OFF-AXIS TENSILE BEHAVIOR OF MULTISTITCHED COMPOSITES

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The off-axis tensile behavior of multi-stitched composites was investigated. The off-axis tensile strength, tensile modulus and tensile strain values were determined. Angular deformation, lateral shrinkage and displacement measurements were performed on the composites after the tensile tests. Because of the filament breakages caused by multi-stitching, the tensile strengths and modulus of the multi-stitched composites slightly decreased. According to measurements, normal deformation, or angular deformation or lateral shrinkage were occurred on all tested composites. However, a new failure mode was observed on four directional densely stitched composite. This structure had only lateral shrinkage following the angular deformation.

Keywords: Off-axis tensile test, multi-stitched composite, lateral shrinkage.

INTRODUCTION

Textile structural composites can serve as advanced engineering materials owing to their exceptional properties such as high delamination resistance and damage tolerance (Brandt *et al*., 1996; Dexter and Hasko, 1996). A wide range of techniques can be used to fabricate textile preforms for composites including weaving, knitting, braiding, stitching, and various nonwoven production methods (Bilisik and Yilmaz, 2012). Stitching has been shown to increase the fracture resistance of the composite by changing the crack propagation pattern, that is, the crack is forced to follow a more tortuous route between stitches, absorbing a large amount of energy in the process (Mouritz, 2004). It was reported that the through-the-thickness stitching of the preform by using only a few per cent of stitching yarn greatly enhances the out-of-plane tensile modulus of the resulting composite at the cost of some reduction in in-plane tensile and shear moduli (Dickinson *et al*., 1999). It was shown that the positive effect of stitching on the delamination resistance increases as the stitch density is increased. This was attributed to the fact that more closely positioned stitches can be more effective at keeping the individual cracks within a small area without further propagation (Tan *et al*., 2012). In this study, the off-axis tensile behavior of multi-stitched composites was experimentally investigated.

MATERIALS AND METHODS

Multistitched Preform and Composite

E-glass woven fabrics (Cam Elyaf A.S., Turkey) were used for producing multi-stitched preform and composites. Table 1 shows the specifications of E-glass woven fabric.

Table 1. The specifications of E-glass woven fabric

Weave type	Yarn linear density (tex)		Density (per 10 cm)		Weight (g/m^2)	Crimp (%)		Thickness (mm)
	warp	weft	warp	weft		warp	weft	
Plain	2400	2400	16	18	800	1.24	1.20	1.01

E-glass woven fabric layers were stacked one on top of the other according to the sequence ($[(0°/90°)]_4$). The multi-stitched preforms were produced by stitching these layers in through-the-thickness direction according to various stitching patterns such as one-directional stitching in the warp (0°) direction; two-directional stitching in the warp (0°) and weft (90°) directions; four-directional stitching in the warp (0°), weft (90°) and ±bias directions. A multilayer non-stitched preform was produced as a reference sample. Two different stitching densities (2 and 6 step/cm) were used with 1 cm distance between the neighboring stitching lines. Brother DB2-B736-3TR (Brother Industries Ltd, Japan) stitching machine was used with lock stitching type. Kevlar® 129 and nylon 6.6 were used as the bobbin and needle stitching yarns respectively. Table 2 shows the properties of stitching yarns.

Table 2. Properties of stitching yarns

Fiber type	Fiber diameter (μm)	Fiber density (g/cm^3)	Tensile strength (GPa)	Tensile modulus (GPa)	Elongation at break (%)	Yarn linear density (tex)
Kevlar 129	12	1.45	3.4	99	3.3	110
Nylon 6.6	14	1.14	0.6	2.46	41	44

VARTM method was used for composite fabrication. Unsaturated polyester resin (Crystic 703PA, Scott Bader, UK) and hardener (methyl ethyl ketone peroxide, 2 wt. %) were mixed homogenously before applying to the preforms at a temperature of 20°C under vacuum. Figure 1 shows some of the produced preforms and composites.

Composite Tests

The volume fraction, density and void content of the composite samples were determined in accordance with ASTM D3171-99, ASTM D792-9 and ASTM D2734-91 standards respectively. Off-axis tensile tests of the samples were conducted according to ASTM D3039-76 using Shimadzu AG-XD 50 (Japan) testing machine equipped with Trapezium® data acquisition software.

Some measurements were performed on the composites after the application of off-axis tensile load. Image Pro-Plus image analyzing software (MediaCybernetics, USA) was used to measure the angular deformation (θ_s), lateral shrinkage (b_s) and displacement (w) normal to the loading direction. Figure 2 shows the measurements performed on the samples.

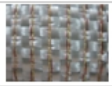
Label	Stitching direction	Stitching density	Preform	Composite
NS	Unstitched	-		
MS1	One direction	2 step/cm		
MS2	Two direction	2 step/cm		
MS3	Four direction	2 step/cm		
MS4	One direction	6 step/cm		
MS5	Two direction	6 step/cm		
MS6	Four direction	6 step/cm		

Figure 1. Multi-stitched preforms and composites

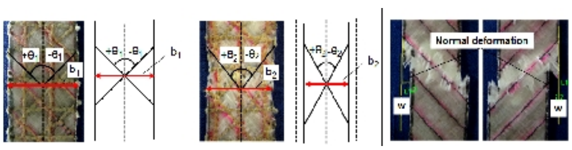


Figure 2. The measurements of the composites after off-axis tensile load was applied

Angular deformation (θ_s) was defined as the change in the angle between the warp and weft yarn sets after the application of off-axis tensile load (Equation 1); lateral shrinkage (b_s) was defined as the change in the sample width after the application of off-axis tensile load (Equation 2); displacement (w) was defined as the recorded displacement normal to the loading direction in off-axis tensile test.

$$\theta s = |\theta 2 - \theta 1| \quad [\text{where, } +\theta 2 < +\theta 1,\ -\theta 2 < -\theta 1] \qquad (1)$$
$$bs = |b2 - b1| \quad [\text{where, } b2 < b1] \qquad (2)$$

Where, θ_s is the angular deformation angle (°); θ_1 is the angle between the warp and weft yarns before the application of off-axis load (°); θ_2 is the angle between the warp and weft yarns after the application of off-axis load (°); b_s is the lateral shrinkage of the sample (mm); b_1 is the specimen width before the application of off-axis load (mm) and b_2 is the specimen width after the application of off-axis load (mm).

RESULTS AND DISCUSSION

Fiber Volume Fraction and Density Results

Figure 3 shows the fiber volume fraction, density, and void content of the samples. The results suggested that stitching impaired the fiber alignment especially at the needle penetration sites. The volume fraction of the stitching yarn increased when the number of stitching directions in the sample is increased depending on the stitching density.

Off-Axis Tensile Results

Figure 3 shows the off-axis tensile strength and modulus of multistitched composites. The off-axis tensile strength and modulus of non-stitched reference sample were slightly higher compared with those of the multi-stitched samples because of the filament breakages that caused by stitching process. The off-axis tensile strength and modulus of 2 step/cm stitched samples were higher than those of 6 step/cm stitched sample because denser stitching caused more filament breakages. A slight difference was observed between +45° and -45° directional off-axis tensile strengths.

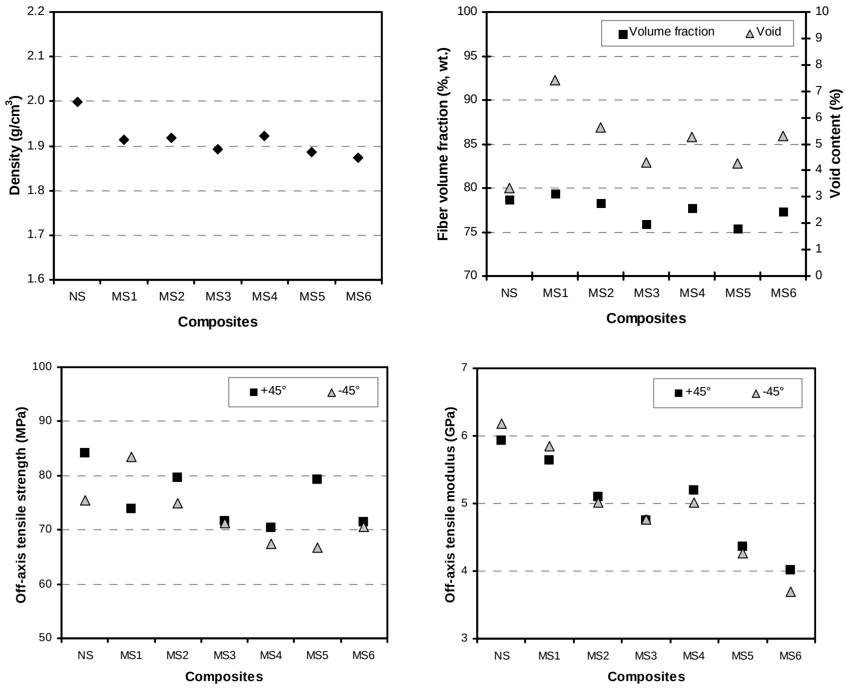


Figure 3. Density, fiber volume fraction, void content, off-axis tensile strength and modulus results of multi-stitched composites

The off-axis tensile strains of the multi-stitched composite samples are depicted in Figure 4. The non-stitched structure yielded slightly higher off-axis tensile strain when compared to the multi-stitched samples except for samples MS5 and MS6 owing to the fact that the displacement of the yarns was restricted by stitching.

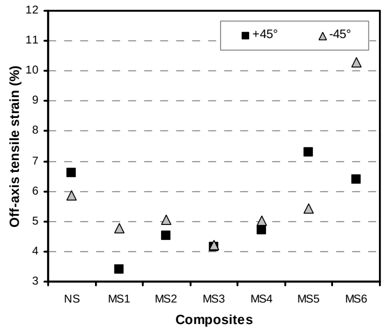


Figure 4. Off-axis tensile strain of multi-stitched composites

Failure Results

Figure 5 and Table 3 show the damaged multi-stitched composites after off-axis tensile test. The failure of multi-stitched composites took place as a combination of matrix, and partial fiber breakage at the surface. The angular deformation of multi-stitched composites increased as the number of stitching directions and the stitching density are increased. The normal deformation was observed generally for all structures except MS6, MS2, MS3 and MS5 which experienced lateral shrinkage in addition to the normal deformation. However, the MS6 sample underwent only lateral shrinkage. The reason is that the off-axis load was confined to a narrow region which, as a consequence, failed abruptly leading to an extensive damage in a larger area involving matrix fracture, fiber pull-out and local multiple fiber breakages.

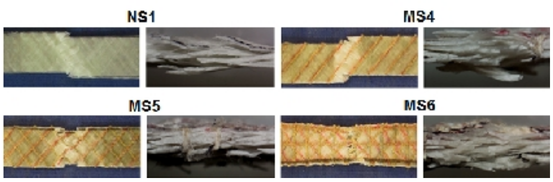


Figure 6. Front face (digital photos, left) and cross sectional (microscopic photos at ×6.7 magnification, right) views of multistitched composites +45°

Table 3. The failure results of multistitched composites after off-axis tensile test

Label	Angular deformation (°)				Normal deformation (mm)		Shrinkage in width (mm)	
	+45°		-45°		+45°	-45°	+45°	-45°
	+θ	-θ	+θ	-θ				
NS	0	1.45	0.94	0	2.78	4.34	0	0
MS1	0	0	0	1.93	4.67	2.79	0	0
MS2	0	0	0.90	0	2.51	2.62	4.57	3.06
MS3	0	0	9.69	3.58	1.43	1.64	1.84	2.72
MS4	0	0	0	0	4.06	4.57	0	0
MS5	5.62	6.75	4.94	6.00	2.14	2.23	4.80	2.23
MS6	3.81	6.84	11.77	9.64	0	0	2.21	2.66

CONCLUSION

The off-axis tensile strengths and moduli of the multi-stitched composites slightly reduced because of filament breakages that resulted from stitching process. The off-axis tensile strain of densely stitched composites was slightly higher compared with that of the non-stitched composite due to restricted movement of yarns. Post-failure examination indicated that four-directional densely stitched composite sample showed (MS6) a new failure mode i.e., it only experienced lateral shrinkage following the angular deformation. These findings suggest that stitching direction and density significantly affect the off-axis tensile behavior of multi-stitched composite materials.

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