Stitching process is used to provide structural integrity and through-the-thickness reinforcement in the composite materials. In this study, the effect of sewing parameters on tensile strength in stitched composite laminates was examined. In the production of composite laminates, Twaron T-750 type plain weave fabric was used as reinforcement material and a Polives 702 Bisphenol-A type epoxy based vinyl ester as resin. The effects of stitch density and stitch direction or stitch pattern on tensile strength of composite samples were studied and, as a result of the experiments, it was observed that higher tensile strength occurs with low stitch densities in stitched laminates.
Keywords: stitch bonding, stitch direction, Twaron woven composites.

1. INTRODUCTION*

Stitching process to join the fabric plies is used widely in the composite industry since it is easily applied and a flexible production method. With the stitching process, two-dimensional textile preforms convert into three-dimensional constructions. In these structures, translaminar properties develop to values comparable to those of three-dimensional woven structures [1 – 3]. Para-aramid sewing yarns, which have high number of twist, are the most widely used sewing yarn type in this field due to their flexibility, which is required to bend into a small curvature in the needle hole. The standard lock and chain stitches are most popular stitch types used in composite industry. Bekampiene and Domskiene [4] have carried out an experimental study about influence of stitching parameters such as stitching pattern, direction, location and stitching step on woven fabric deformation behavior.

In composite applications the most important advantage of stitching is to prevent the delamination among the fabric layers. In this subject, Dransfield et al. [5] explained the studies that were made to develop delamination properties of composites using the stitching technique among layers in the recent year. Huang et al. [6] were one of the first researchers who developed a technique concerning to reduce delamination and to enhance the shear strength of carbon-epoxy composite materials among layers. Holt [7] developed a stitching technique used to joining of composite parts used in aircraft industry. In another study, Mignery et al. [8] thought that the Kevlar sewing yarns were stitched along the edges of the fabrics to decrease the free edge delamination and increase the tensile strength of carbon fiber composites. Stitch bonding also improves the shear strength among layers [9]. In unstitched composite materials, the shear among layers occurs easily and the layers separate from each others, but in sewn preforms the stitching is bonded the layers to each other prevents or limits this separation.

Another advantage of stitch bonding process is its improvement of impact resistance. The effect of stitch bonding on impact properties was researched in various studies [10 – 11].

One of the most important factor among the many stitch parameters is stitch density. In this subject, Dransfield et al. [5] stated that there would be a critical stitch density value in which delamination resistance among layers could be at a maximum level. In the meantime, it was stated by different researchers [12, 13] that a very high stitch density would cause misalignment of yarns in the fabric and, more importantly, caused fiber deformation since needle penetration and affected mechanical properties of the structure negatively. Therefore, excessive stitch density negatively affects mechanical properties of composite materials [14 – 17].

In a previous study [12], influence of stitch density on tensile properties of woven aramid/vinyl ester resin composite plates was investigated. The samples used in the previous study [12] were sewn only in uni-direction as parallel. The main distinction of present study the samples used in the study sewn in bi-direction as orthogonal and diagonal. In the current study, the effects of stitch direction (or stitch pattern), stitch density and fiber volume fraction of the sewing yarn on tensile strength and modulus were examined. The samples were sewn in various stitch densities as biaxial and compared with unstitched equivalent composite samples in terms of tensile strength and modulus. The stitch yarn used in the study, yarn thickness, and stitch type parameters were fixed as constant. The samples were produced with the same fabric, resin and production method with the previous study [12].

*Corresponding author. Tel.: +90-224-2942367; fax.: +90-224-2942303.
E-mail address: *mkarahan@uludag.edu.tr* (M. Karahan)

Table 1. Measured properties of Twaron T-750 type fabrics used in this research

Count (dtex) warp/weft	Yarn type warp/weft	Weave	Density (ends and picks/10 cm)	Fabric weight (g/m^2)	Crimp (%) warp/weft	Tensile strength (MPa) longitudinal/transverse	Young's modulus (GPa) longitudinal/transverse
3360	Twaron 1000	Plain	65	440	2.2	224.6	2.84
3360	Twaron 1000	Plain	64	440	2.1	158.5	2.75

Table 2. Sewing parameters in the samples used in the study

Samples	Fabric ply number	Distances between the stitches (cm)	Stitch density (stitch/cm)	Stitch density (stitch/cm^2)	Stitch type	Stitch direction
A1	4	3	2	1.33	Lock stitch	Bi-axial-Orthogonal
A2	4	3	3	2	Lock stitch	Bi-axial-Orthogonal
A3	4	3	4	2.66	Lock stitch	Bi-axial-Orthogonal
A4	4	2	2	2	Lock stitch	Bi-axial-Orthogonal
A5	4	2	3	3	Lock stitch	Bi-axial-Orthogonal
A6	4	2	4	4	Lock stitch	Bi-axial-Orthogonal
A7	4	1	2	4	Lock stitch	Bi-axial-Orthogonal
A8	4	1	3	6	Lock stitch	Bi-axial-Orthogonal
A9	4	1	4	8	Lock stitch	Bi-axial-Orthogonal
B1	4	1	2	4	Lock stitch	Bi-axial-Diagonal
B2	4	1	3	6	Lock stitch	Bi-axial-Diagonal
B3	4	1	4	8	Lock stitch	Bi-axial-Diagonal

2. MATERIALS AND METHODS

2.1. Materials

In the production of composite materials, Twaron T-750 plain weave fabric was used. Technical parameters of the fabric are given in Table 1. Polives 702 Bisphenol-A type epoxy-based vinyl ester was used as the resin. 2 % ratio and 50 % active methyl ethyl ketone peroxide and 0.25 % ratio 6 % cobalt naphthalene were used as hardener and accelerator.

2.1.1. Preparation of composite samples

Fabric layers were produced with the 300 mm×300 mm dimensions in 4 plies by changing stitch density and distance between stitches with a standard lock stitch. The fabric layer number, stitch density, distance between the stitches and the stitch directions used in the study are stated in Table 2. Stitch density and the distance between the stitches were changed to investigate the effect of stitch density. In the same time 4 plies and equivalent unstitched samples were produced to compare.

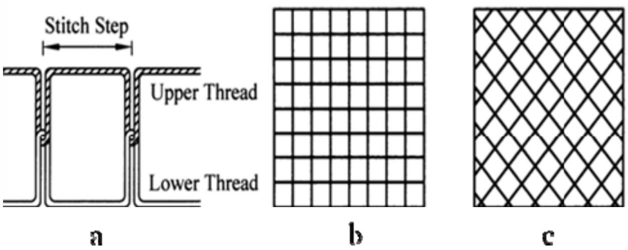

Fig. 1. Schematic view of standard lock stitch (a); orthogonal (b) and diagonal (c) bidirectional stitching patterns used to bonding the samples

The sewing yarn is high number of twisted Kevlar. This sewing yarn has 60/3 tex linear density and (1.42 ±0.12) N/tex tensile strength. The sewing needle has 1 mm body diameter and 100 Nm metric numbers. Sewing operations were done using an industrial sewing machine with constant yarn tension. The schematic view of the standard lock stitch was given in Figure 1, a. Directions and pattern of stitching as bi-directional orthogonal and bi-directional diagonal are shown in Figure 1, b and c, respectively.

Woven aramid/vinyl ester composite panels were produced using Twaron T 750 type plain weave and a Polives 702 Bisphenol-A vinyl ester resin system. After stitching, the laminates were fabricated using the vacuum assisted resin infusion process (Figure 2).

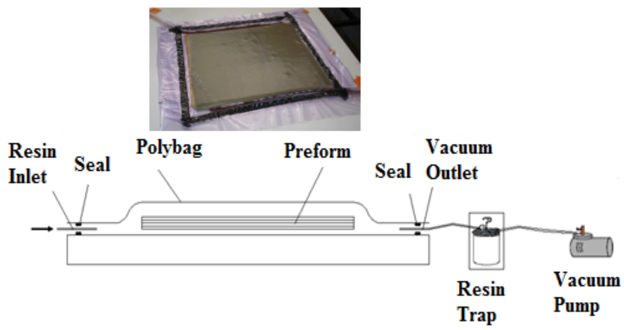

Fig. 2. Schematic representation of vacuum assisted resin infusion process

2.2. Methods

2.2.1. Tensile strength and modulus

The experimental investigation of tensile strength and module in composite samples was carried out using Instron tensile device having 100 kN capacity in accordance with ASTM 1D 638 standards. In all stitched and unstitched samples, tensile tests were carried out on the samples cut in longitudinal (warp) and transverse (weft) directions for observing the variation of strength and modulus in warp and weft yarn directions. Five samples were used for each direction. The sample dimensions used for tensile tests were taken as (40×200) mm and test speed as 15 mm/min.

3. RESULTS AND DISCUSSION

3.1. Tensile properties in unstitched composites

For the stitched and unstitched T-750 Twaron-vinyl ester composite laminates, the fiber volume fractions and plate thicknesses are shown in Table 3. Fiber volume fraction was determined using the weight differences before and after the resin application.

As seen in Table 3, for stitched laminates, thickness is slightly less and fiber volume fraction is slightly higher than unstitched composite laminates having the same layer number. The stitched composite plate thickness was determined 0.19 mm less and fiber volume ratios 2 % higher than for unstitched plates. There is no significant difference between these values. Thickness of the stitched samples are slightly less and fiber volume fraction is slightly higher than unstitched one due to the stitching process increases the compactness of the preform.

Table 3. Sample thicknesses and fiber volume fraction values in stitched and unstitched T750-vinyl ester composites

Samples type	Fabric ply number	Fiber volume fraction (V_f) (%)	Thickness (mm)
Unstitched sample	4	65	2.40
Stitched sample	4	67	2.21

In the experimental determination of tensile strength and Young's modulus, tensile tests were carried out in the longitudinal and the transverse direction of composite laminates. Experimental results for the unstitched composite plates are given in Table 4**.**

3.2. Tensile properties in stitched composites depending on stitching parameters

Tensile strength and Young's modulus of 4 plies stitch bonded composite plates, which have different stitch density, are researched in longitudinal and transverse directions to investigate the effect of stitch density on tensile properties. Stitch densities used in this study are given in Table 2. Stitch densities (stitch/cm^2) were formed depending on the distance between stitches (cm) and stitch density in unit length (stitch/cm). In the examination of the effect of stitch density on tensile strength and module, some parameters such as fabric layer number, sewing yarn and sewing tension were fixed as constant and only stitch density was changed in all the samples. The composite plates prepared in various stitch densities were subjected to tensile tests in longitudinal and transverse directions, as in unstitched plates. Tensile strength and modulus depending on stitch density in longitudinal and transverse directions of T 750-vinyl ester composites bonded with bi-directional stitching are given in Table 5.

Figure 3, a, shows a deformation that happens at a stitch point. During tensile testing the breaking of stitch yarns was observed as the first damage phenomenon (Figure 3, b). The reason of the breaking of stitch yarns first is that sewing yarn's ultimate failure strain is lower than yarns in the the fabric due to high number of twist of sewing yarns. In this situation, it can be stated that stitch points are characteristic damage initiation zones. Especially intersections of stitch yarns in the fabric are weakest point because of needle penetration damage is maximum in there. Ultimate failure of the sample occurred at these zones. Figure 3, c, shows the optical micrographs of fracture surface. Especially stitching line perpendicular to the tensile direction is weakest zone and breaking occurs along this stitching line.

Table 4. Tensile properties of unstitched composite samples having 4 fabric plies and 65 % fiber volume fraction

Strength, longitudinal/ transverse (MPa)	Modulus, longitudinal/ transverse (GPa)	Ultimate strain, longitudinal/ transverse (%)
394.87	3.13	12.62
375.10	2.96	12.70

The damage characteristics of stitched plates are considerably different than those of unstitched monolithic panels [18, 19]. As far as stitch density increases, ultimate strain value decreases. This mean that the damage starts earlier in the stitched composites. Inter layer delamination is mostly prevented in the stitched composites. In the tensile tests, the samples doesn't separate totally and partly protect its' integrity. While unstitched laminates become delaminated even within tensile test, the integrity of the stitched samples is kept. However top and bottom layers have some wrinkle form especially for low stitch densities. As far as stitch density increases, this waviness problem decreases. This problem was seen much more in parallel uni-axial stitched samples, but it can be specified that this problem is significantly reduced by bi-axial stitch bonding compared with uni-axial stitched samples [12].

For lower stitch densities, higher tensile strength values have been observed in the stitched samples. However, it is observed that tensile strength decreases with stitch density increase. 16 % decrease in tensile strength occurs where the distance between stitches reduces from 3 cm to 1 cm. An 10 % decrease is recorded in strength loss when stitch density arises from 2 cm to 4 cm. In stitched plates, an increase in tensile strength in low stitch densities is attributed to stitched plates that have denser structure than unstitched plates. In these plates the fiber volume fraction is some higher than unstitched plates as seen in Table 3. This situation is the most important reason for explaining the increasing of the tensile strength. In addition, the stitch yarn itself reinforced the construction, although it is a very low volume fraction. Tensile strength was reduced depending on the stitch density after a certain value and the most important reasons of this can be stated as fiber breakages on the fabric that occurs within sewing, deviation of fibers around the stitch point from their normal directions and spaces or areas being resin rich zones around the stitch points. These reasons were discussed comprehensively in the previous study [12].

Table 5. Tensile properties of 4-plies T750/vinyl ester composites bonded with bi-axial lock stitching depending on stitch density

Samples	Amount of stitch yarn (g)	Fiber volume fraction of stitch yarn (%)	Strength (MPa) longitudinal/transversal	Modulus (GPa) longitudinal/transversal	Ultimate strain (%) longitudinal/transversal
A1	0.0012	0.42	411.53/ 389.25	3.17/ 3.06	12.62/ 12.70
A2	0.0014	0.49	387.55/ 362.27	2.92/ 2.89	13.91/ 12.52
A3	0.0015	0.52	369.30/ 355.25	3.00/ 2.95	12.30/ 12.04
A4	0.0018	0.62	413.20/ 396.15	3.12/ 2.92	13.26/ 13.11
A5	0.0021	0.73	378.65/ 372.72	3.04/ 3.07	12.46/ 12.13
A6	0.0017	0.59	358.23/ 347.14	3.20/ 3.07	11.20/ 11.18
A7	0.0036	1.25	401.27/ 382.15	3.26/ 3.21	12.30/ 11.92
A8	0.0041	1.42	387.65/ 373.42	3.27/ 3.09	11.85/ 12.10
A9	0.0047	1.63	345.50/ 342.14	3.30/ 3.14	10.48/ 10.52
B1	0.0036	1.25	408.26/ 394.43	3.33/ 3.17	12.25/ 12.55
B2	0.0041	1.42	376.58/ 369.24	3.26/ 3.22	11.55/ 11.07
B3	0.0047	1.63	361.25/ 363.50	3.36/ 3.30	10.75/ 11.01

Figure 3, a, shows the deformation occurring at the stitch point, the deviation of fibers from their normal directions and the space. All the fibers around the stitch points without penetrated by needle have not deformed. However holes have been forming in warp and weft yarn layers both in longitudinal and transverse directions in these points and this situation causes the formation of areas being resin rich zones in the direction of thickness. Since there is not any fiber reinforcement in these areas being resin rich zones, they are the weakest points of the construction and as far as the ratio of this region increases in the construction, the strength of the construction weakens [5, 8, 12]. This situation is seen clearly in Figure 3, b, when looking at the deformation occurring around the stitch point. Matrix cracks initiate from these regions and progress on plate. So we can consider that the damage initiated and developed from around the stitch points. This mean that the stitch points and stitch spaces resin rich zones become stress concentration points during loading as mentioned by some researchers [14–16].

The effect of stitch denity and the distance between stitches on the strength and the modulus are seen in Figure 4. Referring to Figure 4, a, it is seen that increasing of stitch density (stitch/cm) is more effective on the strength than the distance between stitches. Strength degradation depending on the stitch density (stitch/cm) increases. Increase of stitch density (stitch/cm) more effective than increase of distance between stitches (or stitch step) on degradation of tensile strength. There significant differences between the longitudinal and transversal strength values for unstitched and stitched samples. But the variation of that depend on the stitch densities that are very similar to each other. Figure 4, a, also shows the comparison of strength variation of orthogonal and diagonal stitched samples. There no significant differences between tensile strength and modulus values of orthogonal and diagonal stitched samples.

According to Figure 4, b, there isn't a parallel changing in modulus with the strength and since strain ratio also decreases in spite of the decreasing of the strength, the modulus decreases or increases slightly depending on stitch density increasing. Figure 4, b, also shows the comparison of modulus variation of orthogonal and diagonal stitched samples. In this situation it can be state out that stitch density change is not an considerable effect on stiffness of the composites. Figure 5, a and b, show the trend of variation of strength and modulus depending on the stitch densities (stitch/cm^2) with linear regression respectively. The strength is obviously degraded depending on the increasing of the stitch density for both test directions longitudinal and transversal, but a marked degradation or increasing has not observed for modulus.

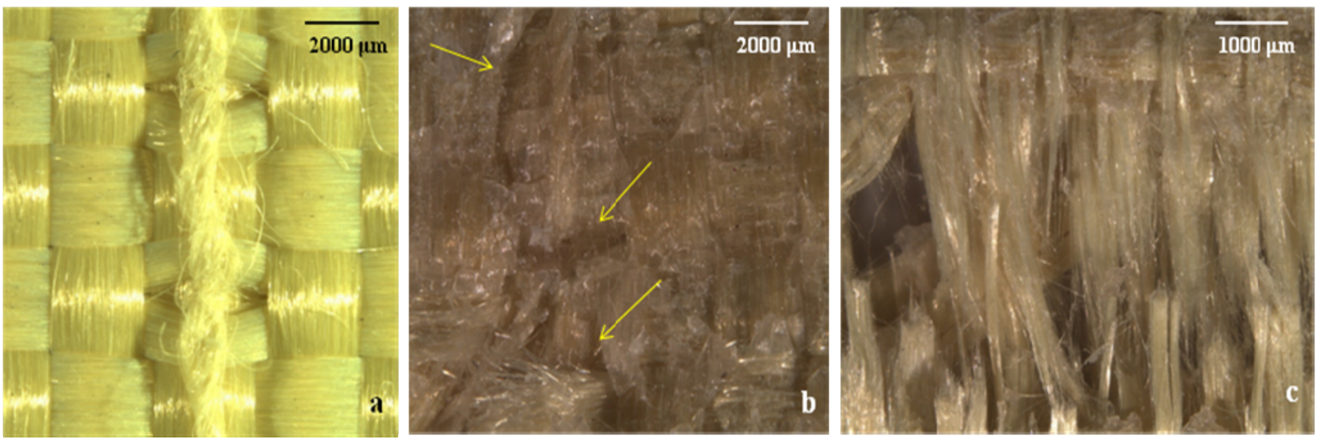

Fig. 3. Optical micrographs of deformation occurring at the stitch point (a); tensile damages around the stitch point (b) (arrows show the matrix cracking around the stitching yarns) and fracture surface of composite plate (c)

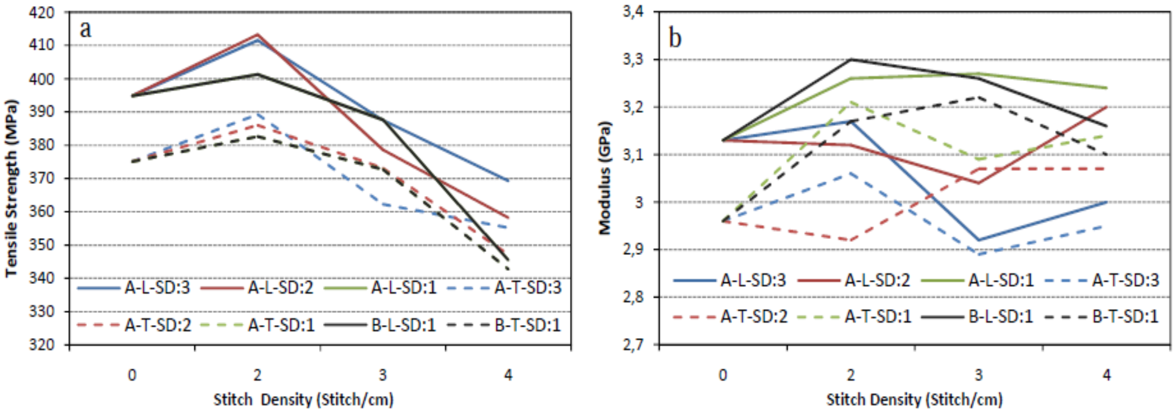

Fig. 4. Effect of stitch density on tensile strength and modulus: tensile strength (a) and tensile modulus (b) variation depend on stitch density for A and B samples; A and B indicate the sample codes, L and T indicate the longitudinal and transversal test directions respectively and SD indicate the stitch distance

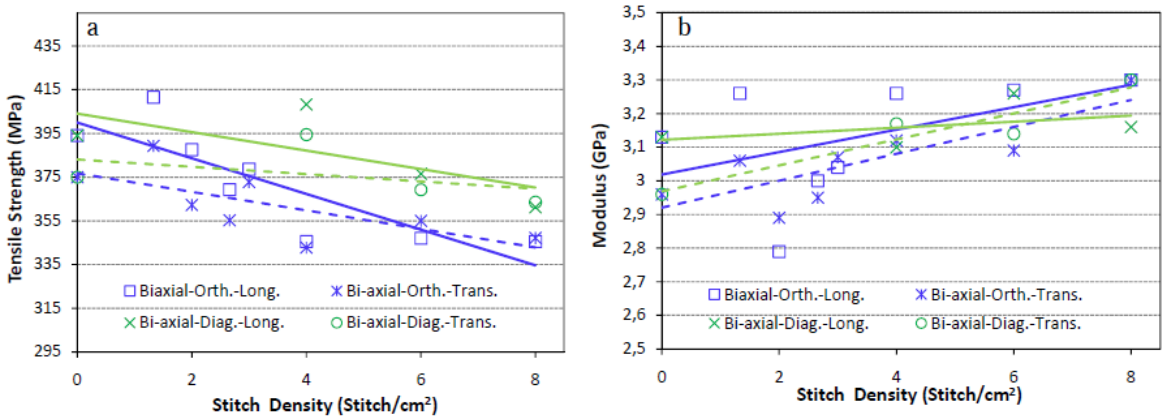

Fig. 5. Comparative plot of tensile strength (a) and modulus (b) variations depending on stitch density (stitch/cm^2). (Orth.: orthogonal; Diag.: diagonal; Long.: longitudinal and Trans.: transversal)

3.3. Fiber volume fraction of sewing yarns

The fiber volume fraction of sewing yarn used in composite was obtained from the below equations depending on the weight and linear density of sewing yarn. Yarn length l_{sy} used per unit area for lock stitch is expressed with the following equation depending on stitch density:

$$l_{sy} = (2 \cdot h + 2 \cdot t) \cdot \eta \tag{1}$$

where h shows stitch step length, t shows thickness of pre-form and η shows stitch density (stitch/cm^2). Stitch step length was measured by optic microscope from the images.

It was accepted that sewing yarn had full circular cross-section, in this situation, the diameter of sewing yarn could be obtained from the below equation depending on sewing yarn linear density:

$$d_{sy} = \sqrt{\frac{4 \cdot T}{\pi \cdot \rho \cdot K}} \tag{2}$$

where T is the linear density of the yarn, ρ is the density of the fibers, and K is the packing coefficient. The value of K: 0.907 is assumed (hexagonal packing). Depending on this equation, the diameter of sewing yarn was calculated as 0.24 mm. Amount of sewing yarns, w, used in composite construction is found from the below equation:

$$w = \rho \cdot \pi \cdot d_{sy}^2 \cdot l_{sy} \tag{3}$$

The fiber volume fraction, V_f, was calculated as:

$$V_f = \frac{w}{\rho \cdot t}, \tag{4}$$

where $\rho = 1.44$ g/cm^3 is density of aramid stitch yarn given by manufacturer and t is the measured (using a caliper) thickness of the composite. Average thicknesses of 4 plies stitched fabric layer before the resin application were taken as 2 mm. In this situation, the effect of sewing yarn in various densities on fiber volume fraction is like in Table 5. As seen in the Table 5, the effect of sewing yarn on fiber volume ratio varies between 0.42 % – 1.63 % depending on stitch density. This shows volume fraction of stitch yarns in the composite plate is very low and it is not possible to mention about reinforcement effect of stitch yarns to composite mechanical properties. If we consider degradation of strength on higher stitch densities, it may be said that the reinforcement effect of stitch yarns to mechanical properties of composite plates is negligible relative to damages that occurred during stitching.

4. CONCLUSIONS

In this study the effects of sewing parameters on tensile strength of stitched Twaron/vinyl ester composites were examined. As a result of this study, the results stated below were observed:

As far as stitch density increases, tensile strength and ultimate strain decrease. The main reason of this situation is stitching points to be weak zones of the plate and damage initiate earlier from these points and progress.

Delamination is mostly prevented in stitched composite plates. In the stitched samples during tensile testing, the construction doesn't separate totally and partly protects its integrity unlike the unstitched samples. After the tensile test, while unstitched plates become delaminated even within tensile test, the integrity of the construction is protected in stitched plates.

Higher tensile strength values are observed in stitched plates for low stitch densities. 16 % degradation occured in tensile strength with the decrease from 3 cm to 1 cm in the distance between stitches. 10 % degradation was recorded in the strength due to the increase from 2 cm to 4 cm in stitch density (stitch/cm).

Tensile strength shows a degradation after a certain value of stitch density. The most important reasons for this can be stated as fiber breakages on the fabric surface that occurs within sewing, deviation of fibers around the stitch point from their normal directions, and spaces occurring around the stitch points or resin rich zones. These zones are damage initiation points

There is no siginificant effect of stitching direction or pattern on tensile strength and modulus of stitched samples.

Volume fraction of stitch yarn in the composite plate is very low and it is not possible to mention about reinforcement effect of stitch yarns to composite mechanical properties. If we consider degradation of strength on higher stitch densities, it may be said that the reinforcement effect of stitch yarns to mechanical properties of composite plate is negligible relative to damages that occurred during stitching.

REFERENCES

1. **Lomov, S. V., Bogdanovich, A. E., Ivanov, D. S., Mungalov, D., Karahan, M., Verpoest, I.** A Comparative Study of Tensile Properties of Non-crimp 3D Orthogonal Weave and Multi-layer Plain Weave E-glass Composites *Part 1: Materials, Methods and Principal Results, Composites Part A* 40 2009: pp. 1134 – 1143. http://dx.doi.org/10.1016/j.compositesa.2009.03.012
2. **Karahan, M., Lomov, S. V., Bogdanovich, A. E., Verpoest, I.** Fatigue Tensile Behavior of Carbon/Epoxy Composite Reinforced with Non-Crimp 3D Orthogonal Woven Fabric *Composites Science and Technology* 71 (16) 2011: pp. 1961 – 1972. http://dx.doi.org/10.1016/j.compscitech.2011.09.015
3. **Karahan, M., Lomov, S. V., Bogdanovich, A. E., Mungalov, D., Verpoest, I.** Internal Geometry Evaluation of Non-Crimp 3D Orthogonal Woven Carbon Fabric Composite *Composites Part A* 41 2010: pp. 1301 – 1311.
4. **Bekampiene, P., Domskiene, J.** Influence of Stitching Pattern on Deformation Behaviour of Woven Fabric During Forming *Materials Science* (*Medziagotyra*) 16 (3) 2010: pp. 226 – 230.
5. **Dransfield, K., Baillie, C., Mai, Y.-W.** Improving the Delamination Resistance of CFRP by Stitching – A Review *Composites Science And Technology* 50 1994: pp. 305 – 317. http://dx.doi.org/10.1016/0266-3538(94)90019-1
6. **Huang, S. L., Richey, R. J., Deaka, E. W.** Cross Reinforcement in a GR/EP Laminate *Presented at American Society of Mechanical Engineers Winter Annual Meeting*, San Francisco, 1978.
7. **Holt, D. J.** Future Composite Aircraft Structures May be Sewn Together *Automotive Engineering* 90 1982: pp. 46 – 49.
8. **Mignery, L. A., Tan, T. M., Sun, C. T.** The Use of Stitching Suppress Delamination in Laminated Composites, in Delamination and Debonding *ASTM STP 876, ASTM* Philadelphia, PA, 1985: pp. 371 – 385. http://dx.doi.org/10.1520/STP36315S
9. **Chung, W. C., Jang, B. Z., Chang, T. C., Hwang, L. R., Wilcox, R. C.** Fracture Behavior in Stitched Multidirectional Composites *Material Science and Engineering* A112 1989: pp. 157 – 173.
10. **Karahan, M. C**omparison of Ballistic Performance and Energy Absorption Capabilities of Woven and Unidirectional Aramid Fabrics *Textile Research Journal* 78 (8) 2008: pp. 718 – 730.
11. **Karahan, M., Kus, A., Eren, R.** An Investigation into Ballistic Performance and Energy Absorbtion Capabilities of Woven Aramid Fabrics *International Journal of Impact Engineering* 35 (6) 2008: pp. 499 – 510.
12. **Karahan, M., Ulcay, Y., Eren, R., Karahan, N., Kaynak, G.** Investigation into the Tensile Properties of Stitched and Unstitched Woven Aramid/Vinyl Ester Composites *Textile Research Journal* 80 (10) 2010: pp. 880 – 891. http://dx.doi.org/10.1177/0040517509346441
13. **Liu, D.** Delamination Resistance in Stitched and Unstitched Composite Plates Subjected to Impact Loading *Journal of Reinforced Plastics* 9 1990: pp. 59 – 69. http://dx.doi.org/10.1177/073168449000900104
14. **Mayadas, A., Pastore, C., Ko, F. K.** Tensile and Shear Properties of Composites by Various Reinforcement Concepts *In: Proceedings of 30th International SAMPE Symposium* 1985: pp. 1284 – 1293.
15. **Morales, A.** Structural Stitching of Textile Preforms *In: Proceedings of 22th International SAMPE Technical Conference* 1990: pp. 1217 – 1230.
16. **Pelstring, R. M., Madan, R. C.** Stitching to Improve Damage Tolerance of Composites *In: Proceedings of 34th International SAMPE Symposium* 1989: pp. 1519 – 1528.
17. **Jain, L. K.** Improvement of Interlaminar Properties in Advanced Fibre Composites with Through-Thickness Reinforcement *Cooperative Research Centre for Aerospace Structures Ltd.*, CRC-AS TM 94012, 1994.
18. **Karahan, M.** The Effect of Fibre Volume Fraction on Damage Initiation and Propagation of Woven Carbon-Epoxy Multi-Layer Composites *Textile Research Journal* 82 (1) 2012: pp. 45 – 61. http://dx.doi.org/10.1177/0040517511416282
19. **Karahan, M.** Investigation of Damage Initiation and Propagation in 2x2 Twill Woven Carbon/Epoxy Multi-Layer Composites *Textile Research Journal* 81 (4) 2011: pp. 412 – 428. http://dx.doi.org/10.1177/0040517510395996