

Evaluation of the Shear Properties of Long and Short Fiber Composites Using State-of-the Art Characterization Techniques



Antonios G. Stamopoulos, Alfonso Paoletti, and Antoniomaria Di Ilio

Abstract As the use of short fiber and textile thermoplastic composites is expanding in many industrial fields, particularly the automotive, it is necessary for each manufacturer in every sector to assess the mechanical characteristics and behavior of these materials in various loading and environmental conditions. Among the most difficult mechanical tests are those for calculating the shear properties and behavior of these materials. As a result, a variety of standards have been developed throughout the years. Among these, the most promising one may be considered the V-notched Rail Shear test as it incorporates the unique features of two different mechanical tests namely the Iosipescu and rail shear test. In the present work, this state-of-the-art mechanical test, originally designed for unidirectional composites, was implemented in different material architectures and its apparatus was modified and used for mainly two purposes; i.e. the investigation of the effect of the infusion direction on the mechanical properties of short and the warp-weft direction of the woven textile thermoplastic composites, as well as producing reliable data regarding the mechanical characteristics and the behavior of these materials for simulating the manufacturing process. The testing device was developed in a way to produce robust and accurate results, ensuring the alignment of its components as well as the stress uniformity in the section gauge. The results revealed a dependency of the infusion direction of the short fiber thermoplastics and the textile direction of the woven composites. To this end, this mechanical testing technique may be considered as a benchmark on the material characterization in shear deformation.

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1 Introduction

In the recent years, considerable attempts were conducted by all the sectors of industry towards the substitution of conventional with more innovative, high performance and more environmental-friendly materials. More particularly, in both the aeronautic and the automotive industry, a huge effort has been given to reduce the weight of the vehicles and to contribute this way to the reduction of the CO_2 emissions. To this end, a notable observation was the fact that the increment of the use of composite materials in the automotive industry helped the automotive companies to cope with the emissions' standardization in Europe and in Japan [1, 2]. Starting with the aeronautics industry, new aircrafts were produced that comprise more than 50% of composite materials, such as the Airbus A350 (53%) and the Boeing 787 (50%). The aeronautical manufacturers took into consideration the unique features of composites into the design process but there are several defects of these materials related mostly with the manufacturing process [3]. Most of these defects (fiber misalignment, porosity) decrease the properties of these materials, especially those related to the matrix properties (shear, flexural) [4, 5]. On the other part, the tendency of car manufacturers was well addressed by Mangino et al. [6], indicating also the skepticism towards the complete substitution of the conventional materials with composites. It is also underlined the necessity of the composite parts manufacturers to achieve high production component volumes which may easily be repaired, formed and recycled. Moreover, the automotive companies are using incrementally the new materials and material manufacturing technologies to new, more sophisticated vehicles which exploit optimally the benefits of the lightweight alloys and composites [7]. A good example is the implementation of carbon fiber reinforced materials in the chassis of the BMW i3 that allowed the manufacturers to use larger batteries (240 kg more). There are some predictions that in the future, a concept car may weight 40% less and may use composites as the primary material (more than 40%) [8].

To this end, the interest of the automotive companies was mainly concentrated to carbon or glass fiber reinforced thermoplastics (GFRTPs) mainly due to their recyclability and the good mechanical to weight properties. In addition, the use of short fiber reinforced thermoplastics has gained an increasing use in the sector of non-critical structural automotive parts as they exhibit satisfying stiffness and they can be produced via injection molding in high production rates reducing, at the same time, the fabrication cost [9]. In more demanding structures, in terms of loads and environmental conditions, the woven textile glass fiber reinforced thermoplastics tend to be utilized.

Nevertheless, as these materials still exhibit a certain anisotropy, a crucial information may concern their mechanical performance, mostly related to the matrix properties, under several loads and conditions. It is well known that several manufacturing defects contribute to the decrease of the shear properties of composites.

For instance, it is widely accepted that the parameters of the injection molding of short fiber reinforced thermoplastics has a strong influence on the fiber alignment towards the injection direction [10–12] or even the population of the remained intact fibers [13, 14], influencing at the same time the mechanical properties of the component. When using textile composites, the mechanical properties are strongly related with the fiber direction (warp or weft) and different results may be obtained while testing them as seen in [15]. Thus, the result of a manufacturing process can only be addressed via mechanical testing of specimens which are representative of the whole component. Consequently, the precise evaluation of the shear properties is based mostly on the representativeness of the specimens and the accuracy of the existing mechanical testing methods. In addition, via mechanical testing can be assessed not only the adequacy of the material in terms of structural condition but also the adequacy of a manufacturing process for the production of a component.

Among the most difficult mechanical tests for composite materials are those concerning the determination of the shear mechanical behavior and properties, especially those concerning the in-plane. Throughout the years, a number of standardized test methods have been proposed. Among these, the most popular are the Iosipescu, the Rail Shear and more recently the V-Notched Rail Shear test method. In the present work, this particular test method was considered as the base for the development of a modified testing apparatus for assessing the shear properties of composite materials of various types. To this end, the modified V-Notched Rail Shear apparatus was used for evaluating the shear response of short-fiber and textile fiber reinforced thermoplastics. During each test, the local and global deformations were measured and the behavior of each specimen under shear deformation was observed. The results of these mechanical tests revealed a strong influence of the direction of the injection molding to the shear properties of short fiber composites and a substantial independence from the warp and weft direction of the textiles. Considering the fact that the V-Notched Rail Shear testing method was developed for unidirectional (UD) composites, the present work contributes to the amelioration of this testing method in two main directions:

- modification of the apparatus for maintaining the specimen alignment during the test with less friction introduced possible;
- implementation of the testing method not only to UD composites but also to short fiber and textiles.

Moreover, other novelties of the present work are:

- the assessment of the effect of the injection direction to the in-plane properties of short glass fiber thermoplastics using the modified V-Notched Rail Shear apparatus;
- the investigation of the potential difference of the shear properties of textile glass fiber thermoplastics when loaded towards the warp or the weft direction.

2 V-Notched Rail Shear Testing Method

2.1 The State-of-the-Art Shear Mechanical Testing Methods

As previously mentioned, there have been developed at least 8 standardized mechanical tests for assessing the shear behavior of composite laminates. These standardized testing methods exhibit pros and cons which are synthesized in Table 1 [16]. As can be seen, the majority of these methods have significant drawbacks, especially concerning the shear stress uniformity and their flexibility for assessing all the shear strength characteristics of composite laminates. A typical example is the $\pm 45^\circ$ shear test which consists of a simple tensile specimen of a textile composite material. Although the profound simplicity of this test, the lack of stress uniformity and the fact that it can only be utilized for measuring the in-plane shear properties of textiles makes it inadequate for unidirectional or short fiber composites.

In addition to the standardized methods there have been developed also other non-standardized methods to overcome the difficulties of the previous ones concerning the complexity of the apparatus, the lack of features and the inaccuracy of the results.

More recently, standardized was a new testing apparatus and method call “V-Notched Rail Shear” [17, 18]. Its name is derived from the combination of two previously existing testing methods, the Iosipescu (ASTM D5379) [19] and the Rail

Table 1 The existing standardized testing methods for evaluating the shear properties of composite materials as presented in [16]

Test method	Standard	Features			
		Uniform shear stress	All 3 shear stresses practical	Shear strength obtained	Shear stiffness obtained
Short beam shear	ASTM D2344M			●	
Iosipescu shear	ASTM D5379	●	●	●	●
$\pm 45^\circ$ shear	ASTM D3518			●	●
Two rail shear	ASTM D4255			●	●
Three rail shear	ASTM D4255			●	●
Double-notched shear	ASTM D3846			●	●
Thin tube torsion	ASTM D5448	●		●	●
V-notched rail shear	ASTM D7078	●	●	●	●

shear test (ASTM D4255) [20]. The specimen of this testing method is similar to the Iosipescu test, it consists of a rectangular specimen with a pair of v-shaped notches at the opposite sides of the specimen. This way the stresses are concentrated near the notches and the cross-sectional region between them is subjected to almost pure shear. The main drawback of the Iosipescu testing method comes from the way the load is transmitted from the apparatus to the specimen, a way which can easily introduce bending moments to the specimen. To overcome this problem, the specimen of the V-Notched Rail Shear method is wider compared to the Iosipescu and the load is applied via shear, just as in the Rail Shear test. Consequently, the ASTM D7078 [21] specimen is less prone to bending deformation and the load is applied uniformly to the specimen.

As the ASTM D7078 was recently introduced to the scientific world, the frequency of its utilization is still rare due to the complexity of the basic configuration of the apparatus. Nevertheless, in recent years it has gained an increasing attention as it overcomes the most significant drawbacks of the other methods. A very comprehensive comparison between the Iosipescu and the V-Notched Rail Shear methods was conducted by Almeida et al. [22] on glass fiber-epoxy composites where the superiority of the ASTM D7078 is underlined. This state-of-the-art method was successfully used for the identification and the evaluation of porosity effect on the shear behavior of UD carbon fiber reinforced epoxies [23]. In addition, this testing method was assessed numerically and experimentally by Taheri-Behrooz and Moghaddam [24] analyzing the behavior of glass/epoxy composites. It is underlined that the most common drawback of this method is the misalignment of the two parts of the apparatus and the misalignment of the specimen itself inside the tabs.

Taking into account the drawbacks of this testing method, Gude et al. [25] proposed two modifications, one regarding the relative alignment of the two main pieces of the apparatus and one regarding the clamping of the specimens for maintaining their proper alignment. In parallel this work represents a first attempt to implement this new testing method to textile composites. Nevertheless, the authors underline that this modification led to excessive friction load between the guide columns and the main part of the apparatus. Moreover, while the size of the fixture makes it rigid its weight is increased compared to the conventional ASTM D7078 [21] apparatus.

2.2 Design and Realization of the Modified V-Notched Rail Shear Apparatus

In the present work, the design of the testing apparatus was based on the following principles:

- rigidity of the apparatus;

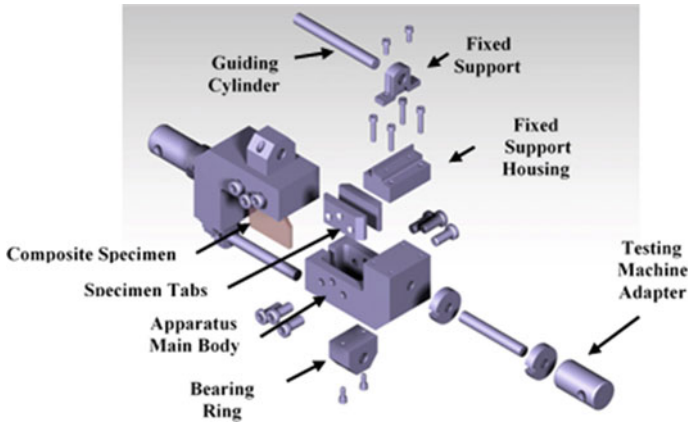


Fig. 1 Exploded view of the modified ASTM D7078 apparatus

- symmetry of the twin main pieces of the main body of the apparatus throughout the execution of a test so as to ensure the pure shear load and the corresponding load uniformity;
- simple to construct and to assemble (components simplicity). This way the apparatus may be constructed in every laboratory and machine shop;
- universality of its applicability in every universal testing machine (UTM);
- the designed testing apparatus should be able to test a variety of materials with different thicknesses varying from 0.5 to 5 mm.

Considering the specifications above, the designed modified V-Notched Rail Shear apparatus is presented in Fig. 1. As shown there, in the original apparatus proposed by the ASTM D7078 [21], 2 guiding cylinders were added in order to maintain the alignment of the two main pieces of the apparatus. To achieve the minimum friction possible, two linear ball guide were added to the columns. Another advantage of the use of these guides is the elimination of the spacers described by the standard ASTM D7078 which appear to be necessary while placing the specimen to the apparatus tabs. The material used for the main body is C45 structural steel, the self-aligning bearing rings and the fixed supports are catalogue commercial items from SKF® model LUND-12. This particular type of bearing rings may support static and dynamic perpendicular load up to 510 N and 695 N respectively [26]. The choice of this particular bearing rings was made on the base of the low friction values as indicated by the manufacturer (SKF®).

3 Experimental

3.1 Materials and Preparation

In the present work, the modified V-Notched Rail Shear testing method was applied to GFRTPs of two categories both with polypropylene matrix reinforced with short glass fibers and textile glass fibers. They both refer to the two most frequently used composites for manufacturing components in the automotive industry.

The polypropylene based PP-GF-30 (30% glass fiber content) short fiber reinforced material was firstly considered. The specimens for the execution of the mechanical tests were cut using water-jet cutting from PP-GF-30 plates made by injection molding. As mentioned in previous works [10–12], the fiber direction is a lot influenced by the injection direction, however the residual properties of the composite are very uncertain, since the alignment of the fibers is not regular. Thus, the specimens were cut in two directions, one parallel to the injection molding direction and one perpendicular to it shown in Fig. 2a. Consequently, the specimens were labeled “Longitudinal” and “Transverse” as their length is parallel or perpendicular to the infusion direction.

The ASTM D7078 standard was also utilized for assessing the effect of the fabrication direction of plain weave textiles. To this end, two similar material, in terms of constituents’ composition are considered. For confidentiality reasons, in the present work, these two materials are named GFRTP Material A and GFRTP Material B. The two materials consist of plain weave glass fibers with similar weight fraction (47% for the GFRTP Material A and 44% for the GFRTP Material B) placed in a polypropylene matrix. The two materials have a considerable unit cost difference; the GFRTP Material A is produced inside the EU while the GFRTP Material B in the Asian market. The specimens were cut according to the two main directions, one perpendicular to the warp and one perpendicular to the weft as shown in Fig. 2b.

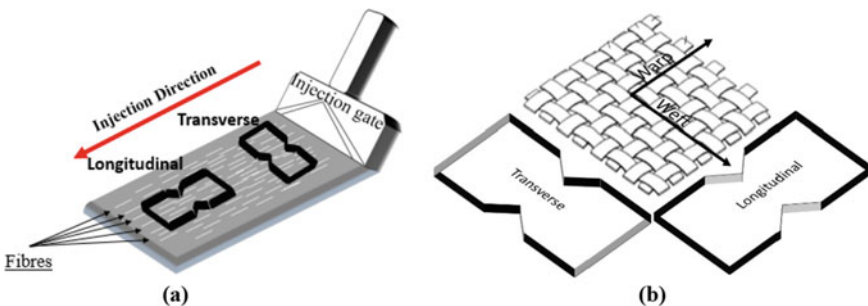


Fig. 2 Schematic representation of the correspondence of the Longitudinal and Transverse specimens with the fabrication direction

Table 2 Test matrix of the specimens of the mechanical tests conducted

Material	Description	Specimen designation	Testing speed (mm/s)	Replication tests
PP-GF-30	Short glass fiber reinforced polypropylene	Longitudinal	0.1	5
		Transverse		5
GF RTP Material A	Plain weave glass fiber reinforced polypropylene	Longitudinal (Warp)	0.1	5
		Transverse (Weft)		5
GF RTP Material B	Plain weave glass fiber reinforced polypropylene	Longitudinal (Warp)	0.1	5
		Transverse (Weft)		5

All the specimens were painted with a speckled varnish in order to create the proper pattern for strain inspection using the Digital Image Correlation technique (DIC). The complete test matrix is presented in Table 2.

3.2 Mechanical Testing and Data Acquisition

As seen above, a total number of 30 mechanical tests were conducted. An MTS servo electrical universal testing machine with maximum load capacity of 50 kN was utilized. The data acquisition rate was calibrated to 100 Hz. Alongside with the mechanical testing device, a Nikon DS5200 photo camera was positioned near the specimen in a way to capture 1 photo per second, allowing this way the DIC data acquisition for further analysis of the local and global strain field. One of the specimens mounted on the apparatus can be seen in Fig. 3. The captured images were elaborated with the Image J [27] software to increase the contrast and analyzed using the MatLab Ncorr [28].

The choice of the DIC analysis was not only performed to evaluate the strain distribution. According to previous research [23], even if the strain gauges are proposed by the ASTM D7078 standard [21] they fail to record the strain after a certain point of the execution of this particular testing method. The reason is the pine cracks which form at the section between the notches causing the de-cohesion of them.

As seen in Fig. 4, the shear strain distribution between the notches of the specimen is quite uniform throughout the execution of the mechanical tests. For calculating the shear strain, the region between the notches was isolated after the DIC analysis and elaboration and the γ_{xy} strain was obtained. For obtaining the stress values, the corrected values of force obtained are divided by the cross-sectional region between the notches tips.

Fig. 3 **a** The modified ASTM D7078 apparatus and **b** a detailed view of the gripping between the tabs and the specimen

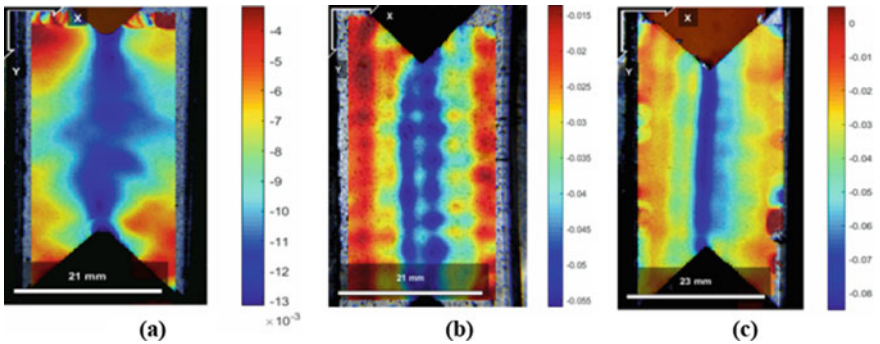
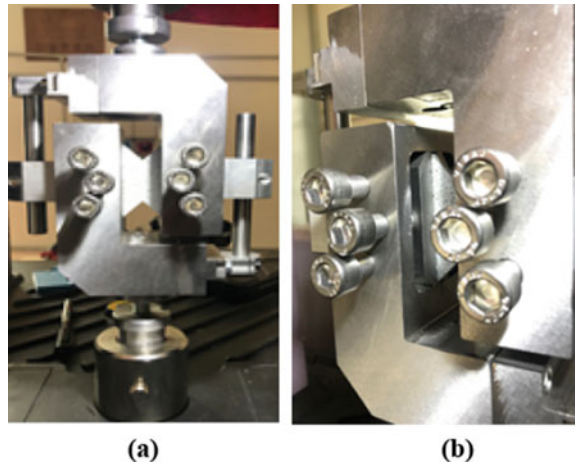


Fig. 4 Typical γ_{xy} shear strain distribution of the **a** PP-GF-30, **b** GFRTM Material A and **c** GFRTM Material B respectively

In addition to the above, for assessing the adequacy and the effectiveness of the guiding mechanism, 3 more tests were conducted without the use of the guiding-alignment system using specimens made of the PP-GF-30 material of the Transverse category. The choice was made in a way to investigate the less reinforced material's response. After the tests, the shear strain distribution and the uniformity of the shear deformation on the region between the notches was measured. In Fig. 5, a comparison between the shear strain distribution, moments before the final failure of the specimens tested with the modified apparatus (a) and the standard apparatus (b) is made. As seen there, the strain distribution is much more uniform, symmetrical and concentrated in the zone between the V-Notches (color dark blue) when the guiding cylinders are utilized. On the other hand, the shear strains out of the region between the notches are more intense in the case without the use of guiding cylinders, leading to the conclusion that the shear strain is less concentrated in the desired zone. This fact which signifies the importance of their implementation.

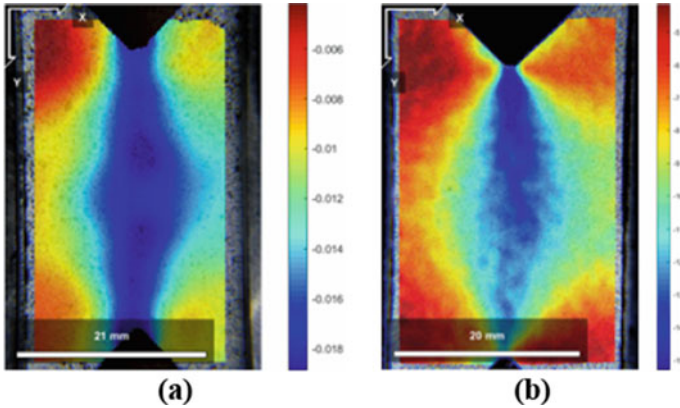


Fig. 5 Shear strain distribution of PP-GF-30 specimens with guiding cylinders (a) and without them (b)

Moreover, in order to understand more profoundly the significance of the guiding cylinders to the uniformity of the shear strain in the measuring region (between the notches), the region was subdivided into smaller regions aiming to assess the progression of the shear strain as the testing machine's crosshead displacement increased. The output of the assessment, even though delivered indicative results, pointed that the shear strain was almost the same for every region while a deviation was observed when the crosshead displacement exceeds 1 mm for the standardized testing apparatus. This phenomenon is resulted presumably by the application of stresses related to bending moments introduced to specimen that contribute to the development of stresses not related to shear.

4 Results and Discussion

4.1 Short Fiber Composites

The PP-GF-30 material proved to be quite fragile as its mechanical behavior was found to be non-linear elastic as it is presumably dominated by the polypropylene. The typical failure mode observed in both Longitudinal and Transverse specimens is an angled crack starting from the zone near the upper or lower notch and propagating almost instantaneously towards the direction of 45° of the loading direction. In Fig. 6a, a typical load-displacement curve obtained by one of the Transverse specimens along with photos recorded at various steps of the specimen deformation are presented. Consequently, after the elaboration of the obtained frames of the photo-camera, a comparison between the Longitudinal and Transverse specimens is

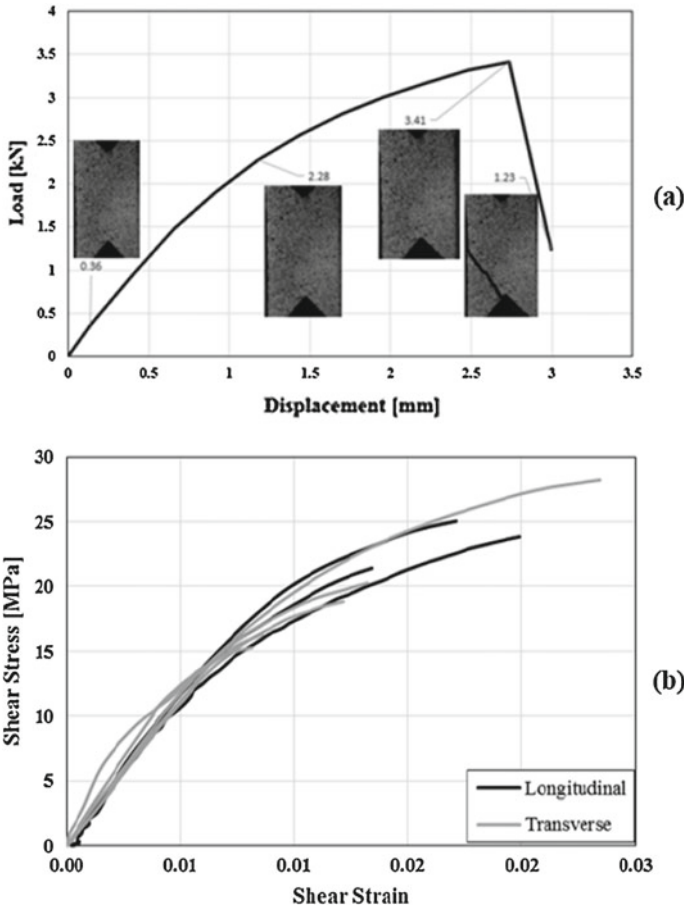


Fig. 6 **a** Typical load-displacement curve of a PP-GF-30 specimen tested according to the ASTM D7078 standard and **b** comparison of the in-plane shear behavior of Longitudinal and Transverse PP-GF-30 specimens

presented in Fig. 6b, while the averaged values of the in-plane shear strength and modulus may be seen in Fig. 7.

A first observation in both cases is that generally the longitudinal specimens tend to exhibit higher values of both strength and modulus, presumably due to the fiber alignment imposed by the manufacturing process as described in the previous sections of the present work. Nevertheless, observed is a significant standard deviation on the results leading to the conclusion that percentage of this fiber alignment is not the same in all of the longitudinal and transverse specimens, thus there must be a deviation on the percentage of the fibers aligned to the longitudinal or to the transverse direction of the injection of the plate from which the specimens were cut.

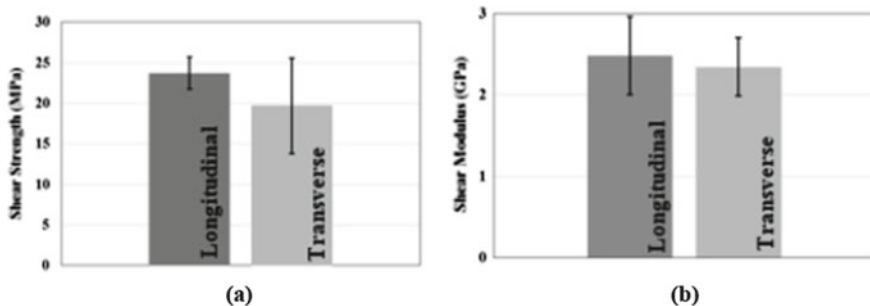


Fig. 7 Comparison of the average shear strength (a) and the in-plane shear modulus (b) of the PP-GF-30 material

4.2 Textile Composites

A representative load-displacement curve of each textile composite material is depicted in Fig. 8. This behavior may be divided into two parts, as follows;

- one which goes from the beginning of the test until the first load drop where the specimen is subjected to pure shear;
- right after this point, the slope of the curve increases due to the progressive fiber alignment which introduces other phenomena apart from shear such as flexural loading, friction between fiber strands, local compression and/or tension.

Starting with the first material (GF RTP Material A), the in-plane shear mechanical behavior is depicted in Fig. 8a while the corresponding behavior of the second in Fig. 8b. As can be seen, the two materials behave mechanically in a similar manner, exhibiting both the two sections of the curve described previously. Considering the above, the nature of the textile composites is the main reason of this particular

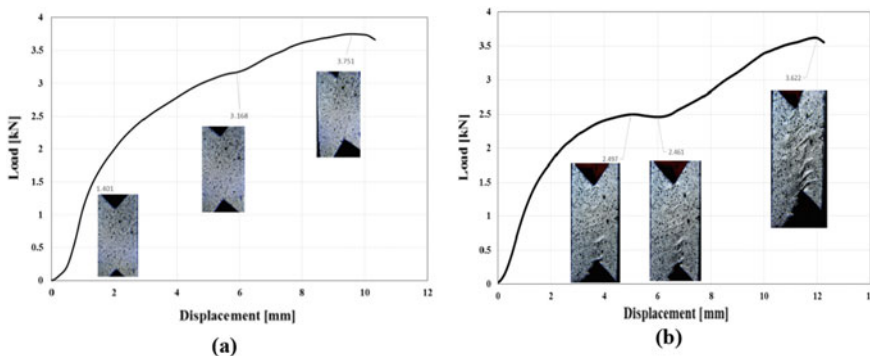


Fig. 8 Typical load-displacement curves of the a GF RTP Material A and b GF RTP Material B, correlated with frames of the deformed central section of the specimen

mechanical behavior and therefore the failure point of the curve should be carefully considered and observed in detail. In the present work, this point has been recognized when the first cracks are observed at the middle section of the specimen (between the V-Notches) and cause the load to drop slightly. By comparing the shear stress-strain curves of the two materials, it can be seen that for the second material (GFRTTP Material A) such point is more easily distinguished.

In Fig. 9 the deformed specimens of the two materials after the execution of the shear tests are presented. It may be seen that, after the second part of the curve a combination of phenomena are observed in the region between the notches, that are highly related with the relative deformation of the fiber strands, leading to the development of pine leaf-shaped cracks before the initiation of the second part of the curve. Then, a combination of phenomena such as local buckling, fiber-matrix decohesion and fiber-fiber friction and several matrix cracks are influencing the mechanical behavior of the material.

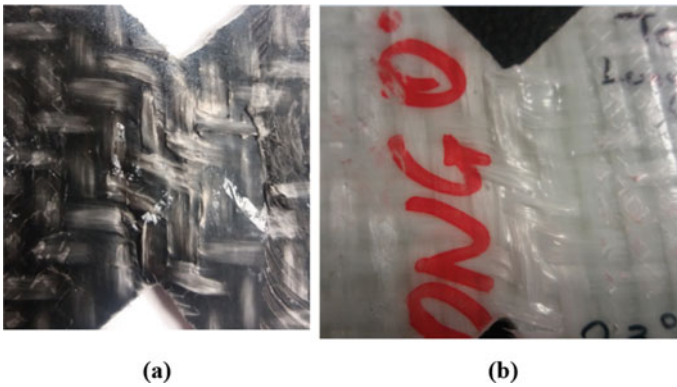


Fig. 9 Deformed surfaces of the GFRTTP Material a A and b B, respectively

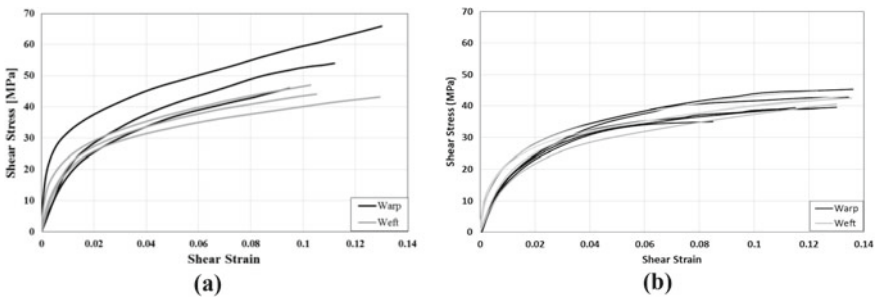


Fig. 10 Shear stress-strain curves of a Material A and b Material B, for specimens oriented along warp (Longitudinal) and weft (Transverse) directions, respectively

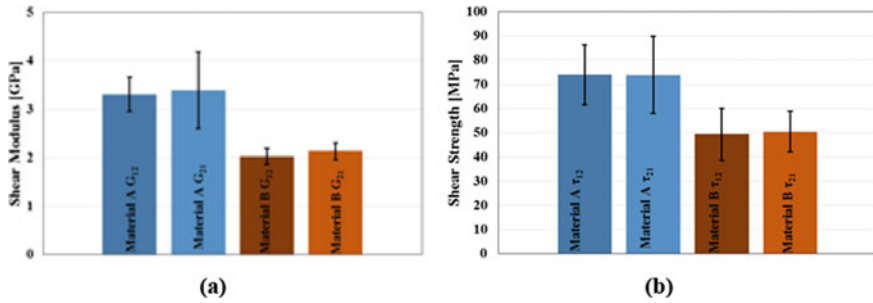


Fig. 11 Results for the two materials regarding **a** the shear modulus and **b** the shear strength

Considering the above, the stress-strain curves of the two materials, may be seen in Fig. 10a, b respectively, where only the first part of the trends shown in Fig. 8a, b respectively is depicted (pure shear part).

From the stress-strain curves it is obvious a certain difference between the 1–2 plane (black curves, warp) and 2–1 (grey curves, weft) plane properties of the Material A which are always accompanied with a certain dispersion. It is also noted that this difference is not so intense in the Material B. Nevertheless, even if the two materials (A and B) are having almost the same material base (matrix and fibers) with a slight difference on the fiber content, their shear behavior appears to be quite different. An overview of the mechanical properties of the two materials is presented in Fig. 11 where the properties of GFRP Material A are colored blue and those of the GFRP Material B are colored orange. As can be seen there, the GFRTP Material A demonstrates an augmented shear strength and modulus compared to the GFRTP Material B, presumably due to the difference between their fiber content (47 vs. 43%). Nevertheless, their difference between their strength is roughly 30% while the in-plane shear modulus of the Material B is almost the half of the Material A. These results are also explained by the observed variations of the strands of the glass fibers of the Material B as well as the not proper fiber alignment (Fig. 8b), a fact which indicates the influence of fabrication process errors.

5 Conclusions

In the present work, an improvement of the apparatus of the most promising and precise, in terms of accuracy, shear test for composite materials was presented and implemented, to authors' knowledge, for the first time on short fiber reinforced thermoplastics. In addition, this attempt appears to be among the few for the assessment of the shear behavior of plain weave glass reinforced polypropylene. The modifications made seem to contribute significantly on the specimen proper alignment during the test with respect to the loading direction and the strain field observed via DIC is very uniform.

Even if this test was not implemented before on short fiber reinforced composites, the results obtained appear to be highly repeatable and accurate in terms of both mechanical behavior and properties. Consequently, this testing method throughout this work may be considered as a benchmark on the characterization of the shear properties and mechanical behavior of these materials.

From the modified ASTM D7078 tests conducted for the textile glass fiber polypropylene (Materials A and B) the apparatus combined with the DIC analysis may provide the user with accurate and repeatable results. The results obtained applying the proposed apparatus enabled to assess the small differences in the behavior of the composites due to the alignment of the fibres caused by the matrix flow during injection or to a small difference in fiber content in the case of textile composites.

Finally, this work may be considered as a benchmark of a further use of this testing method for assessing the, so-easily-influenced by the fabrication, shear properties of not only UD composites but also chopped-fiber or textiles in a range of testing conditions. The presented apparatus may be considered as the first step towards further modifications that can contribute to a universal shear testing apparatus, fabricated with less removable parts, stiffer and more stable while being used in a range of temperatures and humidity conditions.

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