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Assessment of the shear properties of thermoplastic composites using the ±45° tension and the V-notched rail shear methods

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Abstract. Composite materials consisting of thermoplastic matrix are gaining the interest of both the aeronautical and the automotive industry as they comprise a series of advantages regarding their mechanical performance, their recyclability and their ability to be produced in large quantities. Nevertheless, some notable drawbacks have been noticed related to the fabrication process affecting their in-plane shear properties the characterization of which is complicated. Among the notable number of testing methods proposed throughout the years, several advantages and drawbacks were observed, mostly related to the way the load is applied, the stress uniformity and the applicability of each method to various material architectures. In the present work, the modified V-notched rail shear and the ±45° shear testing methods are applied to short and textile glass fiber reinforced thermoplastics aiming to assess the influence of both the fabrication method and the strands direction. Consecutively, the results obtained from the two different testing methods are compared revealing a relatively good agreement while, in parallel, the stress uniformity and the local failures observed on the specimens are analyzed.

Keywords: Shear characterization / injection molded composites / textile composites

1 Introduction

As the use of composite materials has been increasing throughout the years by all the industrial sectors, the thermoplastic composites are gaining the interest incrementally. The main reasons are their strength-to-weight ratio, their recyclability and the ability of the industry to produce them in large quantities and volumes. Nevertheless, there has been noticed that defects related to the manufacturing process may influence significantly their mechanical performance. These defects may be generated in the matrix, such as porosity or delaminations [1,2] or even in the reinforcement such as the fiber knitting or misalignment [3–6]. These material properties' degradation alongside with the production cost has been constantly increasing the skepticism of the industry towards them, for example from the vehicle manufacturers as addressed by Mangino et al. [7] while, on the other hand, the necessity of using more ecological, high strength and widely produced materials is evident.

Of particular interest are the short fibre reinforced thermoplastic composites mainly due to the fact that they can be produced directly into the desired form using the injection molding process and can be used in a variety of applications in which the service load is relatively low [8,9]. Nevertheless, even though there has been noticed a fiber alignment towards the injection molding direction [10–12], the percentage of the aligned and intact fibers as well as the relation between the injection direction and the shear properties is quite uncertain.

Another interesting composite material category are textile composites in which the local fibre misalignment or knitting may influence the overall mechanical behavior of the material [13–14]. In addition, the influence of the fabrication of a component using as primary fibre direction the warp (or the weft) on the shear behavior of composites is also not investigated much. Nevertheless, the nature of the textile, the waviness of the strands towards the out-of-plane direction and how the warp or weft directions, when taken as primary, influence the result is of great interest.

On the other hand, for characterizing mechanically the shear properties, until today there has been proposed a significant number of standardized testing methods. The difference between them lies on their applicability on different composite architectures, the way the load is applied to the corresponding specimen, their limitations and their universality of their application on different composite material categories. In fact some standards were

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Table 1. Test matrix of the experimental campaign.

Material	Description	Lay-up	Specimen orientation	Standard followed	Number of tests
PP-GF-30	Molded short glass fibre reinforced polypropylene	–	Parallel to the injection direction	ASTM D70708 (V-notched rail shear)	5
			Perpendicular to the injection direction		5
Textile Material 1	Textile E-glass Twill Weave fibre reinforced (47%) polypropylene	$[0°]_4$	Warp	ASTM D7078 (V-notched rail shear)	5
		$[90°]_4$	Weft		5
		$[45°]_2$	–	ASTM D3518 (±45° Tension)	5
		[45°,–45°]	–		5
Textile Material 2	Textile E-glass Twill Weave fibre reinforced (42%) polypropylene	$[0°]_4$	Warp	ASTM D7078 (V-notched rail shear)	5
		$[90°]_4$	Weft		5
		$[45°]_2$	–	ASTM D3518 (±45° Tension)	5
		[45°,–45°]	–		5

used almost exclusively for a composite material category such as the ±45° Tension-ASTM D3518 [15] while the load may by transmitted from the apparatus to the specimen either via bending (Iosipescu) [16] or by shear excitation (Two Rail Shear – ASTM D4255 [17], V-notched rail shear – ASTM D7078 [18]). The majority though of these standardized methods is developed mostly for unidirectional (UD) composites. For instance, the V-notched rail shear method, even though exhibits some attracting aspects such us the way the load is transmitted from the apparatus to the specimen and its uniformity, it is not recommended for textile composites as it is critical to maintain the distance between the two parts of the apparatus during the execution of the mechanical test. On the contrary, the only established method for assessing the shear properties of textile composites lacks of stress uniformity on the specimen as seen in previous works [19] and according to the ASTM D3518 standard, the test should be stopped after 5% shear displacement for avoiding the fibre scissoring phenomenon [15].

In the present work, investigated is the effect of the injection molding direction to the in-plane shear properties of short fibre reinforced thermoplastic composites using a modified V-notched rail shear testing method [18]. Moreover, the same testing method is implemented for assessing the in-plane shear properties of textile glass fibre reinforced thermoplastics. In parallel, the same properties are evaluated using the ±45° tension and a straight comparison between the two testing methods is conducted. The applicability of each method is examined as well as the relativeness of the results obtained. In addition, the effect of the textile placement towards the warp or the weft direction of these materials is investigated. Thus, the present work aims not only to assess the differences between standardized methods, but primarily to evaluate the shear behavior of short and textile thermoplastic composite materials, introducing in parallel a modification on the apparatus of a state-of-the-art characterization technique.

2 Materials and specimens

As previously mentioned, there are two main material categories this work copes with, namely the short glass fibre reinforced polypropylene and the textile glass fibre reinforced polypropylene respectively. From the first category evaluated is a typical commercial PP-GF-30 material used in the automotive industry. As for the second material category, there are two similar textile glass fibre reinforced polypropylene composites, the main difference of which lies to their textile architecture and the manufactures; the first one is a plain weave GFRTP which comes from the European market while the second one is a twill weave GFRTP from the Asian market. For reasons of industrial confidentiality and competitiveness the two materials are labeled as Textile Material 1 and Textile Material 2. More details about the materials and the corresponding specimens are presented in the following sections. The overall test matrix is presented in Table 1.

2.1 Short glass fibre reinforced polypropylene

The polypropylene based PP-GF-30 (30% glass fiber content) short fiber reinforced material is considered. For producing the plates of the material from which the specimen were cut, the injection molding process was utilized with a typical injection rate of 80 cm^3/s and average temperature of 220 °C. As previously mentioned, it is noted in numerous works a strong influence of the injection direction on the short fibre alignment as well as the percentage of the intact fibres remained in the materials [10–12]. This particular observation was evaluated experimentally via mechanical testing for defining the tensile properties of these materials. Consequently, even if the percentage of fibres that reinforces the material is relatively small, the material behaves more as a composite and not as a neat polymer. To this end, for evaluating the shear properties of the PP-GF-30 material, as principal direction

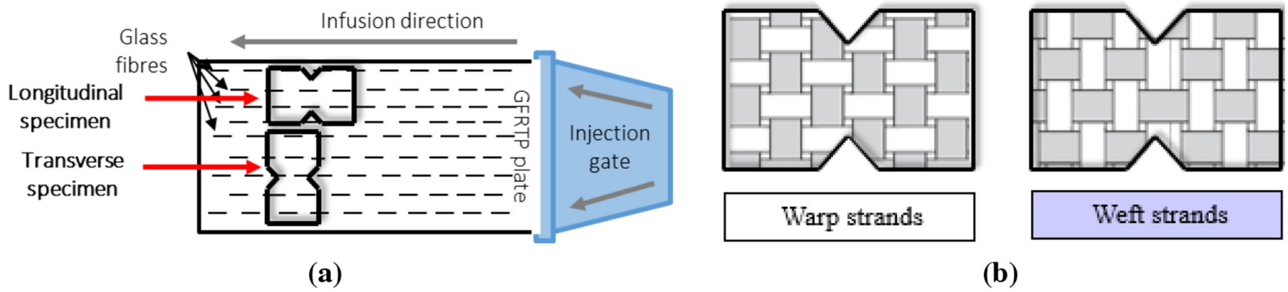

Fig. 1. Schematic representation of the fibre direction related to the fabrication of the PP-GF-30 (a) and the textile thermoplastic composite materials (b).

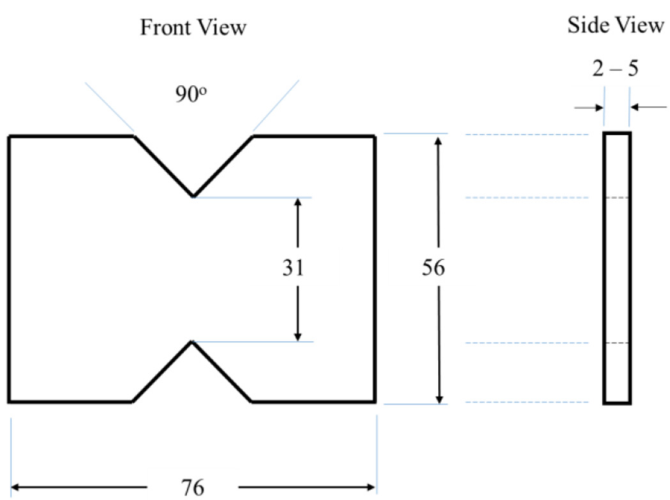

Fig. 2. V-notched rail shear specimen's nominal dimensions.

(0°) is selected the direction of the injection molding. Then, the specimens are cut using waterjet cutting towards the principal direction and perpendicularly to it as shown in Figure 1. Therefore, the produced specimens are labelled "Longitudinal" and "Transverse" respectively. The corresponding specimen nominal dimensions are presented in Figure 2. All specimens are measured after their fabrication in order to ensure the conformity with the ASTM D7078 standard [18].

2.2 Textile glass fibre reinforced polypropylene

The second material category evaluated is the textile glass fibre reinforced polypropylene. In this particular category assessed are, as previously mentioned, two materials, one from a European manufacturer and one from the Asian market. They are both fabricated using automated continuous lamination process in which the fabric is impregnated with polypropylene, a process which allows the production of a quasi-final product which practically means that they are produced directly in the form of a plate. The reinforcement in both cases is E-glass twill weave textile. According to the manufacturers, even though the two materials demonstrate similar densities ($1.67\,g/cm^3$ for the Textile material 1 and $1.4\,g/cm^3$ for the Textile material 2) and almost identical melting points (163 °C), while the material datasheets also report similar tensile properties, they have some interesting differences. More precisely, the Textile Material 1 (European) fibre content corresponds to 47% of the composite volume and, while the composite plate is being produced, additional bond agent was added to the polypropylene, aimed to increase the fibre-matrix bond. On the other hand, the Textile Material 2 (Asian) also consists of E-glass fibre textile but with two main differences namely the fibre volume fraction, which in this case is 42%, and the absence of additional bonding agents in the polypropylene. They both have equal amount of fibres towards the warp and weft direction (50-50 warp-weft fibre weight distribution) while it is evident their difference regarding their cost; the Textile Material 1 costs significantly more than the Asian one. Therefore, even though both of them exhibit similar tensile properties, their performance under shear deformation is to be investigated. To this end, for assessing the in-plane shear properties using the V-notched rail shear testing the specimens were cut from composite plates using a high precision milling machine towards the warp (Longitudinal) and weft (Transverse) directions respectively as seen in Figure 1b. The specimen nominal dimensions are those described by the ASTM D7078 standard [18] and presented previously in Figure 2. The material total thickness in this case consists of 4 layers of 0.5 mm each, achieving a total thickness of 2 mm so as to be in accordance with the minimum thickness of the corresponding testing standard.

For comparing the modified ASTM D7078 results with the ASTM D3518, specimens with nominal dimensions similar to the tensile ones described by the ASTM D3039 [19] standard were also prepared. Also in this case the specimen categories were sub-divided into two categories: one with lay-up consisting of 2 layers of +45° and another one of 2 symmetrical layers of +45° and −45°. The specimen nominal dimensions may be observed in Figure 3.

3 Experimental

3.1 Modified V-notched rail shear apparatus

The standardized apparatus of the V-notched rail shear testing method is described by the ASTM D7078 standard. It consists of 2 independent main parts in which the

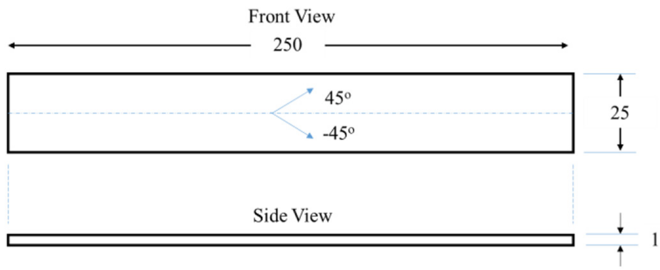

Fig. 3. ±45° tensile test specimen's nominal dimensions.

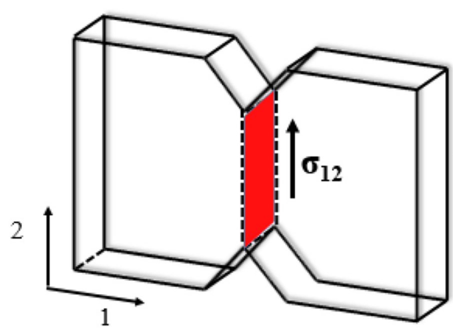

Fig. 4. Cross-sectional area of interest for calculating the in-plane shear properties of a typical ASTM D7078 specimen.

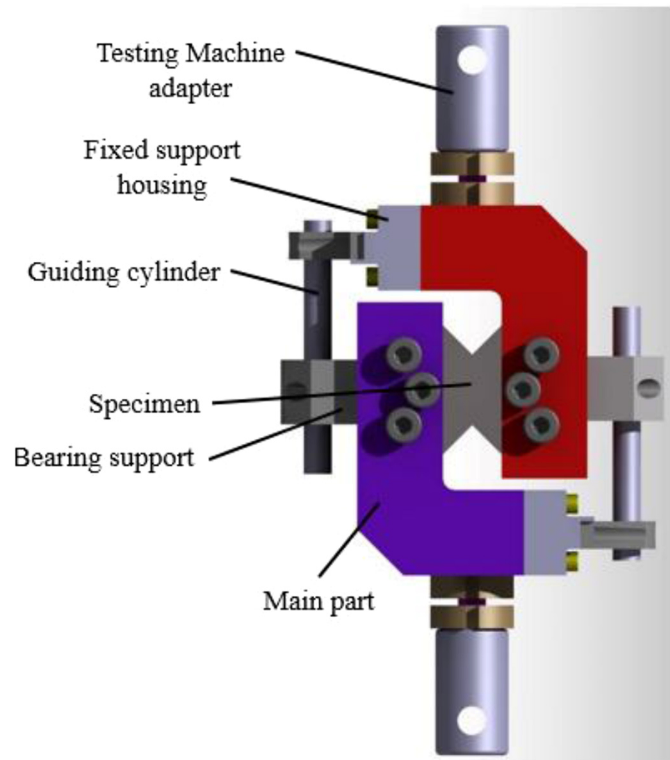

Fig. 5. Rendering of the modified V-notched rail shear apparatus.

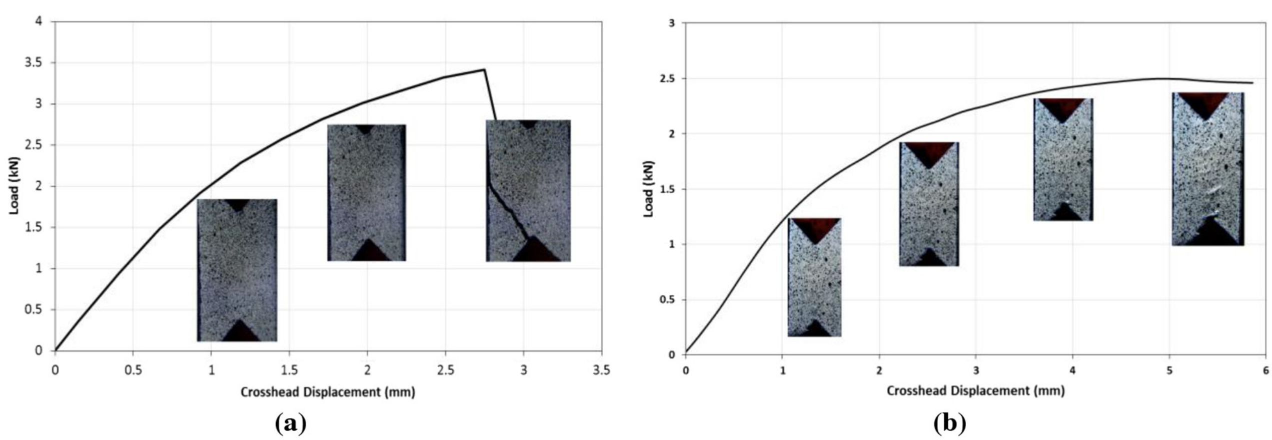

Fig. 6. Typical load-displacement curves for the PP-GF-30 and the Textile Material 1.

specimen is inserted and clamped by the tabs. One part of the apparatus remains fixed while the other half moves along the vertical axis away from the fixed part, intense stress is concentrated between the notches. In this case the stress may be calculated in any instant by dividing the load by the cross-sectional area between the tips as seen in Figure 4.

One of the disadvantages of the apparatus lies on the difficulty in aligning the specimen inside the apparatus and to maintain the proper alignment of the two main parts while testing. The corresponding standard [18] suggests the use of proper spacers placed between the two main parts in order to maintain the right distance and to align the specimen before testing. From the original apparatus, Gude et al. [20] pointed the difficulty of maintaining the horizontal distance between the two main parts during the test and proposed a modification by adding 2 guiding cylinders which are housed in the main body in a copper ring. One of the main problems of this particular modification on the apparatus is the friction between the guiding cylinders and the main body of the apparatus which is developed during the testing procedure as a result of the high horizontal forces caused by the bi-directional composites. This problem practically forces the authors to remove the guiding cylinders, turning the apparatus into the one established, by the standard, ASTM D7078. Based on that modification, in the present work a linear rolling bearing system is added in the cylinders that minimizes the friction between the cylinders and the main part while being loaded with horizontal loads. This system is also capable of performing mechanical tests both in higher and below zero temperatures as the bearing rings exhibit low friction values in a large temperature range. The complete rendering of the modified V-notched rail shear apparatus is presented in Figure 5. The material used for the realization of the apparatus is medium carbon steel C45 (ISO 683-1:2018) while the low-friction bearing rings and supports are commercial provided by the SKF.

3.2 Devices and measuring systems

For conducting the experimental campaign, the MTS Criterion 43 servo-electrical universal testing machine with load capacity of 50 kN is utilized. In parallel, for registering the specimen deformation during the modified V-notched rail shear tests, a Nikon high resolution photo camera is implemented in collaboration with the MatLab's Ncorr [21]. The implementation of the DIC analysis is preferred even though the corresponding standard [18] proposes the use of strain gages. The main reason is the intense deformation of the specimen, the creation of cracks in the region between the V shaped notches that may detach the strain gages. Moreover, this way the strain field may be observed in various phases of each mechanical test, in particular at large deformation stages.

On the contrary, for conducting the ±45° tensile tests following the ASTM D3518 standard [15], even though the same testing machine is utilized, implemented is an MTS standardized extensometer placed at the center of the specimen with a gage length of 25 mm. In parallel to that, a high resolution photo camera is placed so as to potentially observe the failure evolution of the ASTM D3518 specimen.

4 Results

4.1 Shear mechanical behavior and failure modes

Before analyzing the obtained material properties that correspond either to the short fibre or the textile reinforced polypropylene materials, a correlation between the load-displacement curves and the failure modes of representative tests conducted with the V-notched rail shear testing method is presented in Figure 6. Starting with the PP-GF-30 material, the behavior is non-linear and the material arrives to the final failure with a diagonal crack causing an intense load drop as seen in Figure 6a. Regarding the shear mechanical behavior of the PP-GF-30 (30% short glass fibre reinforced polypropylene) a comparison between the "Longitudinal" and the "Transverse" specimens is observed in Figure 7a. It is obvious that there is no significant difference of the shear behavior between the two PP-GF-30 specimen categories. To this end, aiming to conduct further investigation on the fractured surface of the PP-GF-30 specimens, optical microscopy is implemented using a Leica M205 microscope. In Figure 8, typical Longitudinal (Fig. 8a) and Transverse (Fig. 8b) specimen fractured surfaces are presented, where it can be observed a large number of fibres oriented parallel to the x-axis. Even though the number of them appears to be significantly

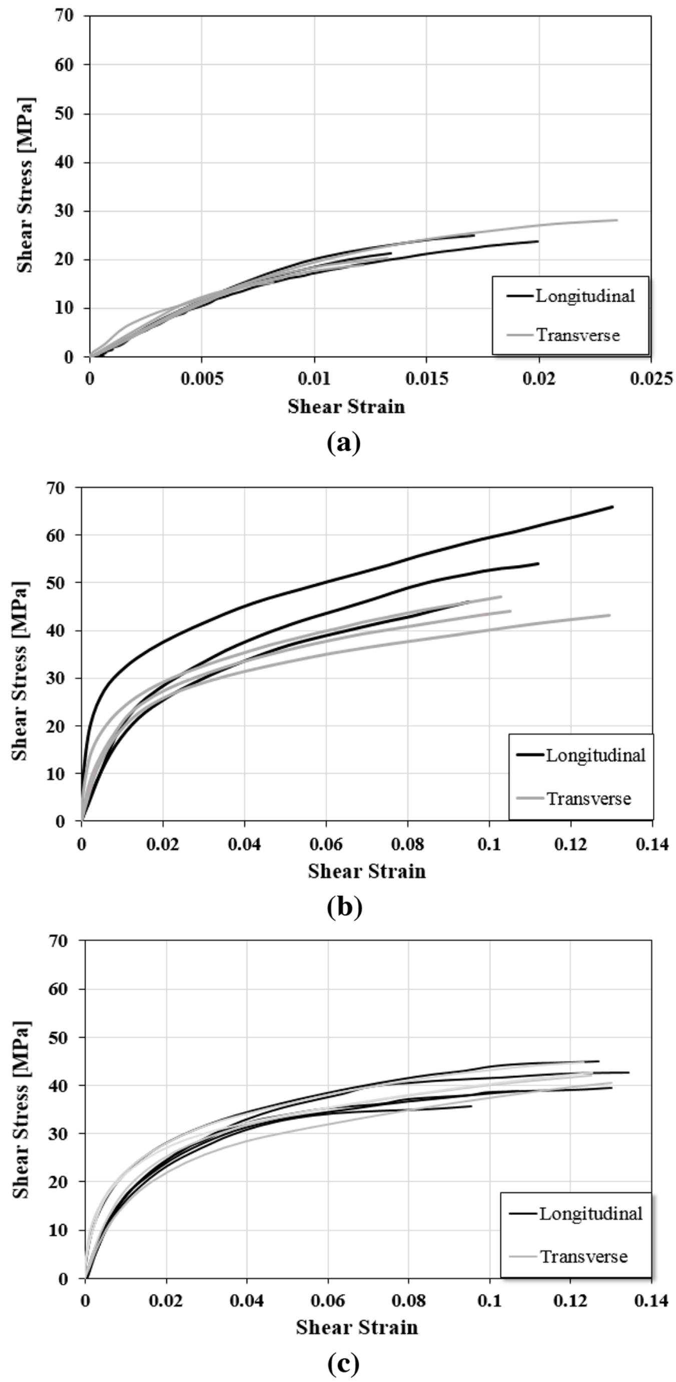

Fig. 7. In-plane shear mechanical behavior of the short fibre (a) and the textile glass fibre reinforced thermoplastic materials 1 (b) and 2 (c).

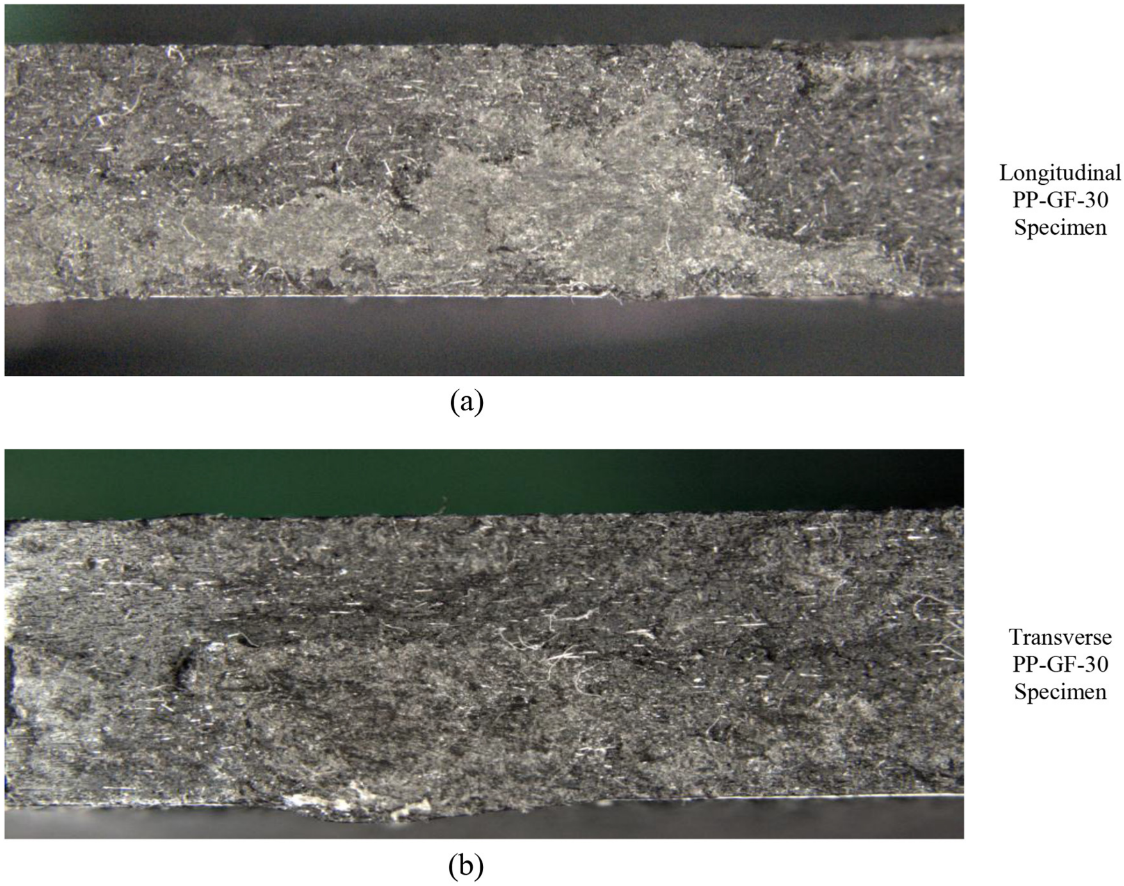

Fig. 8. Short fibre alignment and porosity as seen in optical microscopy analysis of fractured PP-GF-30 specimens.

higher for the case of specimen produced via injection parallel to the x-axis (Longitudinal specimens), there is no absolute orientation of the fibres; in both cases observed are fibres oriented towards the injection molding direction and perpendicular to it resulting similar properties to the two specimen categories. Also, observed is a non-uniform dispersion of the fibres as they are concentrated mostly at the mid-plane region. Moreover, a number of pores are detected throughout the crack line in both the case of the Longitudinal and the Transverse specimen.

On the contrary, a typical textile specimen incorporates more complex phenomena while being deformed as seen in Figure 6b. As indicated also in the corresponding ASTM standard [18], in the case of textiles the fibres are being rotated after the shear failure, allowing this way an increment to the portion of the specimen load carrying capacity. It is, therefore, recommended the determination of the maximum shear load as the point in which there is either a visual failure causing a slight load drop or a radical increase on the slope of the curve. During the execution of the V-notched rail shear tests, minor phenomena such as tow cracks are observed as well as intense deformations on the surface of the specimen, a fact that supports the use of optical systems (DIC) for measuring the shear deformation as this phenomenon may lead to the detachment of any strain gage attached to it. These phenomena may be also observed in Figure 9 in which specimen of the two textile composite materials before and after the test are presented using optical microscopy. Before the analysis, the specimen surface is treated with acetone in order to remove impurities. The specimens are mostly damaged at the central region between the notches while the rest of the specimen remains almost intact. As it can be seen in Figure 9, in the region between the notches a large number of cracks at the top of the fibre strands are observed along with some fibre-matrix debonding or even fibre cracking in the case of the Textile material 2. Also, especially in the case of the Textile material 2, intense delamination is observed at the V region.

Generally, the shear behavior of these materials is non-linear and during the mechanical test the fibres are interacting between the warp and weft direction, increasing the horizontal forces, favoring on the other hand, the use of guiding cylinders for avoiding any potential horizontal relative movement from the two parts of the apparatus. This way also, the shear strain concentration remains constantly concentrated at the central region of the specimen as reported by the DIC analysis presented in Figure 10. The stress-strain curves of the two textile materials obtained with the V-notched rail shear testing method for both the “Longitudinal” and the “Transverse” specimens are presented in Figure 7 b and c, respectively.

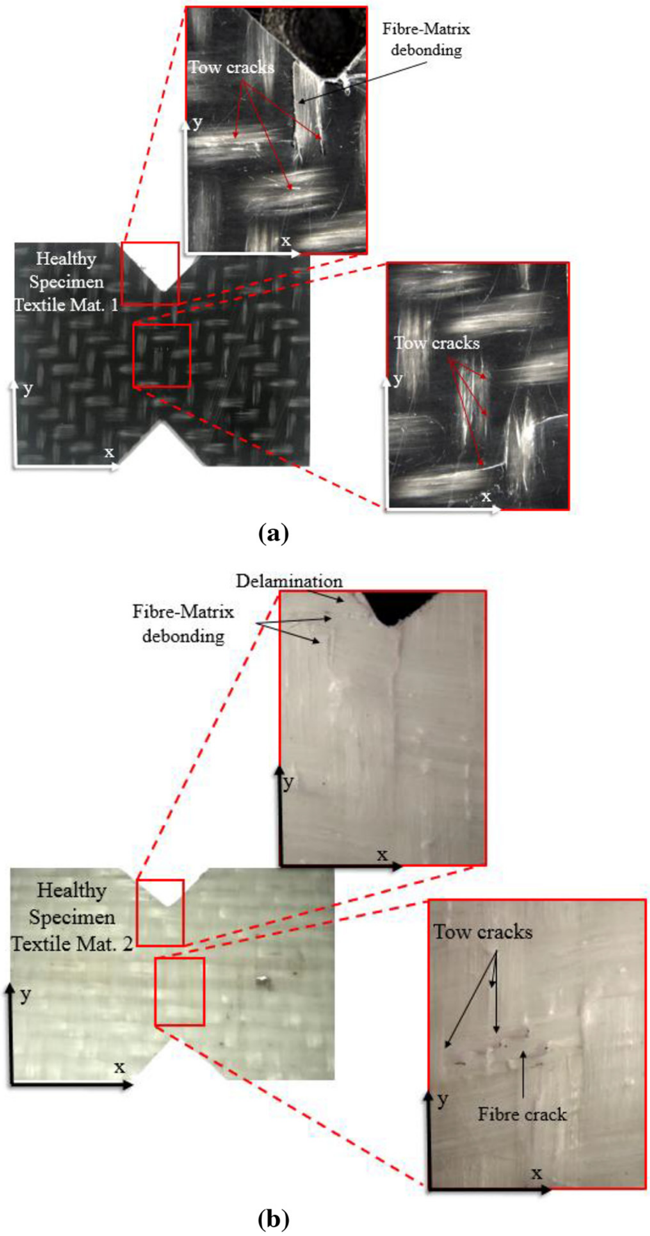

Fig. 9. Failure modes observed in the Textile Material 1 (a) and Textile material 2 (b).

Interesting observations of the failure modes during the deformation of the $\pm45°$ tensile specimen are depicted in Figure 11. Starting from the healthy specimen passing gradually from an intermediate stage prior to the failure where matrix cracks appear at the top of the fibre strands due to the relative shear deformation of the textile and finishing with a variety of local failures such as matrix cracks, fiber-matrix debonding and intense shear deformation of textile specimen at the center of the gage length appear. These tow cracks in direction perpendicular to the applied load appear all over the specimen throughout the execution of the tests as seen in Figure 11. This type of cracks has been reported also in previous works [19]. The number of these cracks increases constantly, consequently the specimen at the end of the test exhibit the previously mentioned combination of failures quite intensively. In addition, two observations should also be noted, namely the non-uniform deformation of the specimen through its length and the intense non-uniform thickening of it as a result presumably by a number of parameters such as the absence of the uniformity of the shear deformation, the specimen size and edge effects as well as the local variations of the material structure (imperfections of the fabric or the matrix). Starting from Figure 12, obvious is a higher degree of the textile deformation at the center compared to the regions of the specimen near the tabs. In Figure 13, an analysis of the distribution of the shear strain of the specimen in the region outside the extensometer is conducted revealing a non-uniform distribution of it after a certain point before the final failure.

The shear stress-strain curves obtained by the experimental campaign using the ASTM D3518 standard for the 2 textile materials are presented in Figure 14a and b respectively. As previously mentioned in Section 1 of the present work, the corresponding standard dictates the consideration of each test of this kind as valid up to the shear strain of 5% considering the general rule suggested by Kellas et al. [22] that every 2% of axial strain causes 1° of relative fiber rotation. Thus, even though the load increases after imposing 5% of shear strain, test cannot be considered valid after the point mentioned before, a fact which is among the drawbacks of the $\pm45°$ tensile test.

4.2 Comparison between materials and standards

In the present section, a comparison between the results obtained for the 3 materials is conducted aiming to investigate the reliability of the testing methods, to assess the difference between the results obtained for the same material using two different testing methods as well as for two similar textile materials tested with the same methods. Thus, the main scope is the comparison between materials of the same kind as well as between the standards with which the shear properties of these materials are evaluated.

All these information are presented in Figure 15 where the in-plane shear strength (Fig. 15a) and modulus (Fig. 15b) of the Textile Material 1 and 2 are presented as obtained by the two testing methods. These values are also reported in Table 2 in which the shear modulus, strength and standard deviation obtained for each material and testing method are presented. The term shear strength in the case of the $\pm45°$ tension refers to a shear strain of 5% while in the case of the V-notched rail shear to the point in which a first slight drop of the curve was observed. The results are accompanied by a notable standard deviation for both testing methods. Considering the restrictions imposed by each standard described in the previous sections of the present paper, the shear strength values obtained by the two testing methods appear to be similar for both the two textile materials in terms of both maximum stress and modulus. Nevertheless, the significant limitation of the $\pm45°$ tensile test does not allow a reliable evaluation of the shear response to such kind of materials beyond the shear deformation of 5% while the modified V-notched rail shear test, considering that contributes to

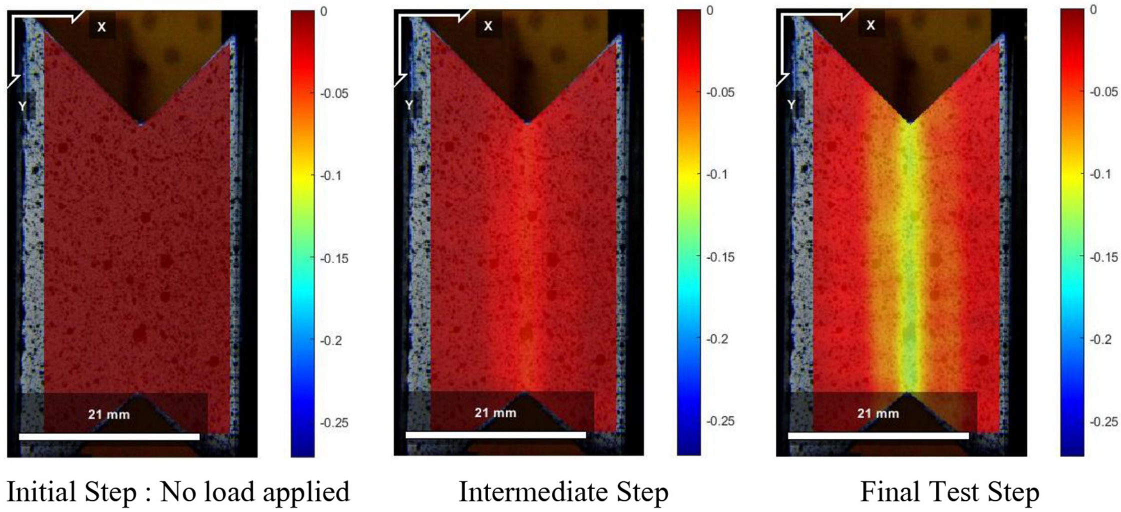

Fig. 10. Typical distribution of the shear strain obtained during the execution of the modified V-notched rail shear test on textile materials.

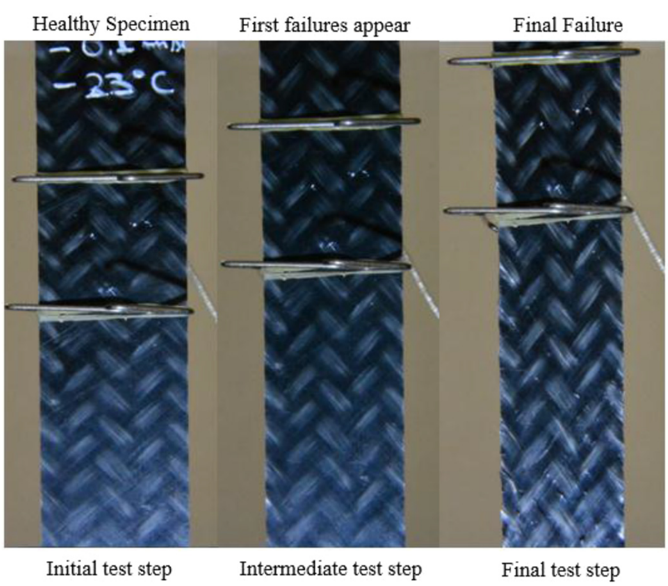

Fig. 11. Progressive failure of the ASTM D3518 specimen.

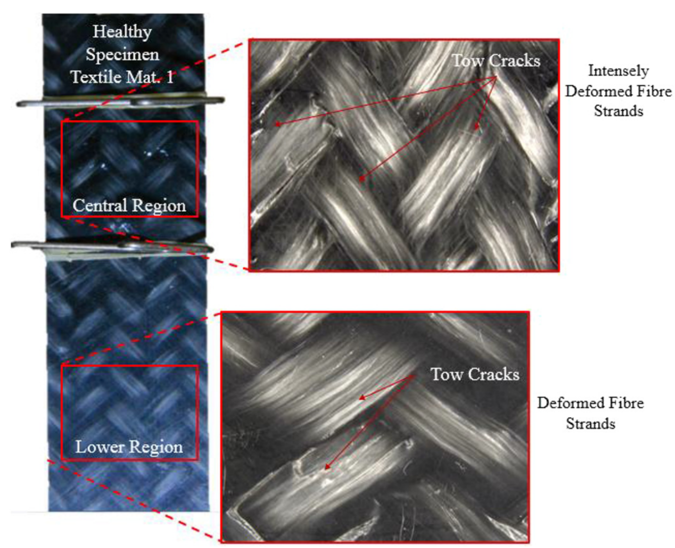

Fig. 12. Typical failure modes registered in the region at the center and lower (near the tabs) of the ±45° tensile specimen.

the maintenance of the strain uniformity of the specimen, is proven useful for achieving shear deformations beyond this point.

Moreover, even though the two textile materials exhibit similar shear modulus with both standards, there is a significant difference between them in the case of the maximum shear stress obtained; the Textile material 1 demonstrates higher values compared to the Textile material 2. Also, by examining the failure modes of the V-Notched Shear specimens, observed is an intense fiber-matrix cracking development which is significantly more intense for the case of Textile material 2. In both materials, no significant difference is observed when the specimen is oriented towards the warp or the weft direction (Longitudinal or Transverse). Finally, for the case of the injected short fibre thermoplastic composite, no significant difference is observed in both the in-plane shear strength and modulus obtained from the specimens cut in parallel or perpendicular to the injection molding direction.

5 Conclusions

In the present work, a variety of GFRTPs' in-plane shear mechanical behavior was characterized experimentally using two of the most frequently used testing methods.

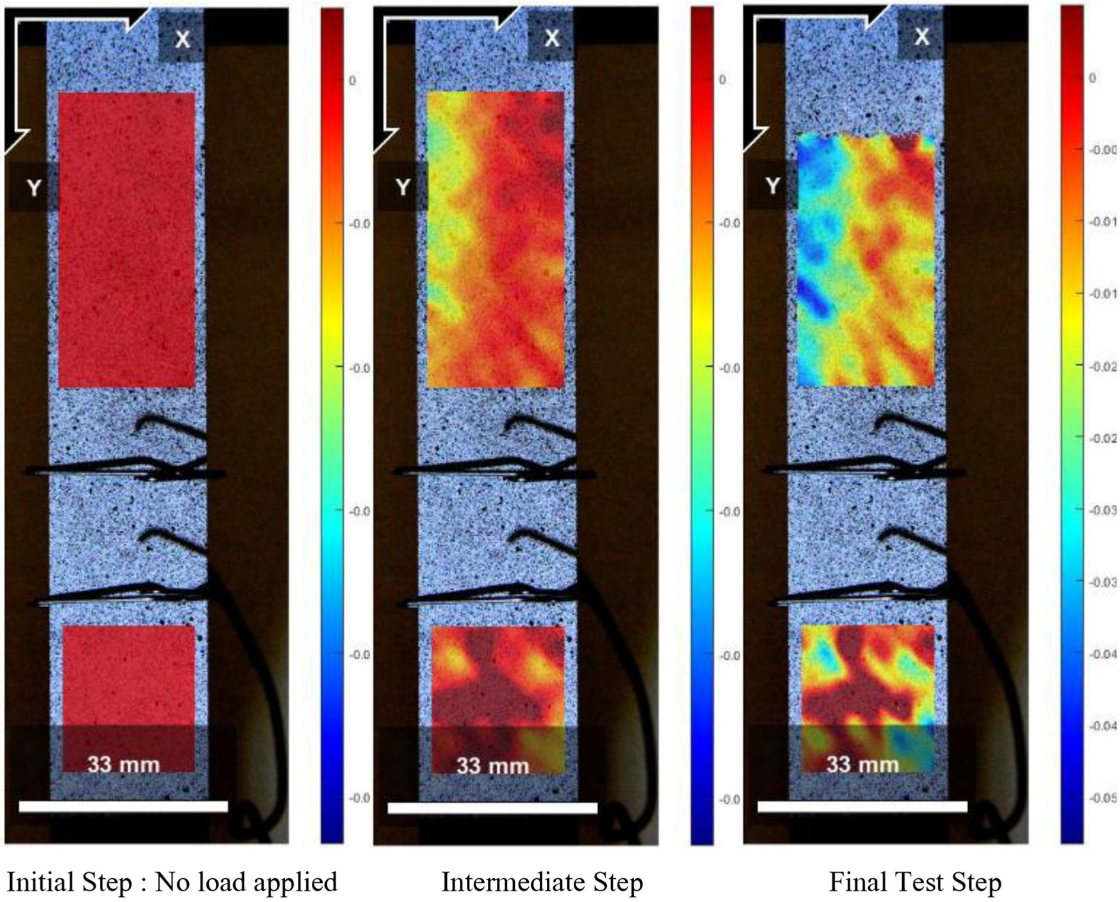

Fig. 13. Distribution of the shear strain in the regions above and below the specimen center during the execution of the ±45o tensile tests for the textile composite materials.

Table 2. Obtained in-plane shear properties of all materials tested according to the two testing methods.

Material	Standard followed	Specimen orientation*	Shear strength** [MPa]	Standard deviation of shear strength [MPa]	Shear modulus [GPa]	Standard deviation of shear modulus [GPa]
PP-GF-30	ASTM D70708	Parallel to the injection direction	23.6	1.1	1.945	0.173
		Perpendicular to the injection direction	19.7	2.12	2.014	0.201
Textile Material 1	ASTM D7078	Warp	62.53	6.75	2.041	0.228
		Weft	58.88	9.36	2.034	0.504
	ASTM D3518	45°	56.14	2.58	2.281	0.311
		−45°	58.15	1.68	2.250	0.137
Textile Material 2	ASTM D7078	Warp	40.43	3.35	2.026	0.328
		Weft	43.92	2.11	1.998	0.146
	ASTM D3518	45°	39.05	1.29	2.171	0.102
		−45°	40.06	3.00	2.137	0.275

* In the case of the ASTM D3518 specimen orientation refers to the 2nd layer direction.
** In the case of the tests conducted using the ASTM D3518 method, shear strength refers to the shear stress at 5% shear strain.

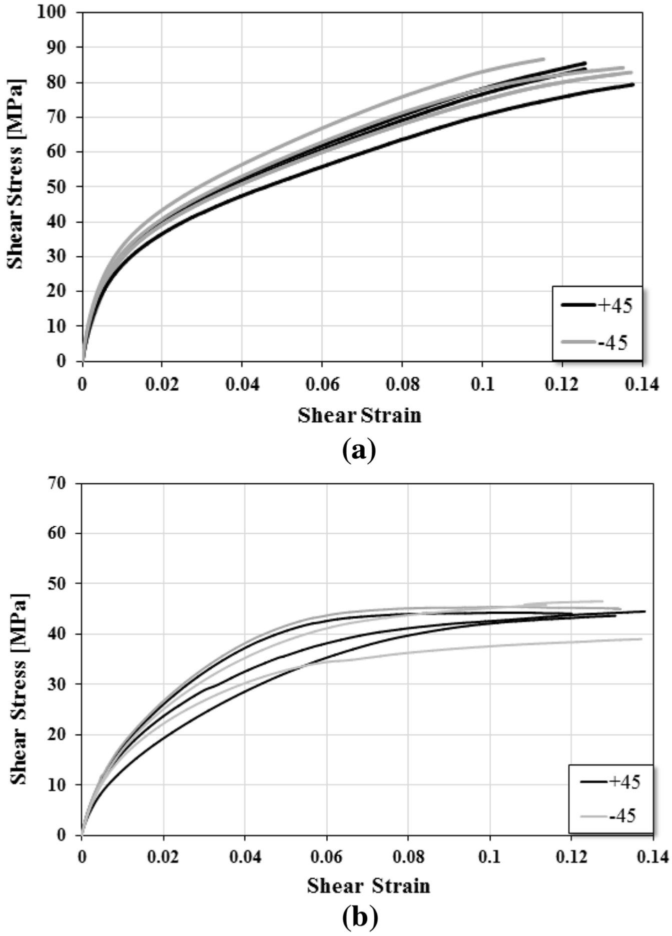

Fig. 14. Shear mechanical behavior for the Textile Material 1 (a) and 2 (b) obtained by the ±45o tensile test.

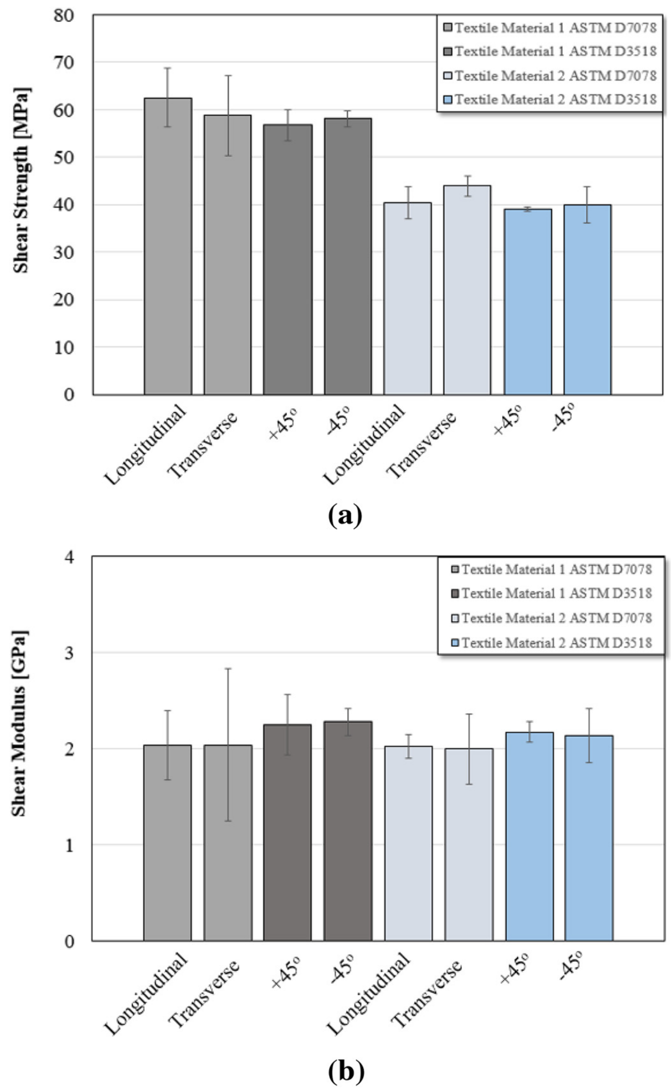

Fig. 15. Comparison of the shear standards and materials in terms of shear strength (a) and modulus (b).

Starting with the injection molded short glass fibre reinforced polypropylene, the V-notched rail shear testing method was successfully applied in specimens cut towards both the longitudinal and the transverse direction of the injection. By comparing the results, no significant difference was observed for the two specimen categories. As for the second material category, the V-notched rail shear testing method was implemented and its results were compared with the more conventional ±45° Tension test. Moreover, two similar materials with different provenance and slightly different fibre content were compared. For maintaining the proper alignment of the components of the standardized apparatus, a modification was proposed on it.

As the main objective was the investigation of the influence either of the injection direction (for the case of the injected short fibre composite) or the textile fabrication direction (for the case of the textiles), no significant difference was observed regarding the shear strength or modulus. Nevertheless, some differences were observed regarding the shear strength of the two textile materials. For the case of the short fibre composite, the injection direction, perpendicular or parallel to the specimen length, does not appear to influence significantly the shear performance of the material.

Finally, by comparing the state-of-the-art standardized testing methods was conducted revealing the advantages and disadvantages of them and their ability to predict the shear mechanical performance of different composite materials. The modified V-notched rail shear appears to be more universal as it may be implemented either to short or textile composite materials, delivering on the other hand accurate results. On the contrary, the ±45° tensile method appears as more easy-to-implement on textile materials, since it is simpler but with less shear strain uniformity compared to the V-notched rail shear. Among the most significant conclusions though, is the use of the modification of the V-notched rail shear testing apparatus which overcomes limitations observed in all the testing methods of specimens containing V notches, such as the Iosipescu, regarding the maintenance of the proper strain uniformity imposed to the specimen and the alignment of the parts of the testing apparatus.

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