BENDING PROPERTIES OF MULTILAYERED NON-INTERLACED E-GLASS/POLYESTER COMPOSITES FOR WIND BLADE APPLICATIONS

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Abstract

The aim of the research was to develop multilayered non-interlaced E-Glass preforms and describe the mechanical properties of multilayered non-interlaced E-Glass/polyester composites for wind blade in green energy applications. For this purpose, the preforms were developed and consolidated where high modulus and high strength E-glass fibers and, polyester matrix were used. The E-glass preforms included unidirectional(0˚), biaxial(0˚/90˚) and multiaxially(0˚/90˚/±45˚) oriented structures. E-glass/polyester composites were investigated with regard to packing density (tight and loose volume fraction) and fiber orientations. The effects of these parameters on bending strength and modulus of the composites were experimentally investigated. Generally, the composites produced by the tightly wound performs showed better mechanical performances compare to those of the composites produced by the loosely wound performs due to the high volume fractions.) Fiber orientation in the preform affected the properties of the composites in where the properties of the composites became homogeneous. It was found that the damage mode in the structure under the bending load was mainly due to the delamination (Mode I). It was also demonstrated that the fibers in developed preform structures were perfectly aligned compare to the state of the art preforms.

Keywords: E-Glass/Polyester composites, multiaxis fabrics, bending strength and modulus of composites, tight and loose preforms.

1. Introduction

Textile structural composites were widely used in various industrial sections, such as aerospace, automotive, marine and recently green energy applications as wind blade component development [1, 2 and 3]. They had some better specific properties compared to the basic materials such as metal and ceramics [4]. Research conducted on textile structural composites indicated that they can be considered as alternative materials since they were delamination-free and damage tolerant [5]. From a textile processing viewpoint they were readily available, cheap, and not labour intensive.

Large wind turbine blade was developed by Sandia Lab. The blade structure had S-glass/carbon fiber triaxial preform/epoxy composite. The structure had 0˚/±45˚ fiber orientation where 0˚ fiber was carbon and ±45˚ was S-glass. The total volume fraction of composite structure was 40%. It was demonstrated that the weight of developed blade structure was reduced 2% whereas bending rigidity under fatigue load increased [6]. Another developed structure on wind blade had three-axis directional fabric where 0˚ fiber had carbon whereas a ±45˚ fiber had E-glass. The structures were consolidated with epoxy matrix by vacuum assisted resin transfer molding. Final blade quality was determined by static and fatigue loading. It was reported that the blade failed at least 160% above the design criteria [7]. Quasi-isotropic E-glass fabric preforms were consolidated by CTBN rubber micro particle epoxy resin. It was approved that the addition of rubber particles in epoxy resin increased the epoxy fatigue life 3-4 times. Therefore, stiffness degradation in E-glass preform composite was continuously monitored during the fatigue test. The fatigue life of composite was increased by a factor of three times due to the addition of rubber particles in the epoxy matrix. The suppressed matrix cracking and the reduced crack propagation rates in the structure caused the increasing fatigue life of the rubber-epoxy composite [8]. Multiaxis 3D non-interlaced E-glass/non-Z preforms were developed for composites. It was observed that yarn sets in the preform were perfectly aligned without waviness due to the non-Z form, and fiber volume fraction and fiber orientation angle affected the tensile properties of the composite. Also, the damage mode in the structure under tensile load was mainly due to inter and intra layer delamination (Mode-I) [9]. Finite element method was used to analyze stiffness properties of fiber reinforced polymer beams for wind turbine blade applications. It was claimed that beam theory and FEM together were correctly capable of analyze the structure especially in homogeneous local inclination angle [10]. The 0˚/90˚ unidirectional laminates of fiber reinforced polymer composites were studied to define overall stiffness reduction in composite. For this reason, structure was analyzed under the fatigue load. The proposed damage model explained the

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cracking mechanism and damage progress in matrix, matrix-fiber interface, fiber and corresponding stiffness reduction of unidirectional composite laminates [11].

2. Materials and Method

2.1. Multilayered Non-Interlaced E-Glass/Polyester Preforms and Composites

State of the art fiber based preforms for structural applications in use wind energy is presented in Figure 1. Figure 1 shows unidirectional weave designed carbon(0˚)/E-Glass(90˚) fiber arrangements (a), biaxial non interlaced weave designed carbon(0˚)/E-Glass(90˚) fiber arrangements (b) and triaxial stitched fabric designed carbon(0˚)/S-Glass(± 45˚) fiber arrangements (c) [2]. However, fiber in all structures had wavy form due to stitching and auxiliary fiber interlacements and caused local stress concentrations in the structure. This decreased the directional properties of the structure. For this reason, multilayered and multiaxis non-interlaced non-z fabric preforms were developed. The fibers in the developed structure were perfectly aligned as seen in Figure 2 and 3. Figure 2 shows schematic views of the developed unit cell base preform structure and Figure 3 shows E-Glass fabric preforms.

The developed multilayered non-interlaced preforms were divided into three sub groups as uni-directional (0°), biaxial (0°/90°), and multiaxis (0°/90°/±45°). Uni-directional preforms had one yarn set which was directed to 0° and the winding procedure was carried out ten times to make a 10-layers structure. Biaxial preforms had two yarn sets as warp (0˚) and filling (90˚). These two yarn sets were all wound around each other to form the structure where first warp (0˚) was wound and later on the filling (90˚) yarns were wound. The winding procedure was carried out five times to make a 10-layers structure. Multilayered non-interlaced multiaxis performs had four yarn sets as bias (±θ), warp (0˚), and filling (90˚). These four yarn sets were all wound around each other to form the structure where first warp (0˚) was wound and later on the filling (90˚), the bias(+) and the bias(-) yarns were wound. The winding procedure was carried out three times to make a 12-layers structure. For each type of preforms, yarn sets were all positioned to the in-plane direction of the preform structures without any interlacement with each other. After each layer was wound, an adhesive plaster was used to hold the all yarn ends around the structure to provide structural integrity during fabrication with a manually driven prototype flat winder [12].

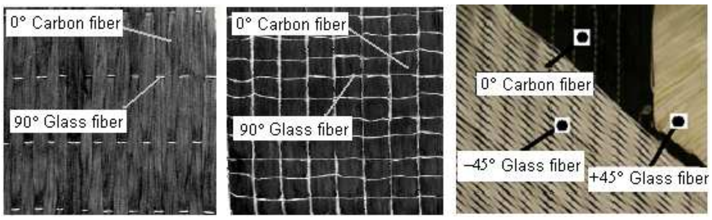

Figure 1. State of the art fabrics. Uniweave fabric(a); Biaxial non-interlaced fabric(b) and Triaxial stitched fabric(c) [2].

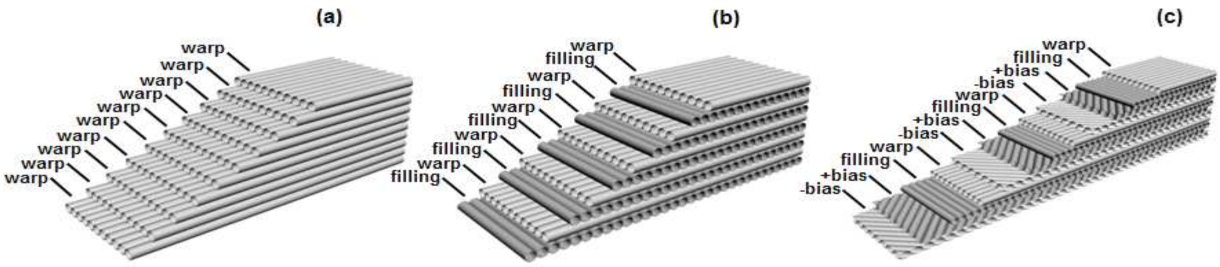

Figure 2. Schematic views of the multilayered non-interlaced preform unit cells, (a); uni-directional, (b); biaxial, (c); multiaxis [12].

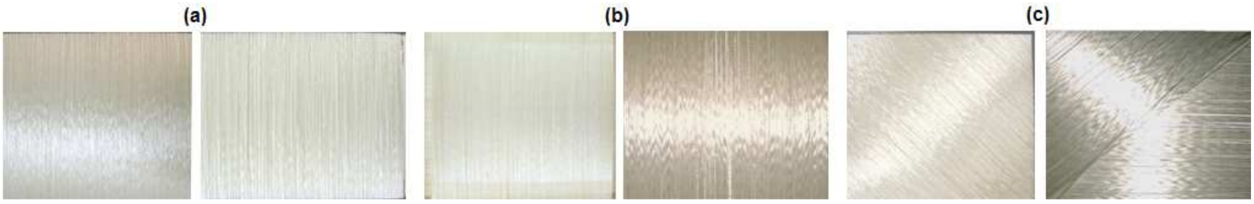

Figure 3. Surface views of the multilayered non-interlaced performs, (a); uni-directional, (b); biaxial, (c); multiaxis [12].

Table 1. Properties of E-glass fiber and resin used in composite structures.

Fiber/material type	Fiber diameter (μ)	Density (g/cm^3)	Tensile strength (GPa)	Tensile modulus (GPa)	Elongation at break (%)	Melting point (Cº)
E-Glass						
E-glass fiber (Cam Elyaf Inc., Turkey)	16	2.56	3.5	76	4.8	841
Resin						
Polyester Resin (Orthophtalic, Cam Elyaf Inc.)	-	1.17	0.055	3.4	2.1	490

High strength and high modulus E-Glass (CE-WR) 600 tex fibers produced by Cam Elyaf Inc., Turkey were used to form the unit cells. The fiber and resin properties are shown in Table 1. The density of the fiber was 2.56 g/cm^3, filament diameter was 16 micron, and the ultimate elongation was 4.80 %. Tensile strength and modulus of the fibers were 3445 MPa and 76 GPa, respectively. Fibers were compatible with polyester matrix and sized for winding and weaving to improve the handling characteristics [13]. Multilayered non-interlaced preforms were consolidated to produce composites. Tensile strength and modulus of polyester resin (CE 92 N8, Cam Elyaf Inc., Turkey) were 55 MPa and 3.4 GPa, respectively. Resin density was 1.17 g/cm^3. A hand lay–up technique was used to consolidate the preforms. Polyester resin (CE 92 N8, 98.7%), catalyst (Cobalt, 0.3%) and hardener (Methyl ethyl ketone peroxide, 1%) were mixed and applied to the preforms at atmospheric conditions.

Packing density of the preforms was considered as tight and loose. The performs produced by using 600 tex E-glass fibers were separated into two groups as tight (47 ends/10 cm) and loose (25 ends/10 cm). The specifications of multilayered non-interlaced preforms and composites are presented in Table 2. Density of composite was determined by ASTM D792-91 [14]. The composite volume fraction and void content were also determined by ASTM D3171-99 and ASTM D2734-91, respectively [15, 16].

Table 2. Specifications of performs and composite structures.

		Structure types					
		PI-600-T	PI-600-L	PII-600-T	PII-600-L	PIII-600-T	PIII-600-L
		$[0°]^{10}$		$[0°/90°]^{5}$		$[0°/90°/±45°]^{3}$	
Preform Structure	Linear density (tex)	600		600		600	
		Tight	**Loose**	**Tight**	**Loose**	**Tight**	**Loose**
	Packing density (ends/10 cm)	47	25	47	25	47	25
	Warp yarn (0°)	10 layers	10 layers	5 layers	5 layers	3 layers	3 layers
	Filling yarn (90°)	—	—	5 layers	5 layers	3 layers	3 layers
	+ Bias yarn (+45°)	—	—	—	—	3 layers	3 layers
	– Bias yarn (–45°)	—	—	—	—	3 layers	3 layers
	Total number of layers	**10 layers**	**10 layers**	**10 layers**	**10 layers**	**12 layers**	**12 layers**
	Cross section	Rectangular		Rectangular		Rectangular	
	Thickness (mm)	2.22	1.51	2.85	1.72	3.44	2.31
Composite Specifications	Matrix type	Polyester (CE 98 N8)		Polyester (CE 98 N8)		Polyester (CE 98 N8)	
	Impregnation technique	Hand lay-up		Hand lay-up		Hand lay-up	
Composite Structure	Volume fraction-V_f (weight base, %)	**64.00**	**61.21**	**58.58**	**45.50**	**67.69**	**48.37**
	Void content (%)	0.72	2.39	0.72	2.39	0.75	0.25
	Density (g/cm^3)	1.780	1.710	1.697	1.474	1.835	1.582
	Thickness (mm)	2.99	1.80	3.20	2.20	3.71	2.99

2.2. Bending Tests

3-point bending tests of composite structures were performed on Zwick Z010/TN2A tester according to ASTM D790 [17]. The test dimensions, support span length and testing speed were determined considering the composite thickness and given in Table 3. Figure 4 shows the composite structures during bending test. The applied bending load was perpendicular to the warp (0°) direction. Figure 5 shows the applied bending load direction based on structure types.

Table 3. Bending test conditions of 600 tex composite structures.

	Structure types					
	PI-600-T	PI-600-L	PII-600-T	PII-600-L	PIII-600-T	PIII-600-L
	$[0°]^{10}$		$[0°/90°]^5$		$[0°/90°/\pm45°]^3$	
Linear density (tex)	600		600		600	
Packing density	**Tight** (V_f: 64.00)	**Loose** (V_f: 61.21)	**Tight** (V_f: 58.58)	**Loose** (V_f: 45.50)	**Tight** (V_f: 67.69)	**Loose** (V_f: 48.37)
Thickness (mm)	2.99	1.80	3.20	2.20	3.71	2.99
Dimensions (width × length, mm)	25×72	25×52	25×80	25×57	25×84	25×62
Support span length (mm)	47.5	29	50	37	56	31
Testing speed (mm/min.)	1.2	1.2	1.2	1.2	1.2	1.2

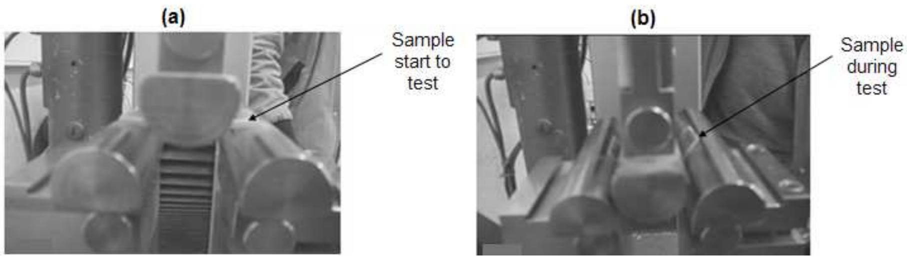

Figure 4. Composite structures start to test (a) and during (b) bending test.

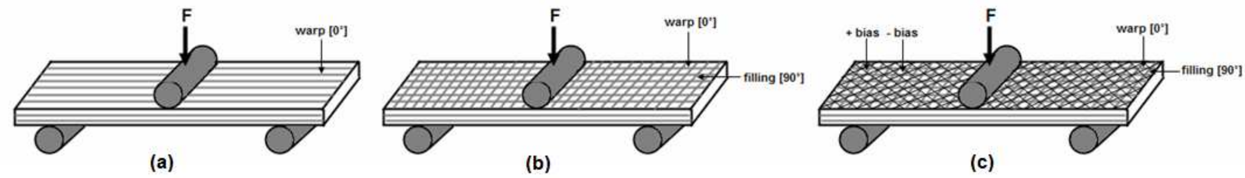

Figure 5. Bending load direction to samples, (a); uni-directional, (b); biaxial, (c); multiaxis.

3. Results and Discussion

Bending test results of composite structures are presented in Table 4. The bending strength and bending modulus values of composite structures were presented in Figure 6.

Table 4. Bending test results of composite structures.

	Structure types					
	PI-600-T	PI-600-L	PII-600-T	PII-600-L	PIII-600-T	PIII-600-L
	$[0°]^{10}$		$[0°/90°]^5$		$[0°/90°/\pm45°]^3$	
Linear density (tex)	600		600		600	
Packing density	**Tight** (V_f: 64.00)	**Loose** (V_f: 61.21)	**Tight** (V_f: 58.58)	**Loose** (V_f: 45.50)	**Tight** (V_f: 67.69)	**Loose** (V_f: 48.37)
Bending strength (MPa)	708.6	538	571.6	287.8	272.8	214.6
Bending modulus (GPa)	8.55	7.85	10.36	5.28	6.3	4.4

As seen in Figure 6, the bending strength and modulus of the E-glass/polyester composites were proportional to their total volume fraction. The high volume fraction of the E-glass preforms generally results high bending strength and modulus of the E-glass/polyester composites. Bending strength of E-Glass/polyester unidirectional preform composite structure was the highest compared to biaxial and multiaxial preform structures. On the other hand, bending strength of E-Glass/epoxy biaxial preform composite was higher than that of E-Glass/epoxy multiaxis preform composite. It was understood that orienting the fiber in the plane of the preform made the structure more homogeneous.

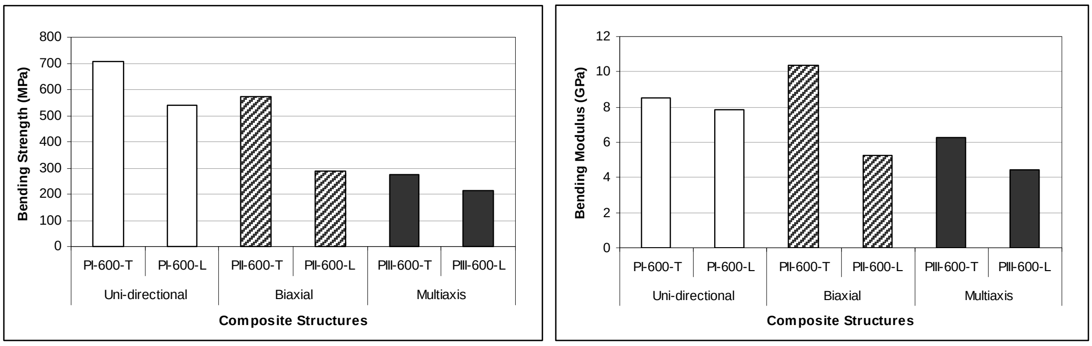

Figure 6. Bending strengths (a) and modulus(b) of composite structures.

Optical views of composite structures after bending test are shown in Figure 7. It was observed that the top surface of all composite had local matrix and filament separation under the bending, whereas bottom surface of the composites PI-600-T, PII-600-T and PIII-600-T had multiple fiber breakages and fiber-matrix splitting especially between warp layers(0˚), warp(0˚) and filling(90˚), and between ±bias and filling(90˚), respectively. Also, there was a local delamination between ± bias, warp and filling layers. In addition, fiber and matrix were sheared to the out-of-plane direction of the structure. The bottom surface of the composites PI-600-L, PII-600-L and PIII-600-L had catastrophic multiple fiber breakages and fiber-matrix splitting especially between warp layers(0˚), warp(0˚) and filling(90˚), and between ±bias and filling(90˚) respectively. The dominant failure mechanism was Mode-I as a form of separation and matrix-fiber breakages. This was because no reinforcement introduced to the out-of-plane direction of the structures. The future research will be conducted on multiaxial testing of composites to identify the directional properties.

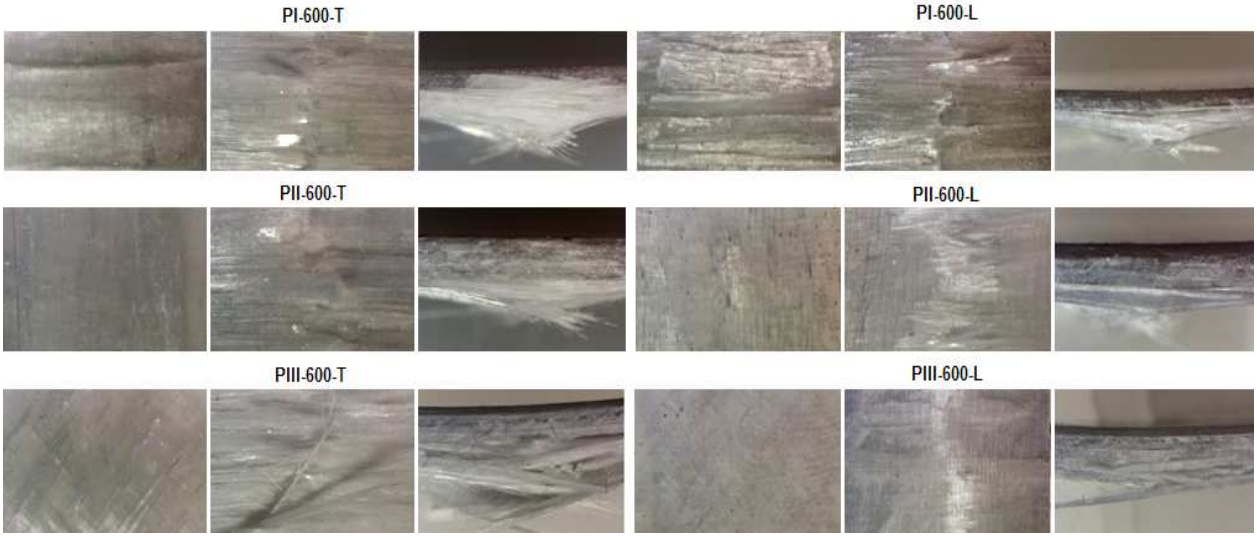

Figure 7. Optical views of composite structures after bending test (bending direction-top surface(a), reverse of bending direction-bottom surface(b), cross section(c), respectively).

4. Conclusions

Multilayered non-interlaced E-Glass preforms were developed for wind blade applications. The preforms were consolidated to make E-glass/polyester composites. The E-glass preforms included unidirectional(0˚), biaxial(0˚/90˚) and multiaxially(0˚/90˚/±45˚) oriented structures. Generally, the tightly wound preforms show better mechanical performance compare to that of the loosely wound preform due to the high fiber volume fraction. Fiber orientation in the preform affected the properties of the composite in where the properties of the composites became homogeneous. It was found that the damage mode in the structure under the bending load was mainly due to the delamination (Mode I). It was also demonstrated that fibers in the developed preform structures were perfectly aligned compare to the state of the art preforms. Future research will be conducted on multiaxial testing of composites to identify and optimize the directional properties based on the end-use requirements.

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