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Article

Investigation on Layer Hybridization of Glass/Carbon Fibre Woven Reinforced Composites Subjected to Low-Speed Impact

Raluca Maier * and Andrei-Cristian Mandoc

Composite Materials Laboratory for Aeronautical Field, Romanian Research & Development Institute for Gas Turbines—COMOTI, 220D Iuliu Maniu Av., 061126 Bucharest, Romania
* Correspondence: raluca.maier@comoti.ro

Abstract: The present investigation was conducted on the low-speed impact response of quasi-isotropic $[\pm 45/0/90°]_{xs}$ hybrid composite through laboratory level experimental tests. The purpose was to understand the behaviour that the different stacking sequences of hybrid glass/carbon fibre composites has on the ability of the material to sustain loads during low-speed impact events without developing critical structural failure in the material and improving the impact energy absorption properties, which is a relevant matter in aerospace and automotive industries. Drop-weight impact tests were carried out on two different laminates, with different stacking sequences, each of which were 16 symmetric inter-ply hybrid laminates named GC $[+45G/-45C/0G/90C]_4$s and, respectively, G-C $[+45G/-45G/0G/90G/+45C/-45C/0C/90C]_2$s, where G stands for glass fibre and C for carbon fibre. Both were comprised of epoxy matrix reinforced carbon/E-glass fibre woven fabric composites. The outcome of changing the hybrid stacking sequence, on the impact performances, was discussed. The damage morphologies and local failure mechanisms were analysed using visual inspection and a high-resolution laser scanner. Under 33 J impact energy, both tested hybrid composites exhibited approximately 10 kN peak load. Nevertheless, one key parameter, the time to peak load, significantly changed; the damage initiation threshold for GC samples occurred immediately before 6 kN, whereas for G-C samples this threshold appeared much earlier. This type of behaviour was partly connected to the delay in the propagation of delamination and fibre breakage, which was influenced by the high elastic energy absorption of the carbon fibres when compared with the glass fibres. The absorbed energy was higher for GC configuration, whereas a higher DI was observed for samples G-C indicating that a high percentage of the total energy was dissipated through the propagation of in-plane and out-of-plane fibre/matrix cracks. No perforation was observed on either configuration; nevertheless, the damage area significantly changed both in size and appearance from one configuration to another.

Keywords: hybrid-laminated composites; carbon fibre; glass fibre; finite element analyses; absorbed energy; low-velocity impact

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1. Introduction

Aircraft impact events [1], such as tool drop during maintenance work, removable element drop during cargo handling, runway debris, hail up to 51 mm in diameter or bird strike during the take-off and landing, and flight or taxiing procedures, where energy ranges from 5 to 80 J, pose a real safety hazard when it comes to the integrity of the structure as they are capable of producing extensive damage. In the last decades, due to their valuable characteristics, high strength-to-weight ratio stiffness and specific modulus, low density, high corrosion, and high endurance limit, carbon-fibre-reinforced polymer composites have become key materials in the aerospace field but also in other advanced engineering applications. Nevertheless, one of the main limitations of carbon-fibre-reinforced composites is their low fracture energy due to their brittle nature [2]. Furthermore, research brought forward that the improvement in the fracture toughness of the matrix shows a very low to moderate rise in the toughness of its composites [3–5]. While metals have been found to absorb, through elastic–plastic deformations, the energy generated during an impact, FRP (fibre-reinforced polymers) have a multitude of mechanisms that help dissipate the impact energy, such as matrix deformation and micro-cracking, interfacial debonding, lamina splitting, delamination, fibre breakage, and fibre pull out [6]. Both damage and impact resistance of FRP are dependent on fibre type, architecture, volume fraction, stacking sequence, resin type, processing parameters, etc. [7].

Carbon fibres are more brittle and exhibit poorly under impact loads, when compared with glass fibres [8]. The research of Babu et al. [9] shows that carbon-fibre-reinforced polymers exhibit lower impact strength in comparison with polymer reinforced glass fibres. The tests concluded that there is an improvement in the deflection for CFRP laminates; thus, extensive damage in the material was identified, compared with glass-fibre-reinforced polymer laminates, together with a smaller capacity to absorb the impact energy.

In addition to fibre treatment, matrix modification, interleaving used to improve impact performances [10], reinforcement hybridization was found to be a suitable way to obtain multi-functional properties for particular cases of composite material applications. Hybridization offers the means for the designer to achieve the desired physical and mechanical properties which could not be otherwise obtained from one type of fibre reinforcement. This means, one can combine two or more types of reinforcements such that one of the materials provides high strength-to-weight ratio, while the other complementary offers a good impact resistance. Depending on the type of hybridization, the behaviour of the laminate subjected to impact and its energy absorbing properties can be of importance for various applications [11–14]. In an investigation on post-impact compressive characteristics and impact behaviour of epoxy glass–carbon hybrid laminates with alternating stacking sequences, conducted by Naik et al. [15], it was found that the energy absorbed upon impact decreases with the carbon content of the laminate. At the same time, Hosur et al.'s [16] study on the low-speed impact response of plain woven glass and twill woven carbon–glass laminates found that, for the hybrid laminates, an increase in the load-carrying capability was identified, having a reduction in stiffness at the same time.

This paper investigated the low-speed impact response of two stacking sequences, inter-ply hybrid glass–carbon fibre laminates, keeping constant the thickness, number of plies/type of fibre, processing, and experimental tests parameters. Glass fibres are characterized by their low specific strength and specific modulus, meaning that the addition of carbon fibres to the volume fraction of GFRP composites could improve the mechanical properties of the laminate. Nevertheless, the high cost and low strain to failure of the carbon fibres suggest that a cost/performance balance needs to be identified for the application. As mentioned previously, low-energy impacts (energy ranges from 5 to 40 J) induced by the fall of foreign objects is one of the most common damages that occur in composite structures [17–19]; therefore, the present study focused on the evaluation of the structural architectural hybridization effect of fibre-reinforced composites on low-velocity (4.57 m/s) impact behaviour. The laminates prepared for this paper were subjected to a 33 J drop-weight impact tower test and load–time, load–deflection, and energy–time curves were plotted and analysed together with other parameters such as DI (ductility index), E_a (absorbed energy), and impact resistance. This study is relevant in determining the dynamic behaviour of hybrid composites for different industrial applications since this type of damage is capable of crippling the integrity of the structure. The fracture modes and the characteristics of the impacted specimens were analysed, while 3D measurements using a high-resolution laser scanner backed up the conclusions of the present paper.

2. Materials and Methods

Composite hybrid laminates' fabrication was developed from 193 g/m^2 HSC 3K Toray carbon fibre and 285 g/ m^2 E-glass fibre, both Twill2x2 woven impregnated with 40% wt. Resoltech 1050 epoxy resin and 1058 hardener (100:35 blend proportions). Inter-ply hybrid laminate [+45G/−45C/0G/90C]4s named GC and, respectively, [+45G/−45G/0G/90G/

+45C/−45C/0C/90C]2s named G-C, both made out of carbon/E-glass fibre woven fabric reinforced epoxy blend composite laminates, were vacuumed and cured at 120 °C, 1.8 MPa, by means of autoclave technology. The panels were cut at approximately 150 × 100 mm, having the nominal thickness of 5.8 ± 0.25 mm. The Hybrid composite configurations developed are provided in Table 1.

Table 1. Hybrid composite configurations developed within the present study.

Specimen/Configuration	Hybrid Structure 16 Plies	Architectural Hybridization
GC	[+45G/−45C/0G/90C]4s	■□■□■□■□■□■□■□■□
G-C	[+45G/−45G/0G/90G/+45C/−45C/0C/90C]2s	■■■■□□□□■■■■□□□□

Drop-Weight Impact Testing and Evaluation Methods

The impact drop tower used for tests was an INSTRON model, CEAST 9340, as shown in Figure 1a. For the ten tested samples in the two configurations described above, the impact energy was set at 33 J, obtained by modifying the height and varying the impactor mass. The test consists of dropping a ∅20 mm hemispherical striker of 3.15 kg weight on the specimens from a 1.06 m height.

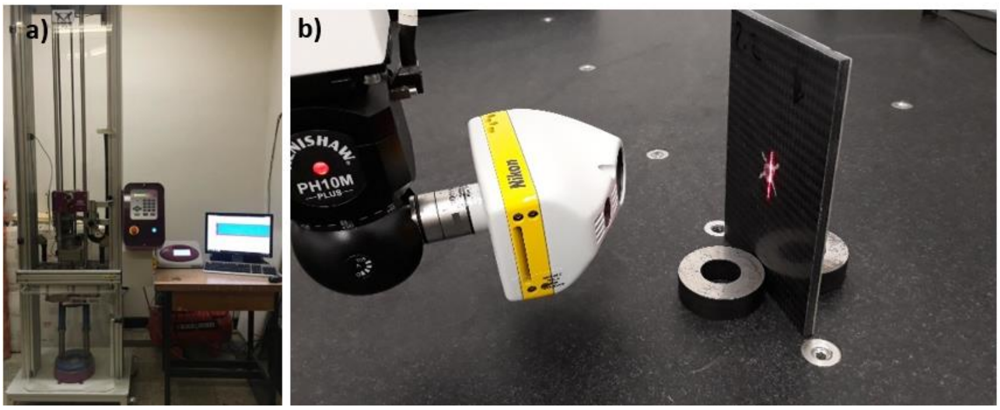


Figure 1. (**a**) INSTRON CEAST 9340 drop-tower impact testing machine; (**b**) Altera coordinate measuring machine equipped with LC15Dx CMM automatic laser scanner.

According to the standard used (ASTM D7136/D7136M), the corresponding impact energy was 33 J and the impact velocity was approximately 4.5 m/s.

The damage of the surface of the samples and their fracture characteristics, when subjected to low-energy impacts, were analysed both visually and using the automatic laser scanner in Figure 1b, LC15Dx CMM. The aim was to create a link between hybridization, stacking sequence of the layers, and impact performances with the damage mechanisms identified.

3. Results

3.1. Low-Velocity Impact Response

Typical load–time curves for both laminate configurations tested at the same energy level are shown in Figure 2. From statistically sight of view of reproducibility, the results for both tested configurations are considered acceptable. Peak loads were comparable, around 10 kN for both tested hybrid composite configurations, indicating equivalent stiffnesses. For every curve of the tested samples, a sudden load drop was identified in area A, immediately after the beginning of the impact. This is also known as Hertzian failure and it indicates the sudden transition of the specimen from an intact state to a damaged one [20–23], showing the incipient damage through, mainly, interlaminar delamination.

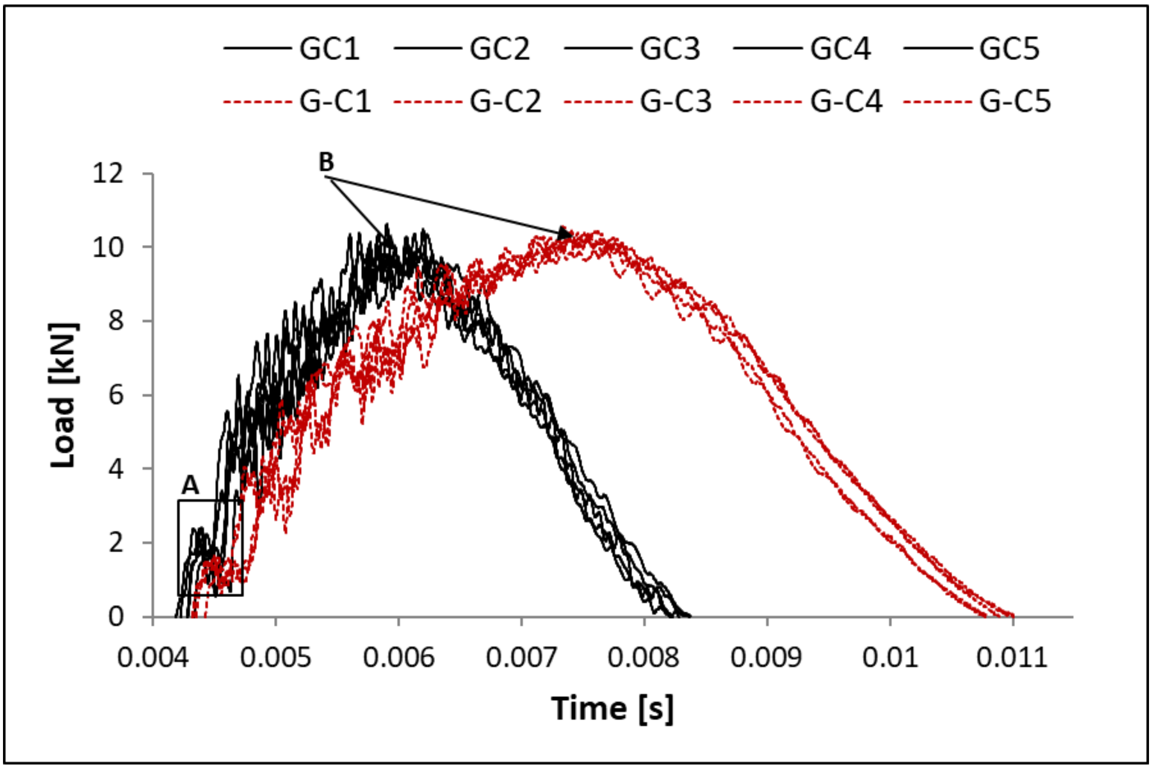


Figure 2. Impact load–time curves of experimental curves of ten hybrid composite tested samples.

The next stage, known as the elastic strain stage, is characterized by multiple load oscillations between zones A and B, which may be caused by the rupture of fibres and the apparition of small cracks unconnected in the sample. In the load-time history data, a damage initiation threshold was observed on both configurations; nevertheless, for inter-hybrid GC samples this occurs immediately before 6 kN, whereas for G-C samples the threshold appears earlier, which is an indicator of the effect of the hybridization stacking sequence. The following stage, after zone B, is characterized by abrupt drops and fluctuations which suggest the initiation of significant damage in the laminate. In this stage, the propagation of damage starts until maximum displacement is reached. Next, the curve presents a plateau with a gradually decreasing load trend, until the impactor rebounds in the rebound stage. Inter-hybrid GC samples have a higher slope rate than that of the G-C samples. This phenomenon is explained by the fact that, in the early stage of the impact, the properties of the first impacted layers are responsible for the laminate behaviour. As the carbon fibre presents a higher modulus than that of the glass fibre, having the first four layers of the laminate made out of carbon fibre presents higher initial slope values. Furthermore, sharp drops in load–time curves after reaching the peak load for inter-hybrid GC samples is a behaviour attributed to the brittle failure of carbon fibre of the impact surface layer. Different from GC hybrid configuration, G-C samples curves smooths until reaching the peak load and a slight fall is observed just after the peak load. These are due to the higher ductility of glass fibres, showing also the important effect of the type of hybridization on the impact performances as well as on the damage mechanisms, when comparing the two tested configurations. No major difference in the peak load was observed between the two tested configurations; nevertheless, one key parameter, the time to peak load, significantly changed. Richardson et al [24] suggested that the stiffness of the laminate directly influences the time to peak load. Figure 1 shows that in the case of the GC laminate structure, the time to peak load is smaller. The cause of this behaviour is the high modulus of the carbon fibre which provides the structural stiffness and load capacity, while the ductility of the glass fibre allows for better damage tolerance and increased energy absorbing properties through the stretching and pulling out of the fibres. This also concludes that stiffness is primarily controlled by the layers that face the impactor. Likewise, overpassing the peak load value, the presence in hybrid G-C sample graphs of smaller fluctuations even in the unloading phase, contrary to what is seen in GC configuration, points out once again that the maximum synergy effect of both glass and carbon fibres, in terms of absorbed energy, can be obtained by inter-hybrid GC configuration, whereas in terms of load-bearing impact time and ductility, the inter-hybrid G-C configuration is more appropriate.

The absorbed energy evolution can be seen in Figure 3 and can be split into three distinct zones.

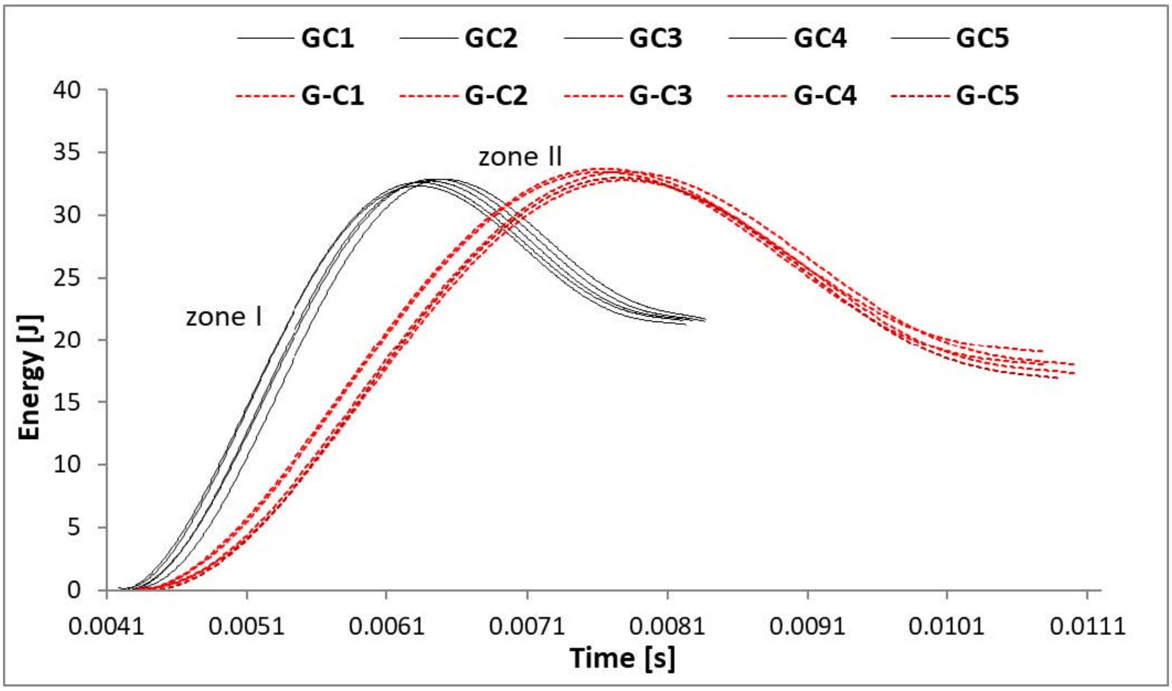


Figure 3. Energy–time curves of the tested hybrid under low-velocity impact tests.

The energy which is absorbed during an impact by the specimen is the sum of the dissipated energy and the elastic energy. While the elastic energy can be defined as the energy absorbed during elastic deformation, the dissipated energy is the one absorbed through plastic deformation and damage of the composite laminate. One find was that the energy which was absorbed increased with the deflection up to the point where the impactor stopped; following that, the impactor was rebounded by the stored elastic energy in the specimen. In the first part (Zone 1), there are low values for the absorbed energy, which is due to the small deformation in the thickness direction formed at the contact of the impactor with the laminate. In the second part (Zone 2), a quick rise of the energy–time curve is identified, given the increased deflection and apparition of internal damage in the laminate. This shows that most of the absorbed energy is the result of the increased contact area between the striker and the tested specimen. In the final zone, a constant value for the absorbed energy is identified, corresponding to the specimen response to the end of the rebound phase of the impactor, and subsequently the absorbed energy will not increase. Alike behaviour was reported by Ying et al. [25]. Numerical results in terms of the impact velocity over time were assessed using Equation (1) below. A total of 20.3 J of absorbed energy was obtained for the inter-hybrid GC architecture:

$$Ea\ (t) = \frac{\mathrm{m}\left(v_i^2 - v_t^2\right)}{2} + mg\delta(t) \tag{1}$$

where:

- $Ea\ (t)$ is the absorbed energy at time t corresponding to the end of the test, J;
- v_i is the initial impact velocity, [m/s];
- v_t is the impact velocity at time t corresponding to the end of the test, [m/s];
- m is the mass of the impactor, [kg];
- g is the acceleration due to gravity, 9.81, [m/s^2];
- $\delta(t)$ is the impactor displacement at time t corresponding to the end of the test, [m].

Force–deflection curves plotted in Figure 4 contain important data on the progression of the damage during the event of an impact. Here, the ascending part of the slope of the curves is the impact bending stiffness, and the peak load represents the highest value obtained in the force-displacement plots. The areas under these curves were determined for absorbed-energy-amount purpose, verified also from the energy–time curve data, the values being provided in Table 2. Inter-hybrid GC exhibits higher absorbed energy values (20–23 J) when compared with G-C samples (15–18 J).

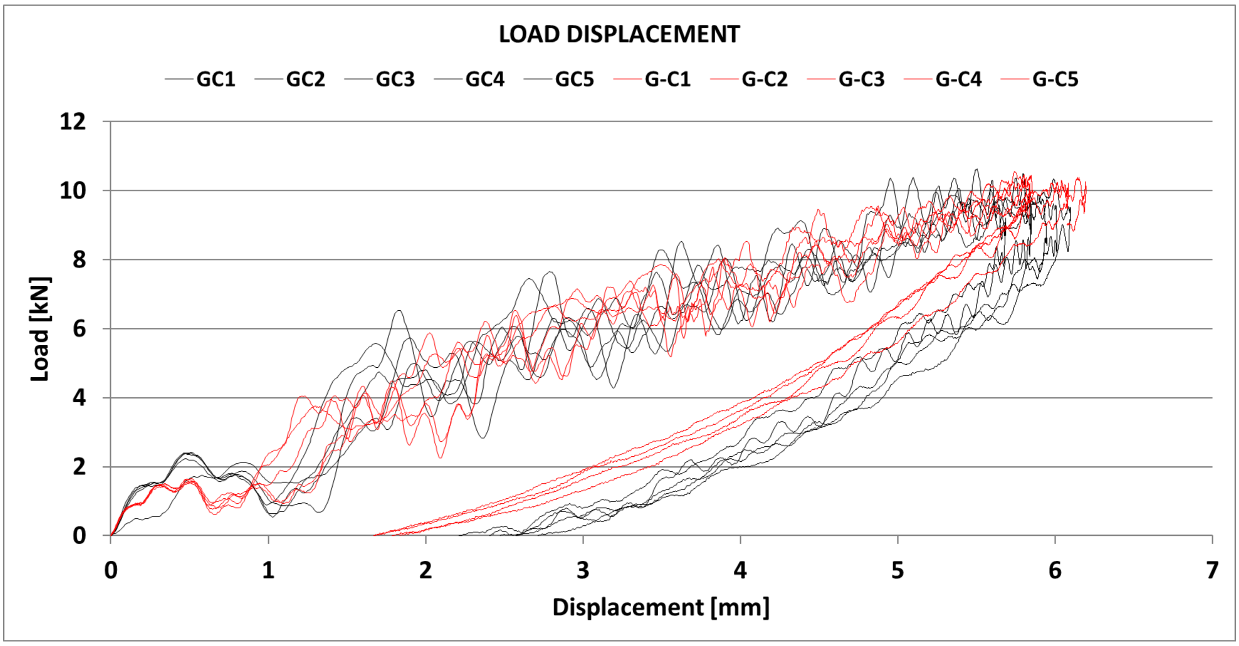


Figure 4. Force–deflection curves of the hybrid composites tested at 33 J impact energy in low-velocity impact tests.

Table 2. Maximum load, E_i, E_p, E_a, and D_I of each hybrid composite tested sample.

Config.	F_m [kN]	F_m [kN] Mean Value	E_i [J]	E_i [J] Mean Value	E_p [J]	E_p [J] Mean Value	E_a [J]	E_a [J] Mean Value	D_I	D_I Mean Value
GC1	10.35	10.25	5.08	4.22	16.80	17.53	21.88	21.65	3.31	4.22
GC2	10.62		4.08		17.63		21.71		4.32	
GC3	10.37		3.89		17.44		21.33		4.48	
GC4	10.05		4.5		17.20		21.70		3.82	
GC5	9.89		3.58		18.60		21.64		5.19	
G-C1	10.46	10.41	2.53	2.73	16.59	15.20	19.12	17.93	6.55	5.73
G-C2	10.38		2.03		16.03		18.06		7.89	
G-C3	10.30		3.05		14.35		17.4		4.70	
G-C4	10.38		3.04		15.06		18.1		4.95	
G-C5	10.56		3.04		13.97		17.01		4.59	

Moreover, the displacement shows the movement of the striker and the deflection of the laminate under the load. Only the closed curve type was obtained for the present study tested hybrid composites. As neither penetration or perforation cases occurred on the hybrid composite specimens tested within the present study, a rebounding path was observed. Nevertheless, the rebound took place earlier on hybrid G-C samples; the integrated force–deflection curves provided a smaller area, and thus a lower energy absorbed, in agreement with the analysis performed above on the energy–time curves. At the point where the maximum energy occurs, the maximum deflection of the specimen is found. Total absorbed energy (which consists of damage initiation energy (E_i) and damage propagation energy (E_p)) and the elastic energy (which is the one responsible for rebounding the striker, not being absorbed by the specimen) are the two components of the maximum energy. The E_i was determined as the energy corresponding to the second major peak drop on the load–time curve as it is believed that the first drop encountered is due to natural vibrations between the impactor and the impacted plate. Regarding E_i, higher values were obtained on inter-hybrid GC, attributed to brittle and high-stiffness carbon fibre integration between glass fibres. Contrastingly, G-C configuration comprising the first four surface layers of glass fibres exhibits a more plastic behaviour, thus a lower initiation energy.

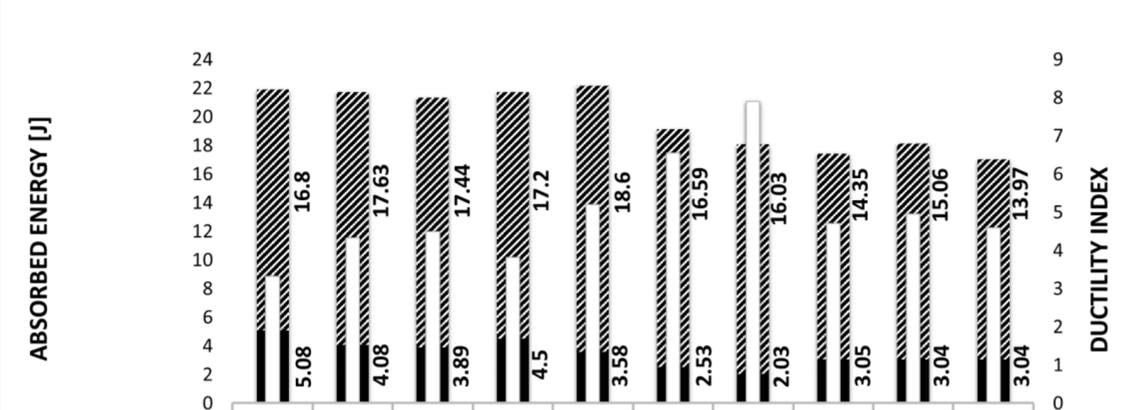
3.2. Damage Analysis and Morphologies

Further considerations about the behaviour under impact loads of the quasi-isotropic hybrid tested composites is provided by the index of ductility DI, a dimensionless parameter that indicates how the total impact energy is divided between initiation and propagation energy in each specimen. Therefore, all these above parameters frequently used in assessing damage process in composites, such as the damage propagation energy (E_p), damage initiation energy (E_i), their ratio defined as the ductility index (DI), and the absorbed energy (E_a), were calculated as described previously for each tested sample configuration and are provided in Table 2.

A higher DI observed for G-C samples indicates that the greatest amount of the load was sustained post peak and most of the total energy was expanded in crack propagation. The creation and propagation of the damage in the laminate represents the main absorption mechanism through which a large amount of the total impact energy is consumed; however, it does not provide enough information on the amount of energy that is absorbed. Based on these considerations, a sample that shows a smaller E_p, while E_i is greater, can be more desirable. Therefore, inter-hybrid G-C samples have the ability to sustain additional loads even after considerable damage, without leading to critical structure failure upon impact. The low DI which was obtained for the GC inter-hybrid samples shows that the amount of energy that is necessary to initiate damage is larger than the one used, while it is clear that once the damage occurs, very little additional energy is needed to cause critical failure in the structure [26]. Figure 5 provides a summary of the absorbed energy divided into E_i and E_p and ductility index DI for each hybrid composite tested specimen.

As the architectural hybridization changed from the GC to G-C configuration, for the same number of plies, thickness, and impact energy level (parameters well known to influence impact performances and behaviour), the damage area significantly changed both in size and appearance. Nevertheless, no perforation was observed on either GC or G-C samples. The three modes of damage (matrix cracking, delamination between plies, and fibre buckling and breakage) are the main influencers of the non-penetrated impact failure mechanism, contributing to the dissipation of the energy [25].

Damage in G-C tested samples is more localized and a dome-type morphology prevails (see Figure 6 lower line), signifying a certain homogeneous deformation indicative of matrix crushing. Fibre and matrix crushing at the contact zone represent the local, more homogenous failure, being influenced by the first four layers of glass fibres which exhibit a higher number of fibres by surface area in the G-C configuration when compared with both the glass and carbon fibres within the inter-hybrid configuration (the latter having a smaller number of fibres by surface area). Likewise, this localized and dome-type morphology of damage is in correlation with the G-C configuration's lower ability to absorb the impact energy.



	GC1	GC2	GC3	GC4	GC5	G-C1	G-C2	G-C3	G-C4	G-C5
Propagation Energy [J]	16.8	17.63	17.44	17.2	18.6	16.59	16.03	14.35	15.06	13.97
Initiation Energy [J]	5.08	4.08	3.89	4.5	3.58	2.53	2.03	3.05	3.04	3.04
DI	3.31	4.32	4.48	3.82	5.19	6.55	7.89	4.7	4.95	4.59

Figure 5. Absorbed energy divided into E_i and E_p and ductility index DI for each hybrid composite tested specimen.

Figure 6 shows the morphology of the damage for both sides of the ten post-impact damaged specimens in both inter-hybrid GC and G-C configurations.

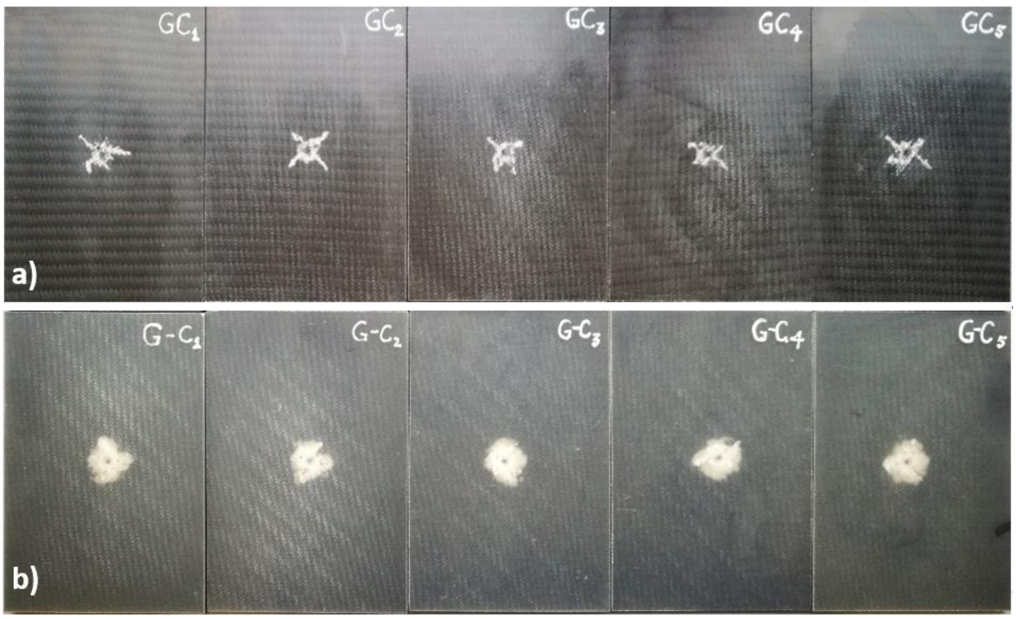


Figure 6. Front impacted side of inter-hybrid configurations (**a**) GC and (**b**) G-C, post-impact damaged specimens.

Figure 6 presents the post impact images of hybrid composite samples whereas the Figure 7 gives a graphical representation of the damaged area of the tested specimens. Furthermore, Figures 8 and 9 provide the laser scan measurements of G-C2 and GC2 hybrid configurations after low velocity impact tests.

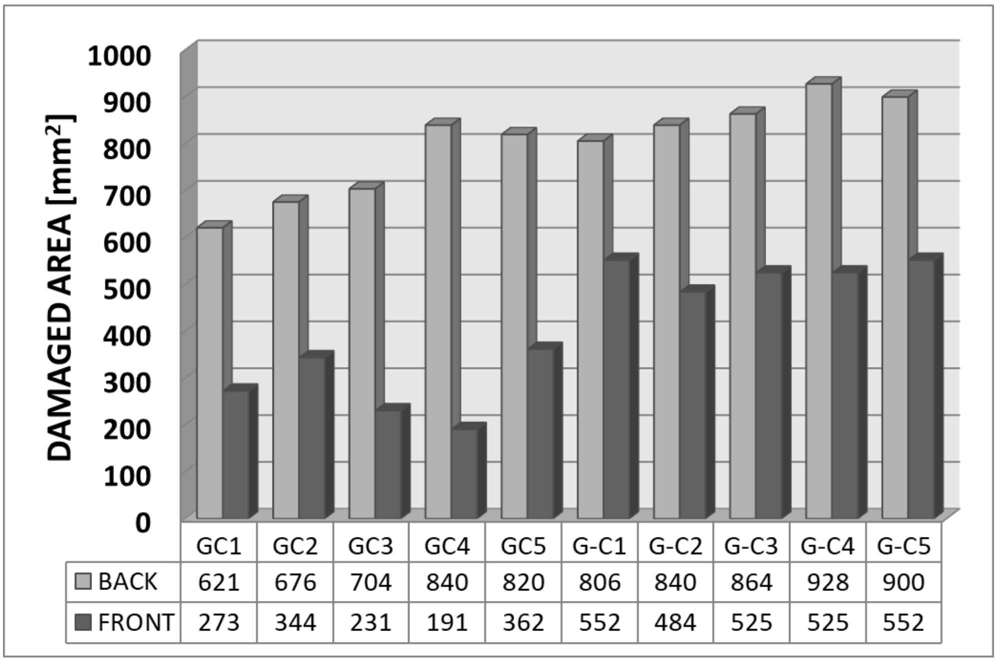


Figure 7. Damaged areas' front–back impacted side measured for all tested hybrid composites.

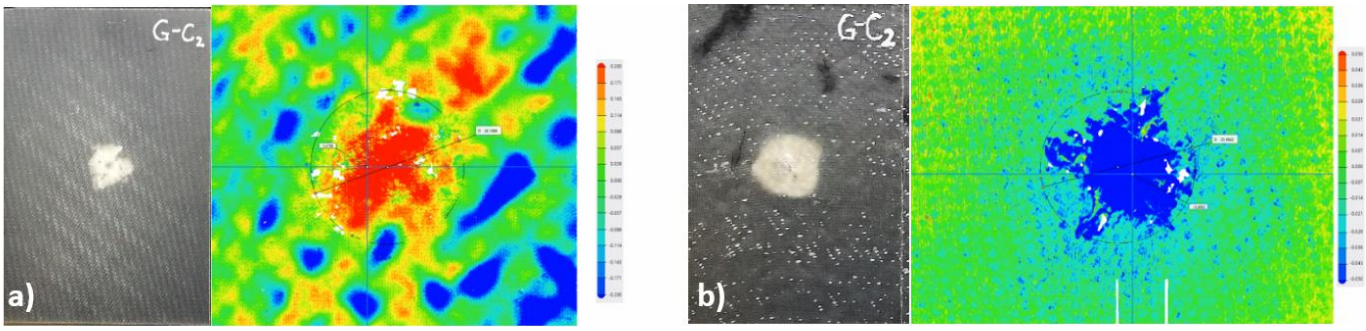


Figure 8. (**a**) Front, (**b**) back sides laser scan measurements of sample G-C2 damaged area.

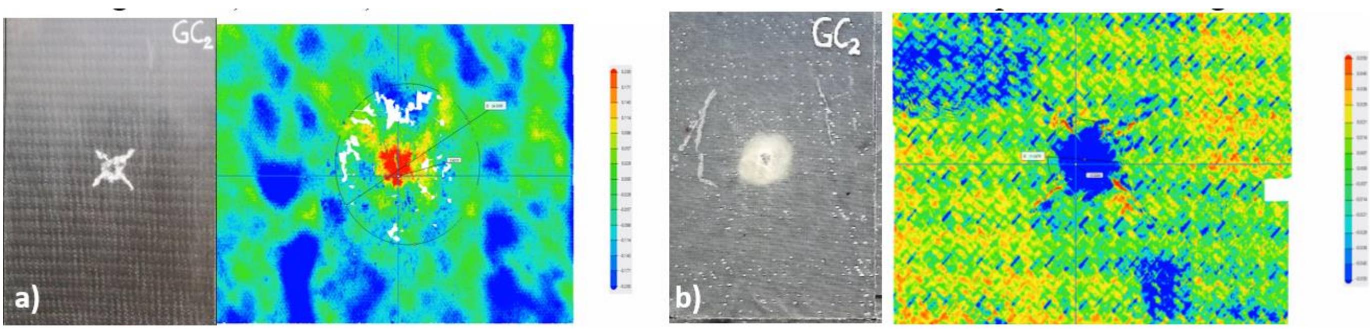


Figure 9. (**a**) Front, (**b**) back sides laser scan measurements of sample GC2 damaged area.

Inter-ply hybrid GC laminates show cracks in the shape of a cross on the impact side, being associated with fibre breakages in the preferred directions (Figure 6a), while on the back a small delamination area is observed, with splitting around the edges (Figure 9a). Mixing both glass and carbon fibre for the first four layers on the side of the impact, for the GC configuration, delamination appears, accelerating the propagation of cracks, due to the stress waves that travel through two different types of fabric layers.

On the impact side, a matrix crack develops immediately after the strike is initiated and is mainly due to the high compression stresses present in the area. On the other side of the impact, matrix cracking can be seen too, due to extension of the crack in the layers subjected to maximum tensile stress, which are the ones farthest from the impacted side.

Cracks in laminates GC with glass and carbon fabric surface layers on the impact surface are more visible and follow fibre orientation along the fill and warp directions, compared with G-C only glass fabric surface layers where cracks are very localized, being related to the ductile nature of glass fibre and the higher tensile fracture strain when compared with carbon fibres. All these various laminate level damage mechanisms observed for inter-ply hybrid GC configuration, fibre fracture energy absorption, crack propagation energy absorption and stratification energy absorption participated to an increased energy absorption amount when compared with the G-C configuration. Figure 7 below reports the damaged areas' front–back impacted side measured for all tested hybrid composite samples.

Two specimens from each configuration, GC2 and, respectively, G-C2, were analysed as representative samples by means of a 3D high resolution laser scanner.

With respect to the above-measured damage-area amounts for all tested specimens (Figure 7), as well as for the two representative samples from each configuration (Figures 8 and 9), it is clearly underlined that the damage area changed both in size and appearance from one configuration to another. Cross-shaped cracks were detected on GC whereas localized and dome-type morphology was observed on G-C, on the front surfaces. Although on both configurations a back-surface splitting on the edge of the pit-type damage was observed on the rear side, the damaged areas were different in size on both front/back sides from one configuration to another.

4. Conclusions

Under the same impact energy of 33 J, no major difference in the peak loads was observed, this being approximately 10 kN on both tested hybrid composite configurations. Nevertheless, one key parameter, the time to peak load, significantly changed; the damage initiation threshold for inter-hybrid GC samples occurred immediately before 6 kN, whereas for inter-hybrid G-C samples this threshold appeared much earlier. This is mostly due to the ability of carbon fibres to delay the propagation of delamination and fibre breakage. The amount of absorbed energy was clearly higher for inter-hybrid GC configuration. Consequently, using carbon fibre (high stiffness) in areas of high stress, as reinforcement, results in enhanced absorbed energy. Regarding E_i, higher values were obtained on inter-hybrid GC, attributed to brittle and high-stiffness carbon fibre integration between glass fibres. Contrastingly, G-C configuration comprising the first four surface layers of glass fibres exhibits a more plastic behaviour, thus a lower initiation energy, and a higher DI indicating that most of the total energy was expanded in crack propagation. No perforation was observed on either configuration. Nevertheless, the amount of energy absorbed was higher on inter-hybrid GC and the damage area significantly changed both in size and appearance from one configuration to another.

It is clearly seen that interlaying different materials to improve the overall behaviour under impact events, of the final part, can be achieved without significant losses of the maximum load that it can sustain. The best way is to interlay these materials, according to the results, from one layer to the other (as carried out with the GC configuration). This shows that pairing two layers of different materials one after another is a better way of obtaining a complementary effect for the lacking mechanical properties between the two. One aspect supporting this affirmation is the front plate damage that is different in the two configurations. From the images of the front impact damage, it is clear that interlaying the fibres one after another helps the damage propagate more through the elasticity of the specimen and thus absorbs more of the damage in this way. For the G-C specimens, provided that the first four layers were carbon fibre, which is more brittle, the damage absorption was carried out through delamination and matrix cracking, which shows a bigger affected area on the impacted face of the specimen.

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