Tensile mechanical behavior of a polymeric composite reinforced with 4-axial carbon fiber woven

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Abstract. During the last thirty years, there has been a growth in the study and analysis of composite materials for automotive and aerospace industry which require lightweight materials with demanding mechanical properties. Textile reinforce composite materials have advantages with respect to laminated composite materials such as better formability and out-of-plane properties. Therefore, the purpose of this research is to determine the mechanical behavior for uniaxial testing of a carbon fiber of a composite material reinforced with a quadriaxial carbon fiber woven in order to decrease the anisotropy of the woven composite material. Five specimens for each of the different orientations at 0, 30, 45, and 90 degrees; In addition, six specimens of a plain woven (the most common on the market) were tested, two specimens per orientation at 0, 45 and 90 degrees, in order to contrast the behavior of these with the proposed tissue. It was obtained that the properties in the composite materials change according to the direction in which the fibers are oriented; therefore, the results showed that the quadriaxial tissue and the stress value are less than the plain tissue, by 39%, only in the zero degrees orientation, then the plain woven has a greater number of fibers in that orientation, the orientation of ninety degrees is higher by 17%, and in the case of forty-five degrees orientation, the value is 82% higher. In the same way, when we study the orientations in there is no fiber, in the plain woven of the direction in which there is no fiber, is forty-five degrees’ orientation and in the proposed tissue it is the thirty-degree one 30 degrees and it can be seen that, in this case, in the behavior of the quadriaxial tissue is greater the stress value by 66%.

1. Introduction
Automotive and aerospace industry is continuously finding new materials to satisfy their demand on fuel consumption reduction. The use of composite materials has been one of the main solutions [1]. They show some advantages compared to other engineering materials. Properties as high resistance to fatigue and corrosion, high strength and stiffness to weight ratio makes the composite materials the best option for many engineering applications [2]. On the other hand, polymer matrix composites (PMC) can be reinforced by either particulates, whiskers, or fibers. Fiber-reinforced composites can be laminated to endow material with good in-plane properties. However, laminated composites are prone to interlaminar delamination and the thickness properties are poor [3].

Textile composites have better out-of-plane stiffness, strength, and toughness properties, and supreme formability than tape laminates [4]. There are three types of textile composites: braided, knitted, and woven fabrics. Braided fabrics are made by orthogonally interlacing two or more sets of yarns to form a structure. One set of yarns is called braided yarns and the other is named axial yarns[5]. Braided fabrics have high impact resistance and stability under tension in the braided yarn system. On the other
way, knitted fabrics are constructed by interlocking loops of yarns. Their advantages consist on high productivity, low cost, and also good formability. Compared with woven, knitted fabrics have better impact resistance [6]. Woven fabrics are the most used textile composites. They consists of two sets of interlaced yarns: warp and weft (or fill) yarns according to the yarn orientation [7]. Warp yarns run lengthwise, and weft yarns run crosswise. Two-dimensional woven fabrics are those with plain, twill and satin weaves. Plain fabrics have one warp yarn which is repetitively woven over and under weft yarns. In twill weaves, warp yarns float over two consecutive weft yarns, and under the following one weft yarn. If warp yarns are woven over more than two consecutive weft yarns, then a satin weave is made [6].

In addition, woven fabrics which have gaps between two adjacent yarns are called opened packing. On the contrary, if yarns are tightly woven with no gaps between two adjacent yarns are named closed-packing fabrics. Woven fabrics can also be balanced if they have same properties and geometric dimensions in both the warp and weft directions. On the other hand, unbalanced woven fabrics have different properties and different geometry [8].

Several models have been developed to predict the mechanical behavior of woven fabric composites. The influence of the undulation of the weaving and of the interactions between warp and weft yarns was included in a constitutive model and assess the biaxial fabric behavior by means of finite element modelling [9]. Similarly, elastic properties and ultimate strength were obtained for a $(0/60/-60)$ triaxial woven and validated with a finite element model [10].

The present study sought to obtain the tensile strength, maximum strain, and modulus of elasticity for a $(0/45/90/-45)$ quadriaxial woven fabric (QWF) composite with an epoxy resin matrix [6]. The results were compared with a plain weave fabric (PWF) composite to assess differences between the two fabrics. It is hypothesized that QWF decrease its anisotropy compared with PWF composite.

2. Methodology

2.1. Fabric processing and sample preparation

Two carbon fiber fabrics were woven on a 0.4 m x 0.5 m frame: 1) a $(0/45/90/-45)$ quadriaxial woven fabric (QWF) which consists on wefts at 0 and 90 degrees, and warps at $+45$ and $-45$ degrees, 2) a plain-woven fabric (PWF) with yarns running at 0 and 90 degrees. The fabrics were processing using the vacuum assisted resin transfer molding (VARTM) technique. They were withdrawn from frame and place it in an aluminum mold which have been previously cleaned and then spread an unmolding substance on it. The fabrics was placed on the mold, and sealed tape around the mold edges. A peel ply is placed on the fabric to apply the vacuum infusion system. A transfer mesh was placed on top which allowed the epoxy resin flow easily. Four orientations were chosen to be tested, one of them is a not-aligned direction. For the $(0/90/+45/-45)$ QWF composite, 30 degrees was the not aligned direction (see Figure 1 and Figure 2). On the same way, 45 degrees is the unaligned direction for the $(0/90)$ PWF composite. Five samples for each orientation were obtained as it is shown in Figure 1. The samples were obtained following the standard ASTM D3039/D3039M–14 [12] (see Figure 3).

2.2. Mechanical testing

The samples were placed into the grips taking care of they were aligned with the longitudinal axis of the universal testing machine MTS Bionix 307.02 (MTS System Corporation, Minneapolis, MN, USA). All the samples were pull to failure at a rate of displacement of 2 mm/min.

2.3. Statistical analysis

Chauvenet’s criterion was used to reject outlier data. Means and standard deviations were obtained for tensile strength, maximum strain, and modulus of elasticity.
3. Results

In our best understanding there is no previous work reporting the tensile mechanical properties of a (0/45/90/-45) quadriaxial woven fabric composite with an epoxy resin matrix. A similar work was done in a (0/45/90/-45) quadriaxial E-glass/polyester composite. However, this fabric was knitted and not woven [13]. Engineering stress and engineering strain curves were obtained from a uniaxial test for four different orientations which are 0, 30, 45, and 90 degrees in the QWF unlike PWF that only was tested for 0 and 45 degrees (see Figure 4). Mechanical properties like tensile strength, maximum strain, and modulus of elasticity was obtained each of the orientations and tested fabrics and they are shown in Table 1. Results showed that 0 and 90 degrees had the higher values for tensile strength whereas max strain, and modulus of elasticity were very similar for the two orientations. Tensile Strength for 30° is 58% smaller with respect to 0° orientation and 63% than 90°. QWF at 45 degrees showed a tensile strength which was only lower by 22% with respect to 0 degrees and 31% with respect to 90 degrees.

Similarly, the values obtained from the modulus of elasticity in the quadriaxial woven fabric showed that the 0 and 45 degrees had very similar values. However, 30 and 90 degrees of orientation have the smallest and the highest values. 0 and 45 degrees are about 9% smaller than 90, and 30 degrees is smaller by 18% with respect to the latter. Maximum strain was also determined and has a similar behavior than modulus of elasticity. 0 and 45 degrees have about the same values, being 0 and 90 degrees the lowest and highest respectively.

The PWF was also tested in order to be compared with the QWF. Tensile strength in PWF was higher at 0 than QWF by 39% (see Table 1). However, it was 82% smaller than QWF for the 45°. The same behavior is observed for modulus of elasticity and maximum strain. The latter is about 21% higher in PWF for 0° and smaller 67% for 45° than QWF. Modulus of Elasticity was higher in PWF for 0° in 32% and smaller for 45° in 74% compared with the QWF (see Table 1).
Figure 4. Representative stress and strain curves obtained from the uniaxial test.

| Orientation | Tensile strength (MPa) | Max. strain (x10⁻³) | Modulus of elasticity (GPa) |
|-------------|------------------------|----------------------|-----------------------------|
| 0°          | 204.83±31.02           | 23.00±0.40           | 10.72±0.88                  |
| 30°         | 86.05±11.05            | 13.00±0.20           | 9.60±0.57                   |
| 45°         | 160.53±9.03            | 24.00±0.10           | 10.71±0.51                  |
| 90°         | 231.63±41.06           | 39.00±0.50           | 11.77±1.16                  |

Table 1. Mechanical properties for QWF and PWF reinforced composite materials.

Fiber reinforced composites are stronger at the orientation of the fibers. Therefore, it was expected to have higher values for 0°, 45°, and 90° for QWF and 0° and 90° for PWF. The way as the fabric is made allowed to the PWF to be more compact and have more fibers in the direction of the load. As a consequence, samples with a higher density of fibers can withstand more load than others. However, it was interesting to notice that PWF had a very low value for 45° orientation. It was only 9% of the value obtained for 0° that in the direction where the fibers are not oriented. Therefore, PWF composite have a behavior that depends mainly in the direction of fibers are oriented. The results of this study agree with a previous work done.

4. Conclusions

QWF composite has better mechanical properties in the case of load are not aligned with fibers compared with PWF composites. If an application has mainly loads aligned to the fibers, the authors suggest to use PWF, however if the application requires working with loads in different directions, the QWF has a better mechanical behavior that PWF. The results of this study will give an option for a opened-packing textile composite which reduces anisotropy and can be used for automotive and aerospace applications. Future projects will involve prediction on mechanical behavior based on micromechanics, and also a finite element analysis.

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