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▶ To cite this version:

Ashok Rajpurohit, Vicky Singery, Sébastien Joannès, Philippe Sanial, Lucien Laiarinandrasana. Manufacturing and performance of hybrid fabric reinforcements and their composites. ECCM 18 - 18th European Conference on Composite Materials, Jun 2018, Athens, Greece. 8 p. hal-01958219

HAL Id: hal-01958219
https://minesparis-psl.hal.science/hal-01958219

Submitted on 17 Dec 2018

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MANUFACTURING AND PERFORMANCE OF HYBRID FABRIC REINFORCEMENTS AND THEIR COMPOSITES

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Keywords: hybrid textiles, hybrid composites, intralayer, interlayer, applications

Abstract
In this paper we present some recent results on our studies on fiber hybrid composites using carbon and glass fibers for novel applications in the field of wind energy, sports and leisure. The fabrics are manufactured from T700SC carbon fiber from Toray and 111A E-glass from Owens Corning while the composites using these fabrics are manufactured using RTM process with epoxy resin. Three hybridization strategies, namely, Interply, intraply and intermingled hybrids, and their mechanical behavior is planned to be investigated. The current work investigates tensile and flexural properties of intraply and interply hybrids. Although possessing a lower strength both in tensile and flexural loading the interply hybrids offer enhanced failure strain to the hybrid composites. Hence, the positive hybrid effect that is also been reported by several researchers for carbon and glass hybrids is actually higher for interply hybridized composites when compared to intraply hybridized ones. The interply hybrids demonstrate a drastic reduction in the strength and modulus properties both in tensile and flexural loading. The results also demonstrate that improved dispersion, leads to better mechanical performance in hybrid composites. Among the intraply hybrids, hybrid with three carbon and three glass tows blocked together demonstrates superior mechanical performance among all.

1. Introduction

One of the most important reason why fiber reinforced composite materials are gaining wider usage in applications ranging from transportation, aerospace, high performance structure, wind energy, sports and leisure goods is the specific mechanical properties, i.e., mechanical properties-to-density ratio, of composite materials being generally higher than those of conventional materials. The others reasons being their tailorability to specific applications. Ideally a composite designer will always want to have a material that combines high stiffness/ strength with high toughness/extensibility. Traditional carbon fiber composites provide exceptional stiffness and strength but these composites can often have a limited extensibility and poor damage tolerance especially at lower operating temperatures. Also, CFRP's tend to fail in a brittle manner catastrophically with little or no warning before failure. Owing to these reasons these composites hence are general over designed. The failure strain and toughness can be dramatically increased if brittle fibers such as carbon fibers are replaced by ductile fibers partially. Because of the drawbacks of existing toughening strategies and the strong need for new lightweight materials with improved toughness, reduced costs and having better balance of different mechanical properties, the research interest in hybridization in polymer composites has been widely reviving.

Hybrid composites consist of two or more fiber types in a common matrix and offer a balanced material in terms of mechanical properties such as modulus, strength, toughness and ductility. A synergistic effect on the mechanical behavior is also observed when combining two different fibers in a common matrix, it is often termed as the hybrid effect. It is defined in different ways but one of the crucial observation is that the failure strain of the low elongation fibers in a hybrid composite appears to be greater in hybrid than in pure low elongation fiber composite [1]; the other being deviation of mechanical behavior from the rule of mixture for combination of the fibers in a hybrid composite [2, 3]. Several studies have been reported on hybrid composites those including combination of different technical polymeric fibers such as carbon, glass and aramid; metal fibers, mineral fibers and natural fibers [4, 5]. Three different hypotheses for the hybrid effect have been mostly reported by researchers now, those include, residual stresses, changes in the damage development leading to final failure of the hybrid composite, and dynamic stress concentrations. Hybrid composites can interfere with this damage development process at several stages. The stress concentrations in the intact fibers as well as the stress recovery in the broken fiber can be altered if the fibers have a different stiffness or diameter and this interferes with the cluster development. The broken low elongation fibers can be bridged by the high elongation fibers, which does not only hinder the development of the clusters but can also increase the critical cluster size. The remaining low elongation fiber fragments will have a higher failure strain, as their weakest link just got eliminated. Also, a size scaling effect can occur. This effect can also increase the apparent failure strain of hybrid composites compared to the reference low elongation composite. More specifically, if a hybrid composite is compared with a low elongation fiber composite of the same volume, then the volume of low elongation fibers is lower in the hybrid composite, and hence its failure probability is lower [4]. Most hypotheses have been applied to unidirectional hybrid composites in either the interyarn or interlayer configuration [6–15]. These hypotheses can be extended to multidirectional composites, as their failure, although more complex, still coincides with failure of fibers in the loading direction. The studies on multidirectional composites manufactured using unidirectional hybrid fabrics have been rarely reported for their balance in different loading conditions. Moreover this study specifically focuses on application developments for hybrid composites specifically in the field of sports and leisure products such as skies and wind blade applications like spar caps.

This paper explores the design of multidirectional hybrid composites by combining high strength T700SC carbon fiber from Toray with 111A E-glass fiber from Owens Corning. The aim of this study is to manufacture hybrid fabrics and their composites in different levels of hybridization, namely, in interply and intraply configurations. Further to investigate the mechanical performance, specifically in tensile and flexural loading conditions for the developed multidirectional hybrid composites in comparison to the reference homogeneous composites. Conclusions will be drawn on possible hybrid effect in different configurations and on the balance of different mechanical properties and the suitability of developed hybrids for specific applications.

2. Experimental

2.1. Materials

High strength carbon fiber, T700SC from Toray and E-Glass, 111A rovings from Owens Corning were used in this study. The 12K 800 tex carbon rovings and 600 tex glass fiber rovings were used to manufacture reference carbon and glass fabrics; while 24K 1600 tex carbon rovings and 1200 tex glass rovings were used to manufacture the intraply hybrid fabric reinforcements. Commercially available epoxy resin system, namely, Araldite LY 564/ Aradur 2954 from Huntsman Specialty Chemicals was selected as resin for composite manufacturing. The mechanical properties obtained from the data sheets of the selected fibers and resin is as shown in Table 1.

Table 1. Properties of the raw materials.

Material	Density [g/cm^3]	Fiber diameter [micron]	Tensile strength [MPa]	Tensile modulus [GPa]	Failure strain [%]
Carbon T700SC	1.76-1.84	7	4510	221-240	1.9
Glass 111A	2.62	17	2400	81	4.5
Epoxy system	1.1	–	71-77	2.5-2.6	4.5-5.5

2.2. Processesing

Unidirectional fabrics containing the selected rovings were further manufactured using Malimo UD stitching technology from Textima. Unidirectional rovings were drawn from the creel up to the stitching zone. A base stabilization fabric in the form of a fine glass fiber woven fabric was introduced below the stitching zone from below. Further a PES stitching thread was utilized to stitch the fabric together to impart stability and handling properties to the reinforcement. Figure 1 below shows the set of fabrics manufactured for the study.

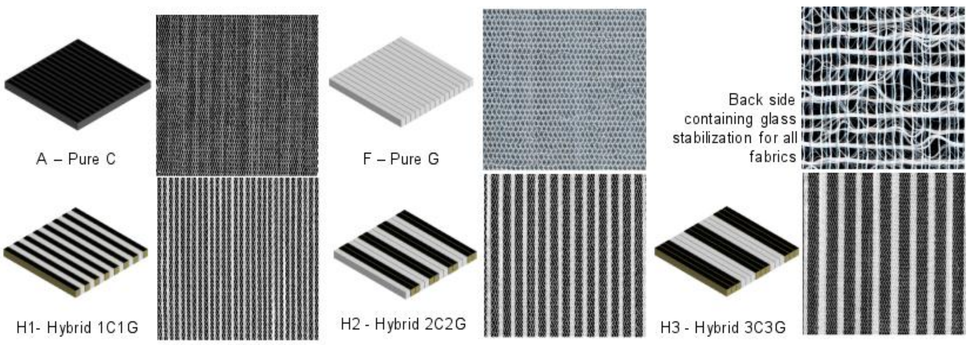

Figure 1. Schematic and pictures of the fabrics manufactured.

Composites were manufactured using the sequential RTM process setup from ISOJET equipments, Corbas, France. Dry fabrics were first used in the preforming process to manufacture a net shaped preform that can be further used in the infiltration process step in the RTM process. The preforming binder used here is a epoxy based thermoplastic binder Epikote 05390 from Hexion. Premixed epoxy resin was delivered into the mold containing the dry preform at a constant pressure basis and maximum injection pressure utilized for the infiltration was 6 bars. In-mold curing was done for these composites at 80°C for 1 hour followed by curing at 140°C for 6 hours. The details of the manufactured composites are presented in Table 2 below.

2.3. Testing

Developed fabrics were tested for its physical properties and its uniformity. The aerial density was calculated by weighing the samples 100mm×100mm cut out from different regions of the fabrics similarly, thickness was calculated for each fabric sample under a uniform load of 400 grams and 28 kgs. The manufactured UD reinforcements were also tested for its coverage using a Cannon high precision scanner and ImageJ image analysis tool. The scanned pictures of fabrics were further utilized to measure the stitching parameters such as stitch length and stitch pitch for each of the fabrics.

Table 2. Nomenclature and details of composites manufactured for the study.

Composite	Fabric used	Number of layers	Layup sequence	Thickness [mm]	Density [g/cm^3]	FVF [%]
H1	C - (1C1G)	6	$[0/90/0]_S$	2.60	1.66	51.28
H2	D - (2C2G)	6	$[0/90/0]_S$	2.62	1.66	54.17
H3	E - (3C3G)	6	$[0/90/0]_S$	2.61	1.66	51.82
I1	A and F	6+6	$[0G/0C/90G/90C/0G/0C]_S$	3.13	1.66	50.04

The weight of each of the constituents in the fabrics were also confirmed by dismantling/unraveling the stitched fabric to recover, the technical fibers, glass stabilization and the stitching thread separately. For all fabrics the amount of each constituent materials was found to be within 5% of the expected values for that constituent.

Composites manufactured with these hybrid fabrics were tested for physical properties such as thickness, density and fiber volume fraction. The density of composites was measured by weighing composites samples in two different mediums, here, air and distilled water. The fiber volume fraction was measured by the burn off method. The tensile and flexural properties (3-point bending test) of the manufactured set of composites were measured on a universal testing machine from Instron. Tests were carried out using ISO 527-4 and ISO 14125 norm respectively. A minimum of 5 samples were tested in each case. The sample dimensions for tensile tests was chosen to be 250mm×25mm×thickness; for flexural tests the sample dimensions, such as width and length were chosen to be 40h mm and 50h mm, where 'h' is the thickness of the composite. The distance between bottom supports in 3-point bending test was chosen to be 16h, and loading rate for both the test was 2 mm/min.

3. Results and discussion

3.1. Density and fiber volume fraction

Fiber volume fraction and density of fabricated composite panels were evaluated to ensure the quality consistency of every composite specimen prior to subsequent experiments. Results from the burn off tests are as depicted in Table 2 in the section above. It is also apparent that, by introduction of glass fibers in the fabrics and composite layup, the density of subsequent composite increases. The densities and the volume fractions of all the hybrid composites are comparable to each other. Besides this, the RTM process used, proves to be a very reliable and robust process to manufacture composites within the tolerance specifications. The void content was not verified individually for each composite sample, but the optical microscopy observations on 2 of the samples showed very little void content and it was found to be less than 0.75 %.

3.2. Tensile properties

The tensile properties of tested composites samples is summarized and presented in Table 3. The hierarchy of the ultimate tensile strain is as follows: (I1 Interply hybrid] > [Intraply hybrid composites, H3, H2, H1]. The hierarchy of tensile strength is as follows: [H3] > [H2] > [H1] > [I1]. It is in general known that carbon fibres are brittle and the composites in tension tend to show no plateu region before catastropic failure. This observation for carbon composites hold true even for the hybrids tested in this study, contrary to the observation by Pandya et al. [10]. The hybrid structures to some degree tend to show some ductility because of having a certain amount of brittle carbon fiber and ductile glass fiber within their structures. However, in terms of final failure it is noticed that they also failed catastrophically. It may be also due to higher higher carbon fiber fraction in the composites.

Table 3. Tensile properties of manufactured composites.

Composites	Ultimate tensile strength [MPa]	Ultimate failure strain [%]	Tensile Modulus [GPa]
H1 - Intraply (1C1G)	935 (± 60.38)	1.60 (± 0.10)	60.83 (± 4.07)
H2 - Intraply (2C2G)	964 (± 44.64)	1.67 (± 0.09)	59.32 (± 1.28)
H3 - Intraply (3C3G)	1024 (± 51.51)	1.67 (± 0.09)	60.48 (± 2.10)
I1 - Interply hybrid	898 (± 45.82)	1.82 (± 0.10)	50.17 (± 0.87)

From the summary of the test data it can be seen that tensile properties of intraply hybrid (H1, H2, H3) composite are to some extent better than that of interply hybrid composite I1; and this performance improvement is attributed by the intralayer hybrid structure. In other words, a ply per ply placement carbon and glass fabrics in hybrid composite gives lower performance (both strength and modulus) in tensile mode than placing the glass and carbon rovings alternatively in the same fabric as can be seen in Figure 2. A similar conclusion has been drawn by Ikbal et al. [15] who reported it for carbon-glass hybrid and Ren et al. [12] who reported it for carbon-carbon UD hybrid. The failure strain for interply hybrids in the current study is observed to be higher than those of intraply hybrids and this can be attributed to the layup selected for I1 composite, where every carbon fiber layer has a glass fiber layer on either side and hence constraining the damage evolution in carbon fiber.

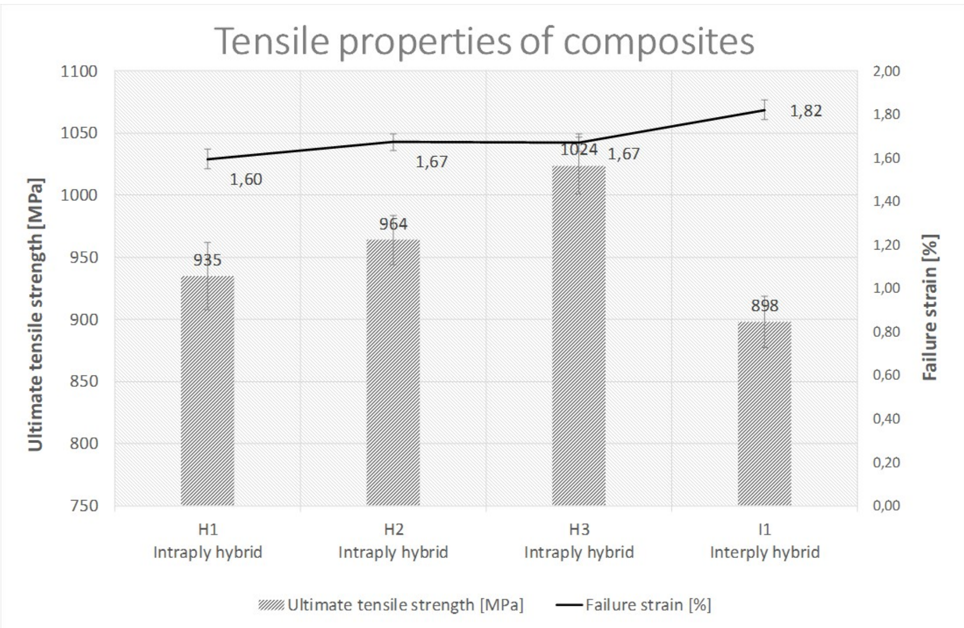

Figure 2. Tensile properties of manufactured hybrid composites.

3.3. Flexural properties

Table 4. Flexural properties of manufactured composites.

Composites	Flexural strength [MPa]	Failure strain [%]	Flexural Modulus [GPa]
H1 - Intraply (1C1G)	798 (± 37.37)	1.45 (± 0.29)	59.28 (± 2.38)
H2 - Intraply (2C2G)	794 (± 37.55)	1.36 (± 0.08)	60.84 (± 1.90)
H3 - Intraply (3C3G)	825 (± 30.57)	1.46 (± 0.13)	58.61 (± 1.78)
I1 - Interply hybrid	563 (± 6.37)	2.07 (± 0.64)	46.24 (± 0.73)

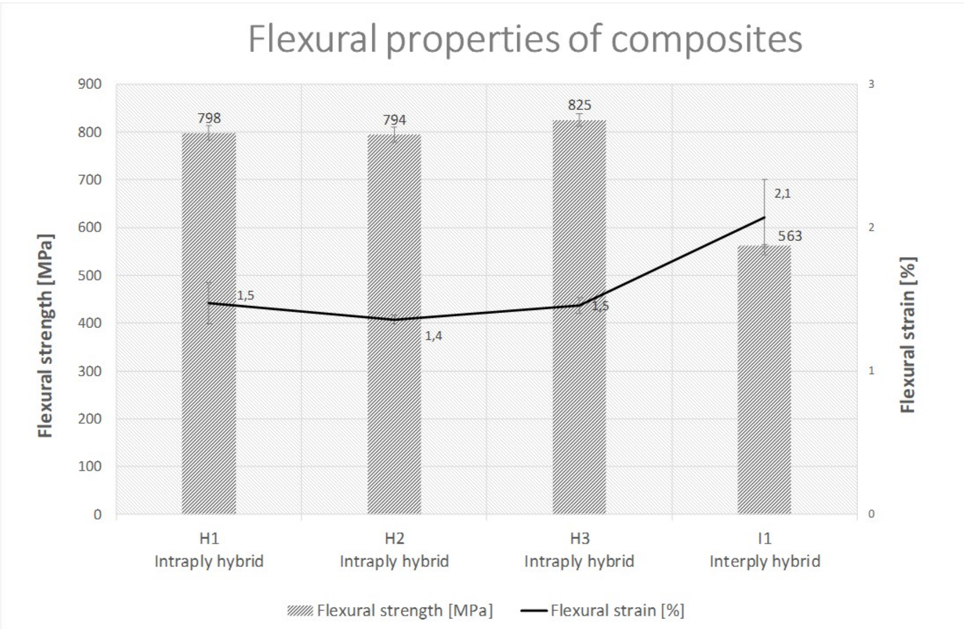

Figure 3. Flexural properties of manufactured hybrid composites.

It is observed that the most common failure mode is kinking or microbuckling at the compression side, which can be found in all three intraply hybrid composite specimens. For inter ply, that is layer by layer hybrid, the failure was more complex involving microbucking at compression side, interlaminar failure and sometimes failure in tension. The interply hybrids also showed a two step failure in the stress strain curve, very different to the intraply hybrids owing to their dicreet laminar structure and presence of glass fibers in the exterior. Signifantly lower flexural strength and modulus is observed for layer by layer hybrid, one of the reason for such phenomena is the because of the glass fiber layer in the exterior (bothe compression and tension) side of the composite. As also reported by Dong and Davies in [8]; the carbon layer in tension side generally adds to the flexural strength and modulus and They also report in [9] that a symmetric layup like in the current interply composites are not the optimal design for the hybrid composites that are subjected to flexural loads. Hence as can be seen by the tests intraply hybrids would be an ideal choice for hybrids where enhanced failure strain as well as better flexural performance is expected by hybrids over the non hybrid composites.

4. Conclusion and future scope

Mechanical properties in tension and bending of intraply hybrid composites (H1, H2 and H3) and interply hybrid composites (I1) made from T700S fiber rovings and 111A glass fiber rovings are evaluated in this study. The specific observations are:

- Interply hybrid composite has higher failure strain than the intraply hybrids both in tension and flexural mode. In tension I1 has 9% higher tensile strain and 24% higher flexural strain than H2.
- Interply hybrids show significantly lower tensile strength (-7%) and flexural strength (-29%) than the intraply hybrids.
- The tensile strength for the three intraply hybrids vary significantly, while the tensile modulus, flexural strengths and flexural modulus for these composites are identical.

As a continuation to the present study, a comparative study including the manufacturing and characterization of reference 100% carbon and 100% glass composite would be done and the properties of the hybrid composites will be compared to that obtained by rule of mixture and/or CLT predictions. Further characterization of the all the composites in quasi static compressive mode is planned.

Acknowledgments

The research leading to these results has been done within the framework of the FiBreMoD project and has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 722626.

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