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Comparison of Mechanical Properties of Biaxial and Triaxial Fabric and Composites Reinforced by Them

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Abstract

In this article, the mechanical properties of biaxial and triaxial woven aramid fabric and respective reinforced composites were investigated. Both fabrics had the same mass/m². The first part of the experimental investigation was focused on the mechanical properties of different non-laminated aramid fabrics (biaxial and triaxial). The second part was concerned with the mechanical properties of composites made of a different combination of layers of fabric reinforced with an epoxy resin matrix in the order of biaxial+biaxial, trixial+triaxial and biaxial+triaxial. The composites were tested for tensile strength, flexural strength, strain and Young's and flexural modulus. It can be seen from the results that the density and direction of the yarns are the most important parameters for determination of the strength of the fabric reinforced composite. The biaxial composite clearly showed better tensile strength, while the bi-tri axial order showed good flexural strength compared to the other composite combinations. These fabric reinforced composites have suitable applications in the areas of medical, protection and in the automotive industries.

Key words: *aramid fabrics, woven, biaxial fabrics, triaxial fabrics, reinforced composites, mechanical properties.*

◼ Introduction

Concepts of superior composites are emerging these days, which have higher overall performance of reinforcement [1-2]. Biaxial and triaxial fabrics are unique structures that have significant application in the medical, space and rocket propulsion and transportation industries [3-4]. The traditional biaxial weaving procedure is designed to interlace two sets of yarns, namely warp and weft, at 90 degree cross-over points [5]. As a result, the structure has a higher cover factor to form a stable structure. Triaxial fabrics are defined as cloth in which there are three sets of threads from a multitude of equilateral triangles, thus forming a more stable construction, because triangles are more stable than rectangles. The weave structure forms locked intersections, giving equal strength in all directions. Two sets of warp yarn are interlaced at 60° with each other and with the weft in basic triaxial fabric, shown in ***Figure 1***, where the warp travels from selvedge to selvedge at an angle of 30° from the vertical. When a warp yarn reaches the selvedge, it is turned through an angle of 120° and then travels to the opposite selvedge, thus forming a firm selvedge. Weft yarn is at right angles (90° to the selvedge. Basic triaxial fabric is fairly open. with a diamond-shaped centre. Standard weaves can be modified by having bi-plane, stuffed, or basic basket weaves [6]. The basic structure of the triaxial configurations is unparalleled in standard fabric construction. These types of fab-

rics have a lot more porosity and open space to form a stable structure. The arrangement of yarns interlacing in these fabrics are at angles of 0, 60° and -60° so that the stiffness and strength is similar in every direction, called quasi isotropic [7-8]. Isotropy, shear resistance and low density can be advantages of triaxial fabrics over biaxial fabrics, while the relatively low quantity of material used is the main advantage over other fabrics [9-10]. The other architecture fabric is multiaxial fabric, which is the inclusion of bias direction yarn at an intermediate angle (e.g. 45°) among the warp and weft, consisting of one or more layers of long fibres that serve as a binder. In this case, four sets of yarn were used: +/– bias, warp (axial) and filling [11-12]. In recent years, more attention has been paid to woven fabric materials due to their good mechanical properties e.g., high specific stiffness and strength, good integral performance and dimensional stability, low thermal expansion, good corrosion resistance etc. The mechanical behaviour of the woven structure is influenced by the yarn set and development. The number of yarns per cm has an effect on the tensile properties of fabrics [12-14].

The mechanical properties of fabrics also depend upon the interlacing angle [15-16]. Woven fabric composites are engineered substances made from one or more layers of fabric embedded in a resin system [17]. Textile preforms can display woven, braided or knitted architectures [18-20]. The mechanical properties of
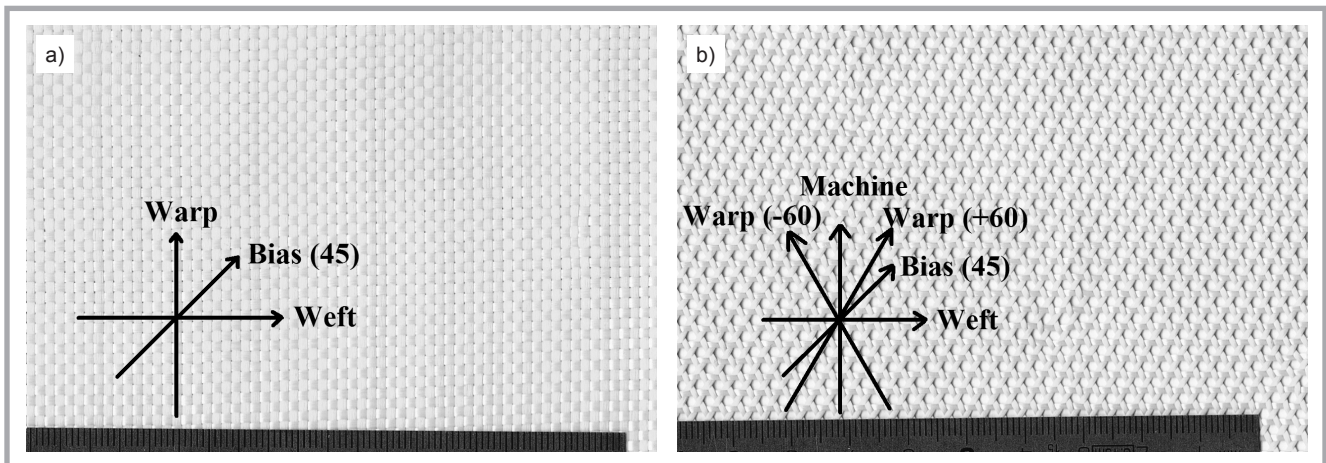
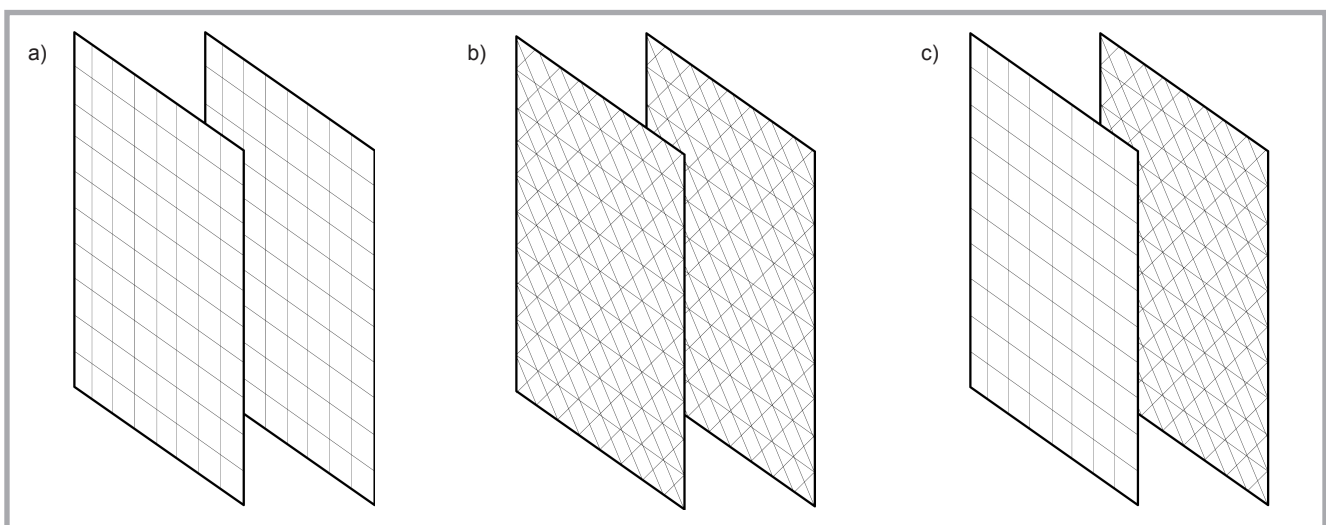**Figure 1.** *a) biaxial woven fabric, b) triaxial woven fabric.*

Figure 2. *Layer arrangement in a) bi-bi, b) tri-tri & c) bi-tri composites.*

a textile composite depend on the fibres and matrix properties as well as the fabric architecture [21-25]. We can increase the nature of the isotropy in a biaxial woven composite by adding more layers of fabric in every direction. Such a problem of de-lamination strength can be avoided by using triaxial fabrics, replacing biaxial fabrics [26].

Technically the fabrication of a woven composite is an easy way for the obtainment of a complex component. It is effectively a large reduction in labour costs as compared to a metal matrix composite. It enhances the useful mechanical properties of woven fabric like strength, stiffness and fracture toughness [27]. The mechanical properties of the composite depend on the yarn size, orientation, volume fraction and interlacing pattern [28]. The mechanical behaviour of the composite concept is divided into linear and non-linear prop-

erties [29]. Applications in the global business market for fabric composites encompass products for energy absorption (e.g., helmet), aerospace and protection application (e.g. engine inlet cowlings, fuselage sections, rotor blade spars and fuel pods), as well as automotive and structure applications (e.g. battery trays, seat structures, front-end modules and load floors) [30].

The main goal of this research was to investigate the mechanical properties and understand the behaviour of biaxial and triaxial aramid fabrics as well as a composite reinforced with combinations thereof. The first part studied the mechanical properties of raw fabrics in a tensile and shearing test with different directions, while the second part of the experiments regarded a composite with a reinforcement of two layers of fabrics in a tensile and bending test. Finally experimental results of the composites

with various combinations of fabrics were compared with their mechanical strength.

■ Experimental methods

Materials

Woven aramid fabric has a high strength, modulus, and fire retardancy. In biaxial fabrics (***Figure 1.a***), the density of warp and weft yarns was the same 65 ± 2 yarns/dm. In triaxial woven fabric (***Figure 1.b***), the warp density was 32 ± 1 and the weft density – 37 ± 1 yarns/dm at $\pm 60°$ directions. The thickness of biaxial fabric 0.32 ± 0.03 mm and triaxial fabric was 0.46 ± 0.03 mm, respectively. According to the producer (UTEK COMPOSITE), the tensile strength of the biaxial fabric was 80 N/mm in both the warp and weft directions. The mass surfaces of both biaxial fabrics was 194 ± 10 g/m² and for the triaxial fabric – 182 ± 10 g/m².
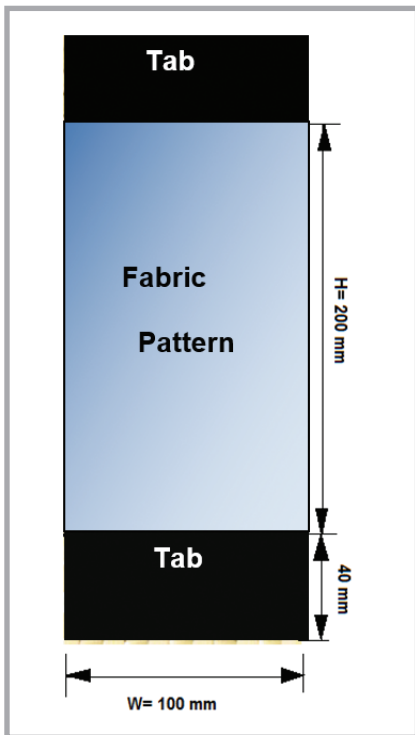
Figure 3. Schematic diagram of bias test sample.

Figure 4. Pictorial presentation of bias tensile tests: a) biaxial and b) triaxial samples under tension on an Instron.

The composites were prepared by the hand lay-up technique using the vacuum bag process [31]. The vacuum bag process allows the uniform distribution of compression stresses on the surface of the lay-up composite, which minimised bubbles and wrinkles in the build-up layers [32-36]. The composite matrix was a combination of two components: epoxy resin LG 385 and hardener LG 387 as a catalyst (10:4 ratio). The density of the epoxy resin was 1.18-1.23 g/cm³ and the viscosity – 600-900 mPa/s at 25 °C. The density of the hardener was 0.94 g/cm³ and the viscosity – 50-100 mPa/s at 25 °C. The curing time at a temperature of about 25 °C was 4 hours, and the sample was removed from the form after 24 hours. In the composite prepared, two layers of fabric as reinforcement were used, such as biaxial+biaxial (bi-bi axial composite), triaxial+triaxial (tri-tri axial composite) and biaxial+triaxial layers (bi-tri axial composite) (see *Figure 2*). Both layers of fabric were equal in size and well fitted inside the vacuum bag. The volume fraction of the bi-bi axial, tri-tri axial and bi-tri axial fabrics in the composites were 53%, 49%, and 50%, respectively.

Tensile test of woven fabrics

The uniaxial tensile behaviour of the warp and weft direction for biaxial fabrics and the machine and weft direction for triaxial fabrics were established in the longitudinal direction in the clamping position on an Instron Machine with a capacity of 200 kN (model No. 4485). In this process, a fabric test specimen of specified dimensions is extended at a constant rate until a number of yarns work collectively to endure the maximum load. According to EN ISO 13934-1: 1999, a rectangular fabric sample of 180 x 55 mm dimensions with a clamp distance of 100 mm was tested under a tensile load using an uniaxial testing machine with a pneumatic system. The loading rate was set within the range of 20 mm/min. Under this test, the maximum force and elongation of the woven fabrics were estimated. 5 samples were tested for the average value and error of standard deviation. Fracture positions of the biaxial and triaxial fabric specimens mostly occurred in the clamping zone, also with the tape on the reinforcing sheet at both ends of the fabric sample. We can expect that the strongest direction of fabrics is along the yarn direction. For triaxial fabric in the machine direction, the force does not operate along yarns, but, like in shear of the fabrics, we can expect that the maximum force will be lower in comparison to that along yarns.

Uniaxial bias extension test

The uniaxial bias extension test requires rectangular specimens of fabric with warp (machine) and weft directions of the tows orientated initially at ±45° to the direction of the tension load applied [28-30]. The sample is characterised by the free length/width ratio, where the total length (H) of 200 mm must be at least twice of the width (W) – 100 mm. (*Figure 3* and *Figure 4*), assuming yarns to be inextensible and no slip occurring in the specimen. When the length/width ratio of the bias extension sample is at least 2, the shear angle (γ) in the centre zone should obey the kinematic relationship in *Equation (1)*, as long as deformation mechanisms, such as inter-ply slip, are significant compared with trellis shearing (γ). The *Equation (1)* is co-related to the shear angle (γ), fabric geometry (length of the un-deformed centre zone D), and end displacement (d) [33].

$$\gamma = \frac{\Pi}{2} - 2cos^{-1}\left(\frac{D+d}{D\sqrt{2}}\right) \qquad (1)$$

The specimen's dimensions were 280 x 100 mm, with s 200 mm free length between the two clamps. The loading rate of the tensile test was 20 mm/min.

■ Result and discussion

Uniaxial tensile behaviour of woven test fabric

The experiment presented dealt with uniaxial tensile properties of the biaxi-
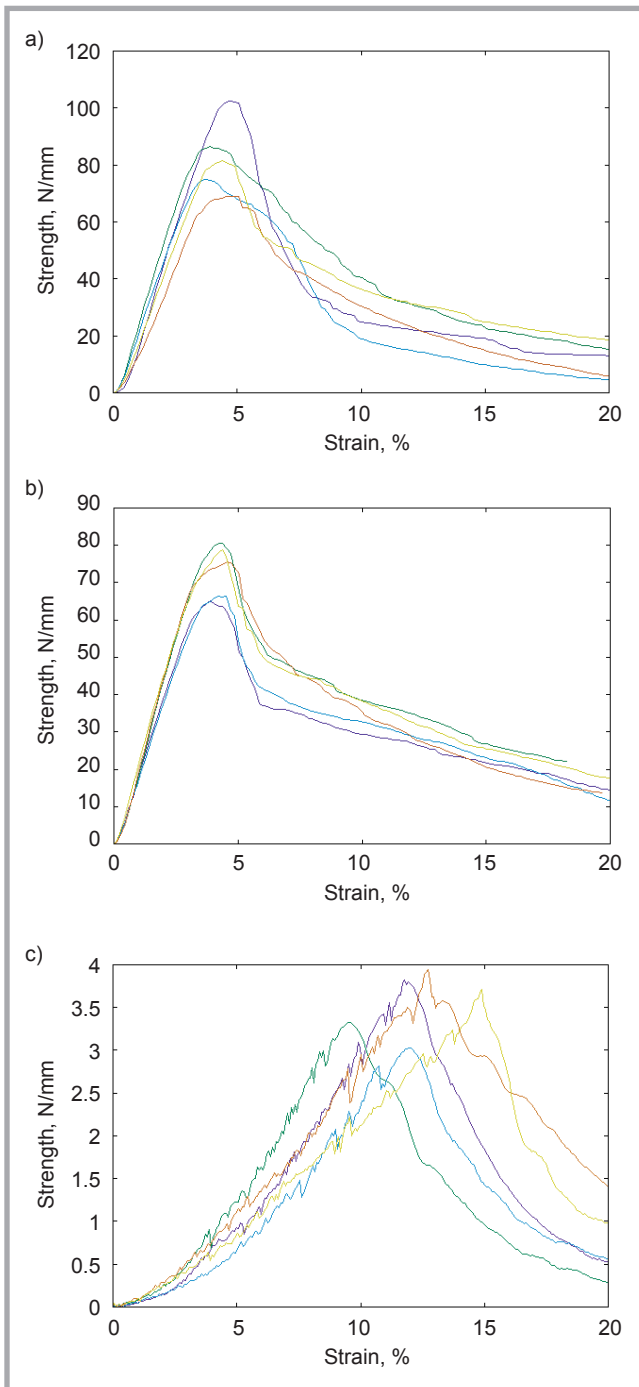
Figure 5. *Strength vs. strain graph of different directions of the biaxial fabric: a) warp direction, b) weft direction and c) bias direction.*
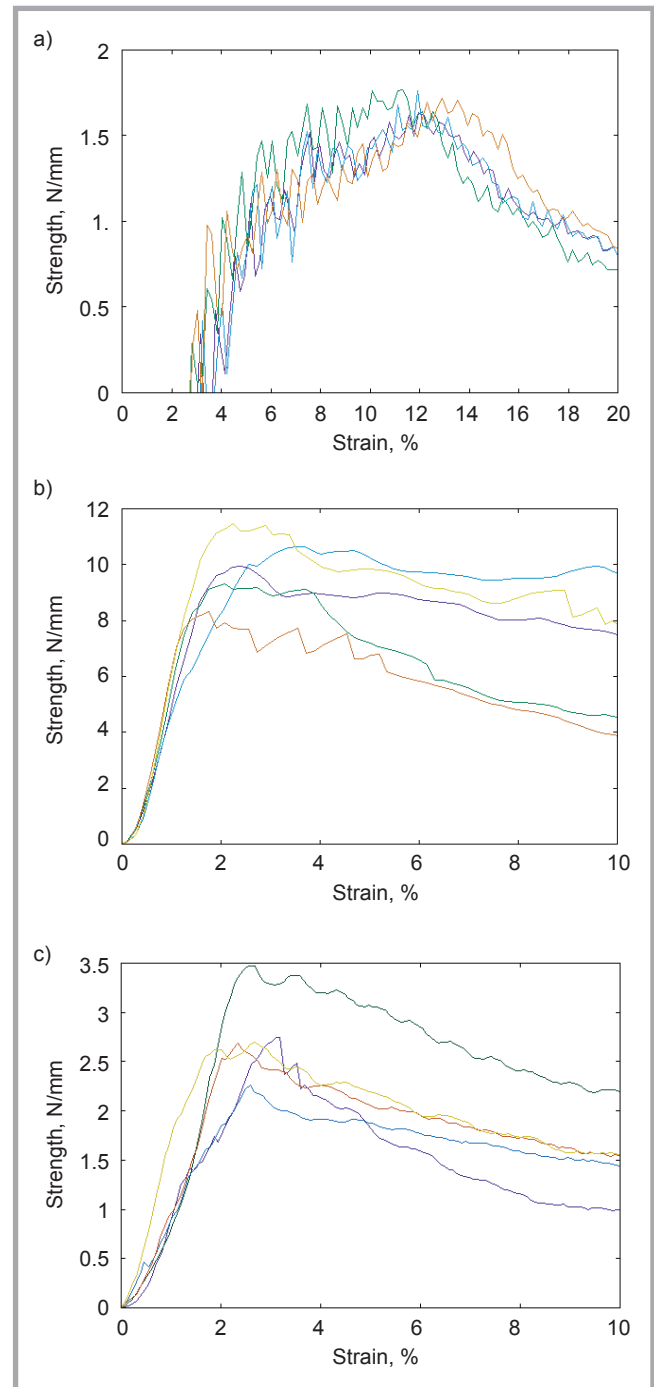
Figure 6. *Strength vs. strain graph of different directions of the triaxial fabric: a) machine direction, b) weft direction and c) bias direction.*

al and triaxial woven fabrics. Preliminarily tensile testing was conducted in three different directions: warp, weft and bias (45°) in the case of biaxial fabric, and machine, weft and bias (45°) in the case of triaxial fabric. Strength (N/mm) vs. strain (%) curves of the woven fabric samples under room temperature are plotted in ***Figures 5*** and ***6***. The principal properties of the woven fabrics are listed in ***Table 1***. Comparing the warp and weft directions of the biaxial woven fabrics (***Figure 5.a*** and ***Figure 5.b***), it

can be noted that the average strength in the warp direction is 10 N/mm higher than in the weft direction. The strain at the ultimate strength for both directions was equal on average**.** Below in ***Figure 6.a***, it can be observed that the tensile properties of triaxial woven fabrics in the machine direction are very low, with the average strength being 0.417 N/mm. The woven sample in the machine direction showed tensile properties well below the values expected, which may be caused by the fact that machine direction

yarns were not perpendicular to the direction of the force applied between the clamps of the Instron machine. It was +60° and -60° degrees to the clamps, see ***Figure 1.b***, and hence it behaved like shearing, and not exactly like tensile, such as in the case of the biaxial sample in ***Figure 1.a***. The average strength of the weft direction is 9.08 N/mm, which is much higher than in the machine direction, because weft yarns are parallel to the load. The biaxial weft direction strength was around 8 times higher than

that in the triaxial weft direction because of the higher density of yarns in the biaxial fabric.

From **Table 1**, it can be seen that the biaxial fabric shows higher mechanical properties along the warp and weft directions, compared to the triaxial fabric. The average strain at a maximum strength of the biaxial fabric is approximately equal in both the warp and weft directions, while for the triaxial fabric in the machine and weft directions average it was 11.4% and 2.2%. The machine direction average strain at the ultimate strength of triaxial fabric was higher than all the other fabrics in all directions apart from biaxial fabric in the bias direction. The average strain in the machine direction reached close to that of biaxial fabric in the bias direction because triaxial fabrics have a unique structure (**Table 1**). In **Figures 5.c** and **6.c**, the shear strength of the woven fabric is presented. The maximum strength in the bias direction was nearly similar for both biaxial and triaxial fabrics; however, there was a higher difference in the values of strain at the maximum strength. The average strain was 12.4% at the highest strength of biaxial fabrics in the bias direction. Values of strain at the ultimate strength for biaxial fabric in the bias direction is six times higher than in triaxial fabrics in the same direction, the reason for which is the high elongation in the close woven structure of the fabrics.

Tensile and bending test of composite

Samples were prepared according to ASTM D3039 for a tensile test and BS EN ISO 14125:1998 for a bending test. The tensile specimens were of 250 x 25 mm dimensions with a clamping distance of 165 mm, and the bending specimens were of 100 x 15 mm dimensions with an outer span length (L) of 80 mm, fixed at three points for the bending tests (the span-thickness ratio was 100). (**Figures 7** and **8**) The loading rate was maintained at 10 mm/min.

Result and discussion of composite testing

Mechanical properties of the composite are represented in **Table 2**. The tensile strength, Young's modulus, ultimate strength and strain [%] of the composite with various combinations of fabric layers are presented. The average standard deviation was calculated from five samples.
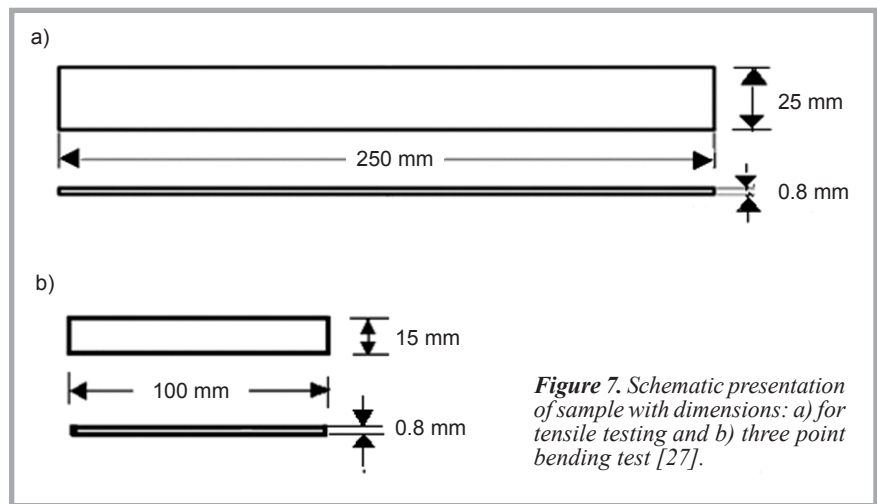

Figure 7. *Schematic presentation of sample with dimensions: a) for tensile testing and b) three point bending test [27].*
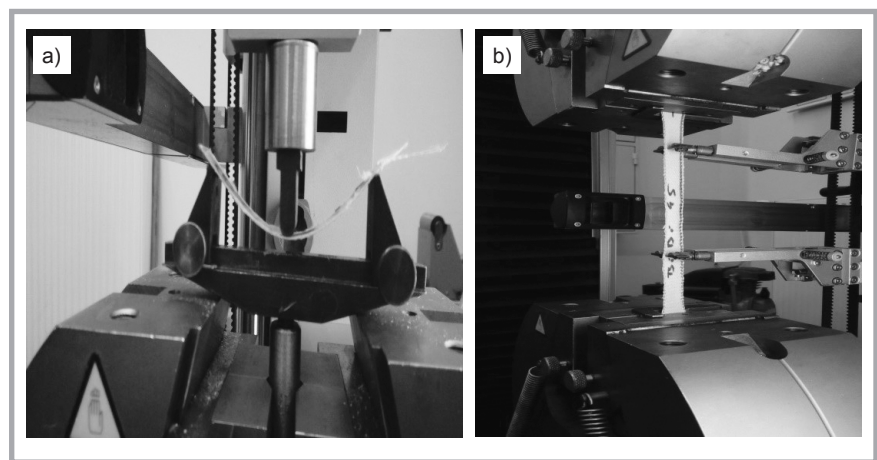

Figure 8. *a) Bending specimen under three-point load and b) tensile sample under tension load.*

Table 1. *Results of tensile test of biaxial and triaxial woven fabrics.*

Woven fabrics	Directions of fabric	Strength, N/mm		Strain, %	
		Average	St.dev	Average	St.dev
Biaxial	Warp	83.56	11.50	4.31	0.44
	Weft	73.69	5.82	4.28	0.27
	Bias (45°)	3.11	0.66	12.40	1.73
Triaxial	Machine	0.44	0.04	11.40	4.21
	Weft	9.08	1.82	2.27	0.69
	Bias (45°)	2.25	0.73	2.52	0.33

Table 2. *Mechanical properties of composite with various fabric layer combinations.*

Composites & directions		Strength, MPa		Young's modulus, GPa		Strain, %	
		Average	St. dev	Average	St. dev	Average	St. dev
Bi-bi axial	Warp	462	18.58	11.1	13.45	3.08	0.07
	Weft	308	4.81	10.7	0.13	2.20	0.08
	45°	138	1.41	2.4	0.07	31.41	0.28
Tri-tri axial	Machine	120	3.60	4.5	0.58	16.55	0.88
	Weft	223	4.78	5.3	0.46	3.12	0.17
	45°	96	11.70	4.1	0.43	13.62	0.93
Bi-tri axial	Warp	225	14.20	8.9	0.11	2.35	0.65
	Weft	251	20.50	8.3	0.37	2.62	0.13
	45°	101	9.40	3.9	0.14	4.63	0.66

Figure 9. Strength vs. strain % of different composites

Figure 10. Bending stress vs. deflection.

er strength than the other two in the same directions.

The more open space, and lower yarn density and volume fraction impacted the strength of the tri-tri axial composite. From *Figure 9*, it can be seen that the biaxial composite in the bias direction has a strain value of 31.62%, at the level of the highest strength. In the machine direction, the tri-tri axial composite has a strain % of 16.55, at the maximum strength, which may be due to the yarns having a ±60° orientation, which offers good shearing properties for the tri-tri axial composite, compared to the other samples.

The bi-bi axial composite strain in the weft and warp directions at the ultimate strength was very low (3.08% and 2.20%, respectively), which resulted in a sudden rupture (see *Figure 9*). The composite reinforced with bi-bi fabric has a brittle nature in the warp and weft directions. The bi-tri axial composite strains in the warp and weft directions at the ultimate strength are similar, but the strain in a 45° direction at the ultimate strength was higher by almost 2% than in the warp and weft directions.

The tri-tri axial composite strain in a 45° direction at the ultimate strength was 13.62%, which was the third highest strain at the ultimate strength compared to all composites in all directions (see in *Figure 9*).

Young's modulus of the bi-bi axial composite had a higher value in the warp direction, while the tri-tri axial composite had a nearly equal Young's modulus in every direction (*Table 2*).

In the case of flexural strength, in comparison to all composites, the bi-tri axial composite has the highest bending strength. In the bi-tri axial composite, the yarns cover all directions: warp, weft and 60°. This factor was influenced by the good bending quasi isotropic properties.

The highest flexural strength – 75MPa was obtained with the bi-bi axial composite in the warp direction. This study indicates that the fabric structure is very important for the composite bending strength.

The flexural strength of the bi-tri axial composite in the 45° direction was nearly 10 MPa higher than for the other two
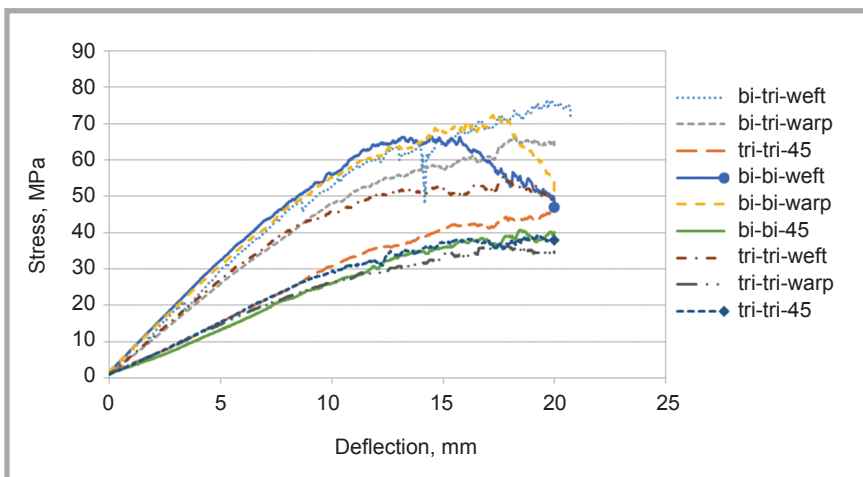
The bi-bi axial composite has a higher strength value in all directions in comparison to the tri-tri axial and bi-tri axial composites because the bi-bi axial composite has a higher density of yarns, fewer voids in the fabric structure and lower volume fraction of fabric in the composite.

For the bi-bi axial composite, the average strength in the warp direction was 462 MPa, which is 3.8 times higher than for the tri-tri axial and more than 2 times higher than that of the bi-tri in the same direction.

In the other two directions (weft and 45°), the bi-bi axial composite had high-

Table 3. Flexural strength and modulus of composites.

Composites & directions		Flexural strength, MPa		Flexural modulus, %	
		Average	St. dev	Average	St. dev
Bi-bi axial	Warp	75	7.10	11.1	1.11
	Weft	64	3.41	9.3	1.44
	45°	41	1.92	3.8	0.02
Tri-tri axial	Machine	40	4.16	3.9	0.62
	Weft	53	4.16	6.1	0.65
	45°	40	5.35	4.0	0.69
Bi-tri axial	Warp	64	1.73	6.9	0.03
	Weft	71	6.02	7.9	1.35
	45°	50	4.04	4.81.44	0.22

composites in the same directions, while the flexural moduli were almost similar (*Table 3* and *Figure 10*) to each other. The bi-tri axial composite had a good flexural modulus in all directions in comparison to other the two composites presented in *Table 3*. The bi-bi axial composite in the warp direction has a higher flexural and Young's modulus by 11.1 GPa in comparison to all directions of all the other composites. The Young's modulus and flexural modulus are of an almost similar value for all composites. This changes in mechanical properties are directly related to yarn orientation within the reinforcement of the composite material.

◼ Conclusions

The experimental study presented in this paper was focused on understanding the behaviour of non-laminated biaxial and triaxial fabric and composites reinforced with two layers of fabric with a different layer arrangement. The experimental investigation was conducted in two phases. The main conclusions drawn from the findings of the research are as follows:

- ◼ The density of yarns in the fabrics is the important factor for the strength of biaxial and triaxial fabrics.
- ◼ Triaxial fabric with a low mechanical strength is dependent upon the low density of fabric and yarn orientation.
- ◼ Both the strength and strain are influenced by the more open space in triaxial fabric.
- ◼ Mechanical properties are higher according to the yarns direction.

The second phase of this research was the determination of mechanical properties of a composite reinforced with two layers of fabric.

- ◼ Tri-tri axial composite strength is influenced by more open space, different orientations and a lower volume fraction of the reinforced fabric.
- ◼ The bi-bi axial composite has higher strength in all directions in comparison to the tri-tri axial and bi-tri axial composites.
- ◼ The bi-tri axial composite has high bending properties in every direction and a high flexural strength and modulus in the warp, weft and 45° directions.
- ◼ The tri-tri axial composite has an almost equal Young's modulus in every direction in comparison to the other composites.

Tests of the composites proved that structure of the fabrics influence the mechanical properties of the composite material. During the design of the final products, it is important to know the applications and what type of load and direction will be operating on the final product.

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LABORATORY OF BIODEGRADATION

The Laboratory of Biodegradation operates within the structure of the Institute of Biopolymers and Chemical Fibres. It is a modern laboratory with a certificate of accreditation according to Standard PN-EN/ISO/IEC-17025: 2005 (a quality system) bestowed by the Polish Accreditation Centre (PCA). The laboratory works at a global level and can cooperate with many institutions that produce, process and investigate polymeric materials. Thanks to its modern equipment, the Laboratory of Biodegradation can maintain cooperation with Polish and foreign research centers as well as manufacturers and be helpful in assessing the biodegradability of polymeric materials and textiles.

The Laboratory of Biodegradation assesses the susceptibility of polymeric and textile materials to biological degradation caused by microorganisms occurring in the natural environment (soil, compost and water medium). The testing of biodegradation is carried out in oxygen using innovative methods like respirometric testing with the continuous reading of the CO_2 delivered. The laboratory's modern MICRO-OXYMAX RESPIROMETER is used for carrying out tests in accordance with International Standards.

The methodology of biodegradability testing has been prepared on the basis of the following standards:

- **testing in aqueous medium:** 'Determination of the ultimate aerobic biodegrability of plastic materials and textiles in an aqueous medium. A method of analysing the carbon dioxide evolved' (PN-EN ISO 14 852: 2007, and PN-EN ISO 8192: 2007)

- **testing in compost medium:** 'Determination of the degree of disintergation of plastic materials and textiles under simulated composting conditions in a laboratory-scale test. A method of determining the weight loss' (PN-EN ISO 20 200: 2007, PN-EN ISO 14 045: 2005, and PN-EN ISO 14 806: 2010)

- **testing in soil medium:** 'Determination of the degree of disintergation of plastic materials and textiles under simulated soil conditions in a laboratory-scale test. A method of determining the weight loss" (PN-EN ISO 11 266: 1997, PN-EN ISO 11 721-1: 2002, and PN-EN ISO 11 721-2: 2002).

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The following methods are applied in the assessment of biodegradation: gel chromatography (GPC), infrared spectroscopy (IR), thermogravimetric analysis (TGA) and scanning electron microscopy (SEM).

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