



# Effects of fibre orientation and content on the mechanical, dynamic mechanical and thermal expansion properties of multi-layered glass/carbon fibre-reinforced polymer composites

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## Abstract

Multi-layered glass and carbon-reinforced polymer composites may exhibit unique properties comparatively with the benchmark, proven they are being tailored bounded by several requirements. The paper herein approaches issues on the influence of the various contents and orientation of UD carbon fibre constitutive on the mechanical, dynamical and thermal expansion if embedded along with glass fibres in different stacking sequencing within an unsaturated polymer resin. The results show that the architectures with the highest content of carbon fibres (e.g. GF:CF(60:40) – 0° and 90°) provide the best tensile and flexural properties, and behave better under dynamical loading conditions and temperature variations, no matter the orientation directions. In addition, it was shown that a thorough understanding can be attained, with respect to the UD carbon fibre content, and different orientations influence on the overall composite material properties, taking into account the data retrieved from dynamical and thermal expansion runs.

## Keywords

Mechanical, dynamic mechanical, thermal expansion, orientation, carbon fibre, glass fibre, polymer, composite

## Introduction

A competitive market situation supplemented by exponentially increasing technological advents are continuously pushing the demands for novel material combinations that would pose excellent to outstanding properties in terms of mechanical, dynamical, thermal or dielectric ones, unrestricted solely to high performance, high-strength or lightweight structures. Advanced multi-layered composite architectures appear to be one of the answers, especially for structural engineering applications driven by design factors such as manufacturing costs, weight, environmental conditions or material compatibilities. Hybrid composites can be considered as another research path under the focus and extensive development, and unfortunately, the source of confusion in a relatively large number of research articles, demanding further clarification and standardization.

Research conducted on hybrid composites, predominantly based on intermingled carbon and glass fibre

fabrics, can be traced back to the early 1970s, from the work of Bunsell and Harris<sup>1</sup> or Summerscales and Short,<sup>2</sup> that were among the first in the investigation of the mechanical properties of various material combinations in view of their prospective use as lightweight load-bearing composite structures. Since then, a variety of combinations emerged as viable architectures to produce fibre reinforced polymer (FRP) composites. However, research conducted to retrieve the mechanical properties has largely been limited to

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configurations in which fibres have been intimately mixed within the matrix or stacked having various ply lay-up sequences.<sup>3</sup>

The success key for developing advanced multi-layered polymer-based composite architectures is to enhance the failure strain of their constitutive. The selection of the constitutive materials, their structural or geometry-related parameters, has a significant influence on the overall composite failure strain. Based on the aforementioned specificities, extensive studies were carried out with respect to the effects of different fibre fabrics multi-layering sequencing on the overall tensile and flexural properties of polymer-based composites.<sup>4–9</sup> When considering the mechanical characteristics, flexural strength was the most common retrieved from three-point bending tests and reported. In the work of Mujika,<sup>10</sup> discrepancy was reported on the elastic modulus in bending while switching from three to four point bending configuration for different polymers based composite architectures. Although some investigations on the advanced polymer composites behaviour in failure have been carried out,<sup>11</sup> published articles scarcely reported tensile and flexural properties in view of the unidirectional (UD) carbon and glass fibre multi-layered polymer-based composites concerning the differences due to the presence, content and orientation of carbon fibres. The latter can be regarded to industrial data protection and may have been unreleased for public on large.

Dynamic mechanical analysis (DMA) proved to be a useful tool in the study of polymer-based composite materials' behaviour under various temperatures, frequency or external loading conditions. Temperature-dependent dynamic mechanical parameters, such as storage modulus, loss modulus and mechanical damping, allow a closer monitoring of the level of interactions between the polymer matrix and the reinforcements, and the derived Cole–Cole or Cole–Davisson plots proved to be the most expressive and useful data processing tools in sizing the constitutive influence.

Literature provides numerous references focusing on the FRP composites and their dynamical material properties revealing their inherent structure-related particularities and thermal history during their manufacturing.<sup>12</sup> Both organic and inorganic fibres were considered as high-potential reinforcement candidates for the different polymer-based composite architectures and DMA as the most used testing method in order to size the overall material behaviour under shock and vibrations. Furthermore, it should be emphasized that carbon fibres were the most preferred reinforcements due to their outstanding material properties unattained so far by any other type of materials. This enabled a wide-range of engineering applications

ranging from aerospace to marine, civil engineering to transport, sporting goods to automotive industry, etc.<sup>13–16</sup>

Next, the multi-layering concept allowed the advent of an entry in the polymer-based composite material class and opened new research directions of studies. Extensive experimental studies were carried out and reported within the literature on these types of materials, aiming the understanding of their structural behaviour while subjected to different design and loading constraints.<sup>17–19</sup>

Further, contraction effects rather than expansion responses from constitutive were often considered in the composite design for those architectures intended to be developed to be used in harsh environments.<sup>20</sup> Supplementary, negative overall CTE response was retrieved for composite benchmarks (e.g. GFRP) whose polymer resins were exhibited low elastic modulus and high expansion material properties. A representative example of the aforementioned can be the glass fibre/polypropylene system developed by Ito et al.<sup>21</sup> Carbon fibres naturally exhibit different CTE responses along their longitudinal and transversal directions and are usually selected as reinforcements for multi-layered polymer composite structures to tailor their overall CTE. Supplementary, several studies were reported in the literature on the multi-layered polymer composites' material properties changes if pre-conditioned under extreme environments.<sup>22–24</sup>

The contribution herein presents a comparative study centred on the design, development and material characterization of some tailored multi-layered polymer composite architectures reinforced with different content of UD carbon and random glass fibres. The elastic and dynamic mechanical properties, along with their thermo-physical changes, were monitored and recorded within a temperature range below and beyond the glass temperature of the unsaturated polymer resin employed as the matrix material, and next analysed and debated. Supplementary, it will emphasize the differences on the effective material properties under the focus due to the orientation of the UD carbon constitutive with respect to the general reference system. Moreover, the content of the UD carbon fibres ply-ups, that are balancing symmetrical or unsymmetrical the overall composite design, will be considered for further explanations.

## Experimental research

### *Materials selection and specimens preparation*

The composite specimens have been manufactured as a 5-ply laminate with different volume fraction ratio of the reinforcement materials – glass fibre chopped strand

mats (n. GF; MultiStrat<sup>TM</sup> Mat ES 33-0-25, Johns Manville, USA) and UD carbon fabrics (n. CF; Panex<sup>®</sup> 35 UD300, Zoltek Co., H). The reinforcements were bounded together by an unsaturated polyester resin (Synolite 8388-P-1, DSM Composite Resins, CH) and further cured at room temperature for 24 h before cut into specimens for the experimental tests. The curing agent methyl ethyl ketone peroxide (MEKP) was purchased from AKZO Nobel (Butanox M-50, NL). The multi-layer composites were labelled according to their relative volume fraction with the hybrid structure as GF:CF(100:0), GF:CF(60:40) and GF:CF(80:20), respectively, keeping constant the overall fibre loading (35 vol.%). Thus, the glass fibre loading was lowered from 100% to 60 % while keeping balanced the relative carbon fibre content to preserve the same value of the overall fibre volume fraction for all composite architectures.

The wet lay-up method was preferred to prepare the herein five-layer polymer-based composites. Thus, each impregnated layer of composite's constitutive was stacked to build a final symmetrical or non-symmetrical composite architecture. Specifically, in case of symmetrical multi-layered architecture, both UD carbon fibre layers were layered symmetrically with respect to an E-glass sheet taken as the middle layer of the composite configuration. On the other hand, in case of non-symmetrical architecture, a single UD carbon fibre sheet was considered and layered as the middle plane of the final multi-layered composite. The outer skin of each composite architecture consisted of impregnated E-glass mat layers to avoid the problems associated with carbon fibre impregnation. Air bubbles were carefully removed by the aid of a small roller. Final plates of approximately 400 mm × 300 mm were generated using a mould that was previously anointed with a mould-releasing agent (wax). The thickness of the cured composite laminates was between 4 mm and 5.5 mm.

All samples were cut in accordance to their related standards for characterization procedure to account for the 0° and 90° different UD carbon fibre orientation.

### Material testing procedures

**Mechanical testing.** Tensile and three-point bending loading were performed to assess the mechanical properties in accordance with SR EN ISO 527-1:2000 and SR EN ISO 14125:1998 standards. LS100 and LR5K Plus devices from Lloyd Instruments (UK) were used to retrieve the stress/strain dependencies, followed by elastic modulus, yield stress, ultimate strength recovery procedures to preliminary assess the multi-layered reinforced polymer composites' toughness. A 100 kN load cell has been used for the tensile tests while a 5 kN load

cell for the flexural ones. The crosshead speeds were set at 1 mm/min and 5 mm/min for tensile and flexural configurations, respectively, followed by experimental data acquisition and processing using the Nexygen Plus<sup>TM</sup> analysis software accompanying these devices. Statistically representative 10 specimens, individually considered to account for the 0° and 90° directions of UD carbon fibres, have been tested and their mean values reported.

**Dynamic mechanical thermal analysis.** The dynamic mechanical thermal analyses were performed using a DMA 242 C analyser (Netzsch GmbH, D, Selb, Germany) running in a three-point-bending mode at an oscillating frequency of 1 Hz. The storage modulus ( $E'$ ) and loss modulus ( $E''$ ) as well as the damping factor ( $\tan \delta$ ) of each composite specimen were retrieved under the following conditions: a temperature range from -40°C up to 150°C at scan rate of 3°C/min, a controlled atmosphere due to the liquid nitrogen used as a cooling agent. The samples were shaped having 60 mm in length and 10 mm in width, while the thickness were individually measured as dependent on the layering sequence. Two successive thermal scans were applied to ensure that no further chemical modifications occur within the samples and to remove any residual stresses. The reported data were retrieved from the second scan after their further processing.

**Thermo-physical changes.** Thermo-physical changes of specimens were performed on a differential dilatometer DIL 420 PC/1 from Netzsch GmbH (D), in accordance with ASTM E228-11 and DIN 53752-A standards. The specimens were shaped into rectangular bars of 25 mm in length and 5 mm wide while the transversal external surfaces were polished to guarantee plan-parallel surfaces for precise positioning within the measuring head. The temperature mode was set up as a dynamic heating ramp trend from 25°C up to 250°C. The heating rate imposed was 1°C/min. Two successive thermal scans were also considered for these measurements based on the same reasons as mentioned earlier.

## Results and discussion

### Mechanical properties

There is evidence that the individual constitutive fibre content has an influence on the composite's failure strain. The UD carbon fibres content increase and their different orientations with respect to the reference system led to a shift in the overall fracture event curve. A shift was encountered in the load-deflection curves retrieved from flexure tests on the GF:CF(100:0) reference and both GF:CF(80:20) and GF:CF(60:40)

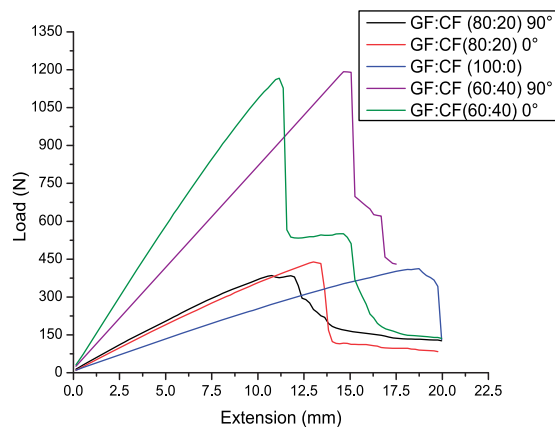
multi-layered specimens, on  $0^\circ$  and  $90^\circ$  directions of UD carbon fibres as shown in Figure 1.

The composite elastic modulus is another dependent material property on the fibre volume fraction; the experimental flexural modulus is much lower than the tensile modulus as the content of UD carbon fibres increases. This it can be seen from data provided in Table 1. The decrease in the flexural modulus can be regarded as a shear-deformation effect within these multi-layered polymer composite specimens, being one of the failure mechanisms that are particular about these types of materials. Furthermore, the effective elasticity modulus in flexure can be correlated with the fibre's length, especially for the UD carbon fibres. The aforementioned is acknowledged in the technical literature to dominate this elastic property.<sup>3</sup>

Inconsistencies between the experimental values, proven various UD carbon fibres orientation and number of layers, can be ranked as being relatively low for data retrieved based on the flexure tests in

comparison with the tensile tests where a severe drop of approximately 50% in the elastic modulus was found to occur for the same composite architecture but different UD carbon fibre orientation. Moreover, the discrepancies between the multi-layer composites' overall strength are evenly more accentuated, especially in the composite architectures with longitudinal ( $0^\circ$ ) oriented UD carbon fibres. The effective mechanical properties of these advanced composites are being also influenced by the capacity of stress transferring between the fibre–matrix interfaces and fibres' different breakage mechanisms. Further insight on the above is beyond the purpose of the present study.

In Figure 2 was plotted the maximum bending stresses at maximum extension of the reference, and the multi-layered composite specimens considered in this study. Data scattering can be regarded to the increase of the carbon fibre-reinforced content, different orientation directions and less to the uncontrolled random distribution of the glass fibres.



**Figure 1.** Load versus extension curves of the multi-layered composite architectures in flexure.

### Dynamic mechanical thermal analysis

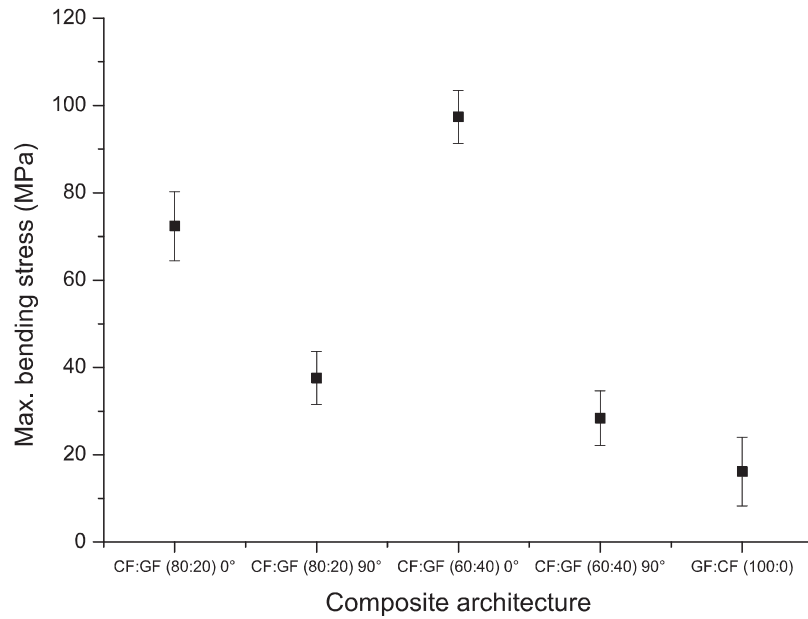
Dynamic mechanical properties of the multi-layered FRP composites can be regarded to reveal the same dependencies on several influencing factors as their benchmark, such as *material-related dependencies* – nature of the matrix material, constitutive material type; *structure-related dependencies* – layer architecture (e.g. reinforcing fibre orientation), number of layers and nature of fibre–matrix interfaces; *loading conditions* – frequency, temperature range, type of load and temperature history.<sup>12</sup>

In this section, a detailed analysis will be made with respect to the dynamic mechanical properties of the multi-layered polymer composite specimens investigated, and some of the influencing factors mentioned earlier will be closely monitored and ranked on the retrieved experimental data.

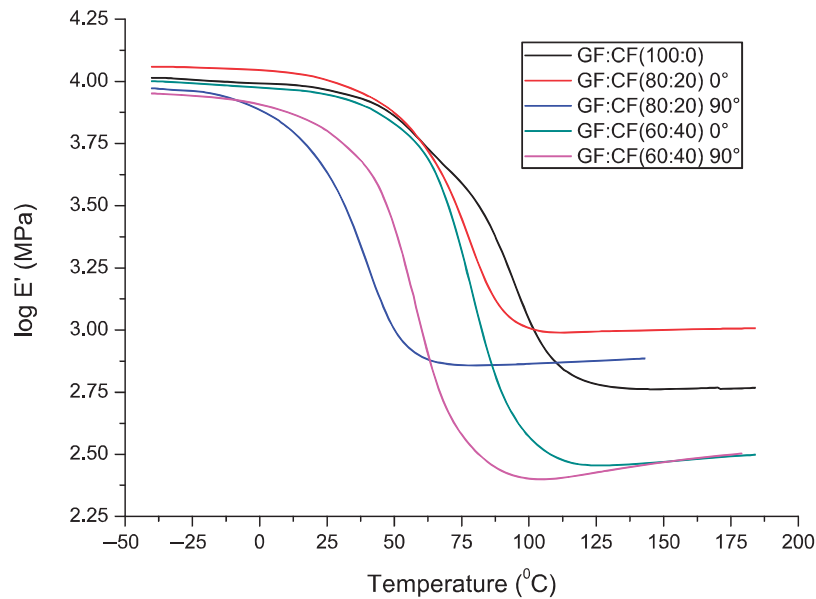
**Table 1.** Tensile and flexural mechanical properties accounting for different UD carbon fibres content and orientation.

Sample architecture	UD CF orientation	Tensile		Flexural	
		Strength (MPa)	Modulus (GPa)	Strength (MPa)	Modulus (GPa)
GF:CF(100:0)		$116.17 \pm 6.34^a$	$4.81 \pm 0.03$	$162 \pm 15.112$	$4.68 \pm 0.03$
GF:CF(80:20)	$0^\circ$	$295.6 \pm 14.12$	$14.64 \pm 0.09$	$204.16 \pm 19.683$	$4.74 \pm 0.07$
	$90^\circ$	$95.8 \pm 9.46$	$7.60 \pm 0.05$	$188.24 \pm 19.219$	$4.23 \pm 0.07$
GF:CF(60:40)	$0^\circ$	$331.37 \pm 16.845$	$16.21 \pm 0.07$	$373.78 \pm 15.303$	$4.48 \pm 0.05$
	$90^\circ$	$93.15 \pm 6.853$	$7.22 \pm 0.05$	$214 \pm 10.64$	$4.21 \pm 0.04$

<sup>a</sup>Standard error.



**Figure 2.** Mean maximum bending stress values retrieved for all multi-layered polymer-based composites under the study.

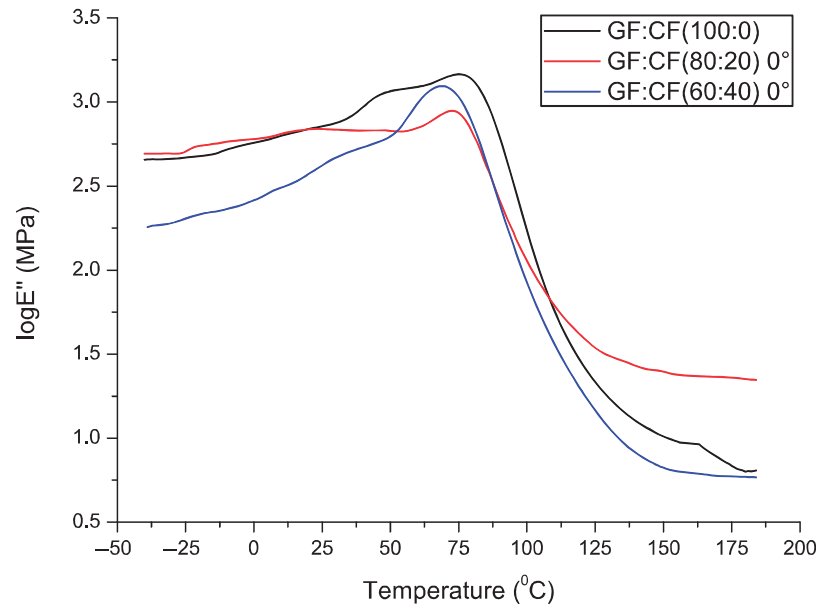


**Figure 3.** Effect of UD carbon fibre loading and orientation on the storage modulus of the multi-layered composites.

**Storage modulus ( $E'$ ).** The storage modulus is closely related to the load-bearing capacity of a material and is analogous to the flexural modulus measured as per ASTM-D 790.<sup>12</sup> Figure 3 reveals the effect of temperature dependence of the storage modulus of GF:CF(100:0) and the multi-layered composite architectures under the focus. Accordingly, one might observe that  $E'$  values decrease as the number of the UD carbon fibre ply-ups increases and changes their orientation with respect to the general reference system. The latter can be regarded to the fact that the

modulus of elasticity (i.e. Young's modulus) of the UD carbon fibre is much lower in the transversal direction than in the longitudinal direction. Addition of carbon fibre ply-ups was expected to lead to an increase of the  $E'$  modulus of these architectures of polymer-based composites. Nonetheless, based on these simple observations herein and of other authors,<sup>14,16</sup> UD carbon fibres can be viewed as behaving better in standalone configurations than in combined multi-layered structures but are proving once again that their presence may contribute significantly to an efficient stress





**Figure 4.** Temperature dependence of  $\log E''$  curves for composite specimens with  $0^\circ$  oriented UD carbon fibres.

transfer within the structure as well as from the fibre constitutive to the matrix.

As temperature increases, close to glass transition temperature ( $T_g$ ), the  $E'$  of the reference and multi-layered composites experience a sharp decrease indicating that the materials are passing through the glass/rubbery transition stage. Further, above  $T_g$ , the storage modulus of the GF:CF(100:0) is lower than that of GF:CF(80:20), having UD carbon fibres of both  $0^\circ$  and  $90^\circ$  oriented but higher than that of GF:CF(60:40) of the same type. The aforementioned can be regarded to the increase in molecular mobility of the polymer chains above  $T_g$  temperature, as well as to the UD carbon fibre content and temperature dependence.

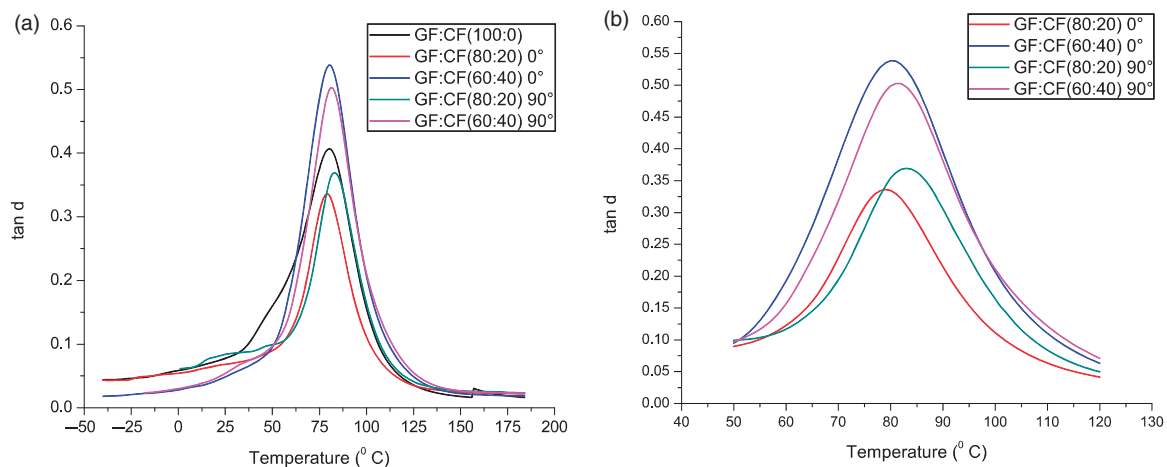
**Loss modulus ( $E''$ ).** Generally, the loss modulus represents the viscous response of the polymer-based materials or can be a measure of energy dissipated as heat/cycle under deformation.<sup>12</sup> As in the case of the storage modulus, the loss modulus preserves the same tendency of high values over the temperature range for reduced numbers of carbon fibre ply-ups embedded within the multi-layered composite architecture (see Figure 4). A discrepancy can be observed throughout the transition region, especially for the maximum  $E''$  in case of GF:CF(60:40) and GF:CF(100:0) specimens. This can be attributed to the inhibition of the relaxation process within the composite structures with the addition of the UD carbon fibres as a supplementary phase. However, GF:CF(80:20) multi-layered composite architecture has resulted in higher  $E''$  values within temperature range above its  $T_g$ .

Below the  $T_g$  values of each specimen, the  $E''$  curve for GF:CF(100:0) composite is closer to the curve retrieved for the GF:CF(80:20) architecture, whereas above these values, it is getting nearer to the curve retrieved for the GF:CF(60:40) combination, proven the longitudinal orientation of the UD carbon fibres. In Table 2 is listed the glass transition temperature values retrieved from the  $E''$  curves, for all the specimens involved in the present study, revealing once again the influence of UD carbon fibre relative volume fractions and their orientation. Glass temperature values retrieved using aforementioned curve types were reported within the literature to be more realistic compared to those obtained from damping factor plots and their associated experimental values.<sup>19</sup>

**Damping factor ( $\tan \delta$ ).** The material loss factor or loss tangent is related to the impact resistance of a material and depends, as has already been shown in literature, on the applied frequency.<sup>12</sup> The damping properties of the investigated polymer-based composite materials provide the balance between the elastic and viscous phases of the individual architectures. Generally, the higher  $\tan \delta$  peak values the better the material performances are in shock and vibrations, whereas the lower  $\tan \delta$  peak values the higher the load-bearing capacity properties are of the polymer-based composite materials. It is widely acknowledged that a peak in  $\tan \delta$  curve represents an energy-absorbing transition, whereas the area beneath represents the amount of energy absorbed.<sup>12</sup>

**Table 2.** Peak height and glass transition temperatures (from  $\tan \delta$ ,  $E''$  and  $dL/L_0$  curves) of multi-layered composite architectures.

Sample architecture	UD CF orientation	Peak height of $\tan \delta$ curve	Temperature ( $^{\circ}\text{C}$ )		
			$T_g$ from $\tan \delta$	$T_g$ from $E''$	$T_g$ from onset $dL/L_0$
GF:CF(100:0)	—	0.3762	91.2	89.0	52.0
GF:CF(80:20)	$0^{\circ}$	0.3030	87.4	85.0	55.0
	$90^{\circ}$	0.3241	88.4	83.6	55.0
GF:CF(60:40)	$0^{\circ}$	0.5182	86.2	81.3	58.0
	$90^{\circ}$	0.4782	88.0	83.4	59.0

**Figure 5.** (a) Temperature dependence of  $\tan \delta$  curves for all the composite specimens under discussion. (b) Zoom around  $\tan \delta$  peaks accounting for different UD carbon fibre content and orientation within the multi-layered composite architectures.

In Figure 5(a) was plotted the  $\tan \delta$  curves function of temperature, accounting for different UD carbon fibre content and orientation, whereas in Table 2 was provided the  $\tan \delta$  peaks and  $T_g$  values retrieved from  $\tan \delta$  for all the combinations considered. Figure 5(b) represents a detailed excerpt from the  $\tan \delta$  curves to reveal the influence of the UD carbon fibre content and orientation.

It is interesting to note that the loss factor experiences, in almost all cases, a positive small shift as the UD carbon fibre content and orientation change. These positive shifts in  $T_g$  values show the effectiveness of the GF and CF fibres as reinforcing agents and will be not linked to any post-curing effects. For example, in case of GF:CF(60:40) multi-layered composites, the shifting of  $T_g$  to higher temperatures may be associated with the decreased mobility of the polymer chains by the addition of supplementary carbon fibre ply-ups. Based on the diminishing in the  $\tan \delta$ , an improved fibre/matrix interface bonding behaviour can be observed in case of GF:CF(80:20) architecture while compared to the GF:CF(100:0) specimen. Moreover, in case of  $90^{\circ}$  UD

carbon fibre configurations, the same tendencies hold with respect to the  $\tan \delta$  variations.

**Cole–Cole plots.** Generally, these types of graphs are reported to be good indicators of the homogeneity of the structures subjected to dynamical loading. Departure from the ideal circular shape reveals the heterogeneity of polymer-based systems.<sup>12</sup>

Figure 6(a) and (b) shows the Cole–Cole plots of the loss modulus ( $E''$ ) as a function of the storage modulus ( $E'$ ) for the reference and multi-layered composite structures accounting for different UD carbon fibre content and orientation. As can be seen, both content and orientation of the UD carbon fibre contribute to the Cole–Cole plot shape changes. While in case of the  $0^{\circ}$  disposed UD carbon fibres, the changes give rise to imperfect semicircular shapes to the Cole–Cole plots, for their reverse configuration (i.e.  $90^{\circ}$ ), and the form of plots changes to an irregular shape. These imperfections indicate that there is heterogeneity among the glass and carbon fibres, as well as the polymer matrix material. Consequently, the content and

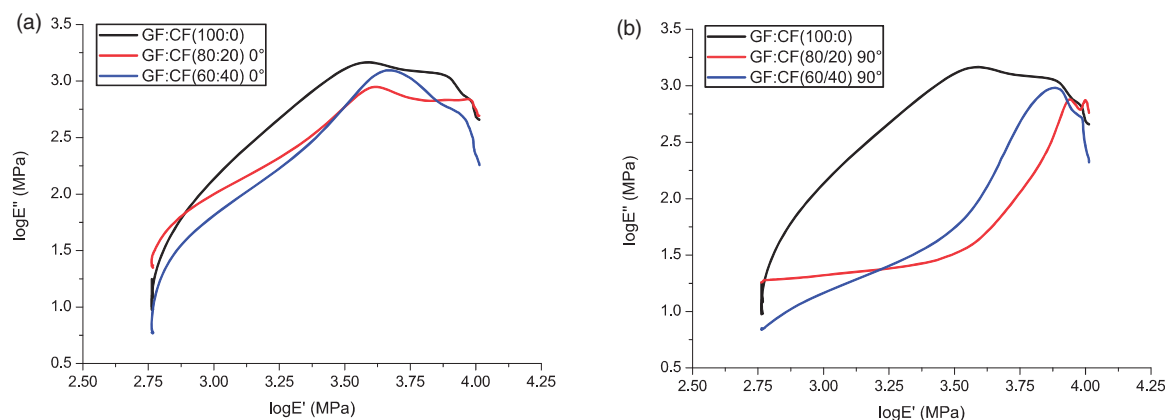
orientation of constitutive, supplemented by their individual material properties influence the shape of the Cole–Cole plots, thereby the tailoring process regarding the dynamical mechanical properties of these multi-layered composite architectures.

### Thermo-mechanical analysis

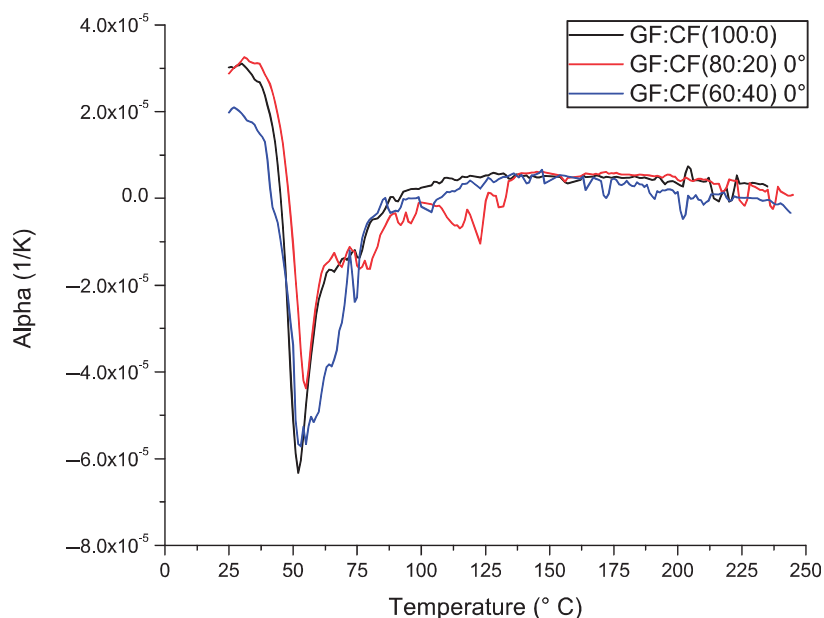
The instantaneous coefficient of thermal expansion (CTE) as well as the thermal strain field recorded for the polymer-based composite specimens herein can be viewed in Figures 7 and 8, respectively. These are accounting for different orientation and content of the UD carbon fibre constitutive. Supplementary, as it can

be seen from Figure 7, the different layer architectures induce the occurrence of little peaks (i.e. noise) in the instantaneous overall CTE field over the temperature range, departing from the linear variation for temperatures higher than  $T_g$  values. These can be associated to the weak cross linked network of the unsaturated polymer matrix herein, to the transitions from the glassy state to the rubbery state as well to the different fibre/matrix interfaces.

With respect to dimension changes, the differences in the recorded variations reveal the influence of both UD carbon fibre content and orientation. One interesting observation that must be underlined herein concerns the similarities revealed by the GF:CF(80:20) with  $90^\circ$

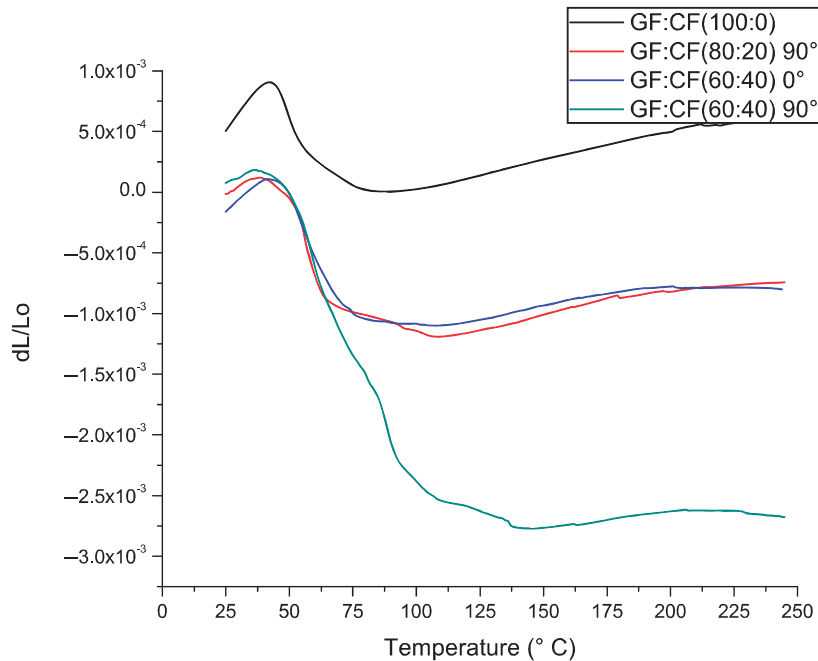


**Figure 6.** (a) Cole–Cole plot of the composites with (a) different content and  $0^\circ$  orientation of UD carbon fibres and (b) different content and  $90^\circ$  orientation of UD carbon fibres.



**Figure 7.** Instantaneous overall CTE temperature variations accounting different content and  $0^\circ$  orientation of UD carbon fibres within the composite architectures.





**Figure 8.** Thermal strain fields evolution from the composite specimens under the study.

UD oriented carbon fibres and GF:CF(60:40) with 0° UD oriented carbon fibres during the temperature rise. It seems that the specimens exhibit almost identical behaviour in terms of dimension change over the temperature range, as shown in Figure 8, and relatively close instantaneous CTE values within the same interval. This may be useful while manufacturing costs come as one of the major issues in the structures design and applications development.

Concerning the  $T_g$  values retrieved from the onset in the  $dL/L_0$  curves, these are lower than the ones retrieved from the DMA runs, as has been reported also in Table 2. As it can be seen from the table, a shift of approximately 30°C from the DMA reported values was recorded for all values retrieved for the multi-layered composite specimens. This can be assigned mainly to the experimental device working principle that cannot be ranked as providing the best results concerning the  $T_g$  values comparatively with the DMA method. Any further debate on this issue is beyond the purpose of the article herein. It must be pointed out that the DIL measurements give good indicators on the compatibility of the reinforcements with the matrix materials as well as on the influence of the individual constitutive on the overall material properties of the composite architecture.

## Conclusions

These architectures of advanced polymer-reinforced composites exhibit unique material properties while

compared with the benchmark polymer composites, either glass or carbon fibre reinforced. They were developed to replace the benchmark polymer composites in engineering applications where the manufacturing cost and weight are key issues in the lightweight structure's design.

High flexural properties and high-tensile strength were retrieved in case of GF:CF(60/40) multi-layered composite architecture. The increase in the carbon fibre-reinforced content was found to contribute further to the improvement of the structural strength, both in tensile and flexure mode. Furthermore, carbon fibre-reinforced ply-ups are revealing improved stress transfer behaviour between fibres and polymer matrix as compared to their benchmark (i.e. glass fibre reinforced composites). Further studies should be considered to investigate the stress transfer mechanisms among the individual layers and fibre to matrix interfaces as well as concerning the effective material properties at a level of a single lamina. Complete studies on other types of material characteristics (e.g. shear modulus and Poisson's ratio) supplemented by monitoring their changes under different environmental (e.g. high or low temperature range, hygro-thermal aging, etc.) and/or loading conditions may naturally follow to enable a comprehensive understanding of these multi-layered composite architectures' behaviour.

Furthermore, the GF:CF(60/40) architecture was found to exhibit improved resistance if subjected to shock and vibrations comparatively with the reference. It was also shown that the UD carbon fibre content and

orientation with respect to the general reference system contribute to the shape changes in the Cole–Cole plots.

The instantaneous CTE responses were also found to be influenced by the UD carbon fibre content and orientations. Besides, the influence of the constitutive individual material properties on the effective CTE was also underlined and revealed in the retrieved experimental curves.

The automotive industry was identified as the primary industry that can benefit from the use of these advanced polymer-based composite structures. One may also include the aerospace or marine structural components, sporting goods manufacturing, etc., proven the presence of the carbon fibre constitutive within the composite architectures and supplementary, their yearnings for development of lightweight structures.

Nevertheless, the advent of advanced polymer-based composite architectures based on particle/particle, particle/fibre or fibre/fibre multiple tailoring largely opened the combination possibilities and allow outstanding achievements with respect to their effective material properties, manufacturing technologies and costs as well as their wide-spread application areas.

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### Conflict of interest

None declared.

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