THIN PLY CARBON/GLASS HYBRID LAMINATES TO ACTIVATE NEW DAMAGE MECHANISMS UNDER INDENTATION

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Abstract

Low velocity impacts on composite laminates can cause a significant amount of delamination that is often referred to as barely visible impact damage (BVID). This damage can cause significant degradation of structural properties, especially the compressive strength after impact. The aim of this work was to utilise thin ply carbon/glass hybrid laminates to activate new types of damage mechanisms under indentation (quasi-static impact) that are more gradual and easier to detect. Therefore, 3 different types of hybrid composite plates fabricated from novel hybrid architectures of thin ply high modulus carbon (HS40) and standard thickness S-glass laminates were investigated. For comparison, a laminate containing only S-glass plies was investigated as well. The investigated specimens were interrupted at different load-levels and a detailed assessment of the damage evolution was carried out using X-ray Computed Tomography (CT). For all the hybrid configurations, a larger damage area was observed mostly under the indenter and the delaminations were smaller in the middle plies compared to the upper plies. In contrast, for the Glass laminates the delaminations were larger in the middle plies compared to the upper plies. For the hybrid laminates, the percentage of the first load drop in the global load–displacement curves was lower whereas the percentage of the stiffness reduction after the first load drop was higher, compared to the Glass laminate. Overall the hybrid results showed some different damage mechanisms, i.e. carbon ply fibre fracture and delamination under the indenter, with a gradual failure behaviour and less damage to the inner layers. The degradation mechanisms were visually detectable from the indented face from the early stage of the loading for some of the hybrid configurations, which can act as impact damage indicator.

1. Introduction

Composite materials are widely used in different industries, e.g. automotive and aerospace, and their use is increasing exponentially. Especially in the aeronautical field, structures are subjected to different loading conditions during a typical aircraft service life, e.g. tensile, compressive and fatigue loads. However, an important and yet unsolved problem is the composite susceptibility to impact and indentation. As a matter of fact, the damage that occurs is generally barely visible. Low-velocity impacts and indentations generally cause two main types of failure mechanisms in laminated composites: intralaminar and inter-ply damage [1]; intralaminar failures produce damage to single plies in the form of matrix cracking and fibre breakage. Interply failure, on the other hand, involves separation between adjacent plies (delamination) and has a significant effect especially on the compressive strength which may decrease by up to 60% compared with an undamaged laminate [2].

Different procedures have been used to increase impact damage resistance of composites such as modifying the properties of the constituents [3], sewing high-strength yarns through the laminate [4], Z-pinning by inserting metal pins or cured carbon fibre pins into the laminate through the thickness [5] and nano-size reinforcements [6]. To avoid catastrophic failure, hybrid composite materials have been studied and designed to gradually fail [7-8]. Recently, Wisnom et al. have developed a new generation of high-performance ductile composites by hybridization of thin-ply carbon and glass prepregs which show a pseudo-ductile behaviour [9].

The aim of this work is to investigate the indentation behaviour of novel thin ply carbon/glass hybrid laminates. The tests were performed using a test set-up configuration close to the one proposed by the ASTM 7136 standard [10] for low-velocity impacts. Moreover, interrupted tests were performed to observe the damage evolution as the loading level increases. From the results, the investigated hybrids showed a gradual failure, experienced large deformations and less damage in the inner layers with visual evidence of damage on the indented face.

2. Materials and Methods

2.1. Materials

Hybrid laminates were laid-up using two different materials (Table 1): a low failure strain high modulus material with ply thickness of 0.07mm (SkyFlex UPN069 carbon prepreg from SK Chemicals with HS40 fibres) and a high failure strain standard modulus material (Unidirectional S-glass/913 epoxy prepreg supplied by Hexcel) with ply thickness 0.155mm. Four different configurations were considered as illustrated schematically in Fig.1:

- Material dispersed, angle blocked laminate (Fig. 1a) with total thickness of 4.16 mm and stacking sequence of $[(90_G/90_{3C}/90_G)/(45_G/45_{3C}/45_G)/ (0_G/0_{3C}/0_G)/ (-45_G/-45_{3C}/-45_G)]_S$.
- Material blocked C/G/C angle-dispersed laminate (Fig. 1b) with total thickness of 4.16 mm and stacking sequence of $[(90/45/0/-45)_{3C}/ (90/45/0/-45)_{2G}]_S$.
- Material blocked C/G angle-dispersed laminate (Fig. 1c) with total thickness of 3.94 mm. and stacking sequence of $[(90_C/45_C/0_C/-45_C)_3/(90_G/45_G/0_G/-45_G)_2/(45_G/90_G/0_G/-45_G)/(-45_G/0_G/45_G/90_G)_2]$.
- Glass laminate (Fig. 1d) with total thickness of 4.34 mm and stacking sequence of $[(90/45/0/-45)_3/(-45/0/90/45)/(-45/0/45/90)_3]$.

The hybrid layups were chosen based on our previous studies [11-12] on tensile behaviour of two different designs for pseudo-ductile quasi-isotropic (QI) hybrid composites in tension; a) angle dispersed, material blocked and b) angle blocked, material dispersed hybrid composites. Both of the designed laminates showed pseudo-ductility in tension, but an undesirable free-edge delamination damage was observed for the angle blocked configuration.

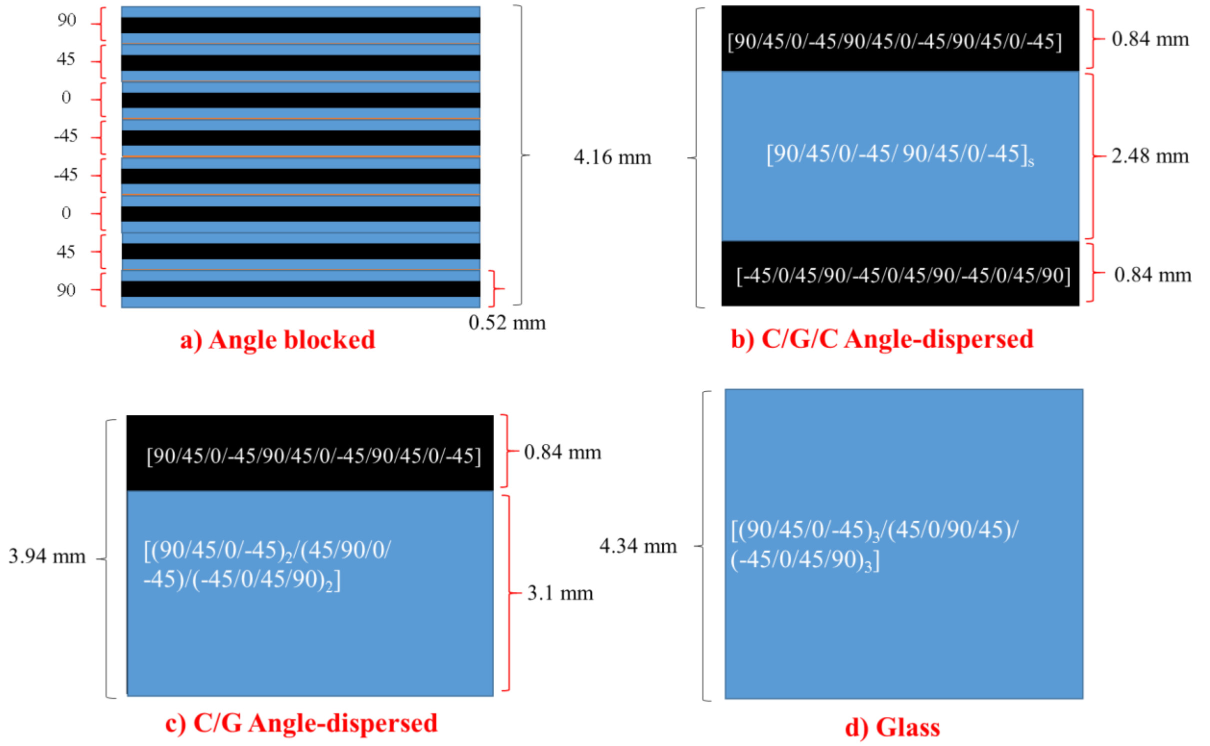

Figure 1. Schematic view of the investigated configurations. Black and blue colour refer respectively to carbon and glass layers.

Table 1. Prepregs and fibres main characteristics [9].

	S-glass/epoxy	HS40/epoxy
Fibre modulus E (GPa)	88	455
Fibre failure strain (%)	5.5	1
Cured nominal thickness (mm)	0.155	0.07
Fibre mass per unit area (g/m^2)	190	65
Fibre volume fraction (%)	50	50

2.2. Test setup

To perform indentation tests, an Instron 8872 hydraulic system was used. The tests were carried out by mounting a 16 mm diameter steel indenter with the 150 ×100 mm specimens simply supported on a 125 × 75 mm window and clamped lightly to it using four rubber-tipped clamps (Fig.2). The tests were conducted in controlled conditions imposing a displacement rate of 2 mm/min. The load curves, provided by a 25 kN load cell, were recorded at a sampling rate of 20 Hz. Interrupted tests were also performed between the first load drop and the final load to investigate the damage propagation as the load increases.

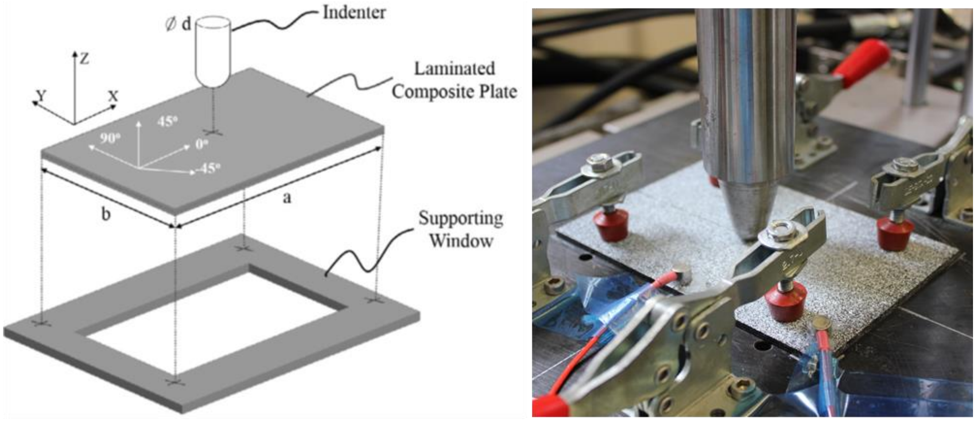

Figure 2. Experimental configuration for the static indentation tests.

X-ray CT scanning was conducted to study the degradation mechanisms during the tests at different interrupted indentation load levels.

3. RESULTS AND DISCUSSION

The load-displacement results provided by the Instron system are shown in Fig. 3. Comparing the results for each layup, there is good repeatability in the tests as the load-displacement diagrams for the fully indented and interrupted samples overlap. As illustrated in Fig. 3, the initial stiffness is the slope of the linear elastic region in the load-displacement diagrams, and the second stiffness is the slope just after the load drop/plateau in the load-displacement diagrams. There is an obvious difference in the initial stiffness of the hybrid laminates due to the carbon layers compared with the other laminates. For the C/G/C angle-dispersed laminates, damage initiates at significantly higher loads (4580 N) compared with the angle blocked laminates. No obvious load drop in the load-displacement diagram is visible for the angle blocked laminate, whereas, there is a noticeable load drop for the others. After the load drop, there are a number of subsequent small load drops and significant stiffness reduction for the angle blocked and C/G/C angle-dispersed hybrid laminates, caused by a series of damage events, and the percentage of this reduction has the largest value for the C/G/C angle-dispersed laminate. This stiffness reduction is lower for the C/G angle-dispersed hybrid laminate compared with the other hybrid configurations. For the hybrid laminates, the load recovery after the initial load drop is lower than for the Carbon specimens investigated previously by Abisset et. al. [12]. The hybrid laminates experience larger displacements compared with the classical carbon plates when subjected to the same loading level. The displacement is the largest for the pure glass laminate.

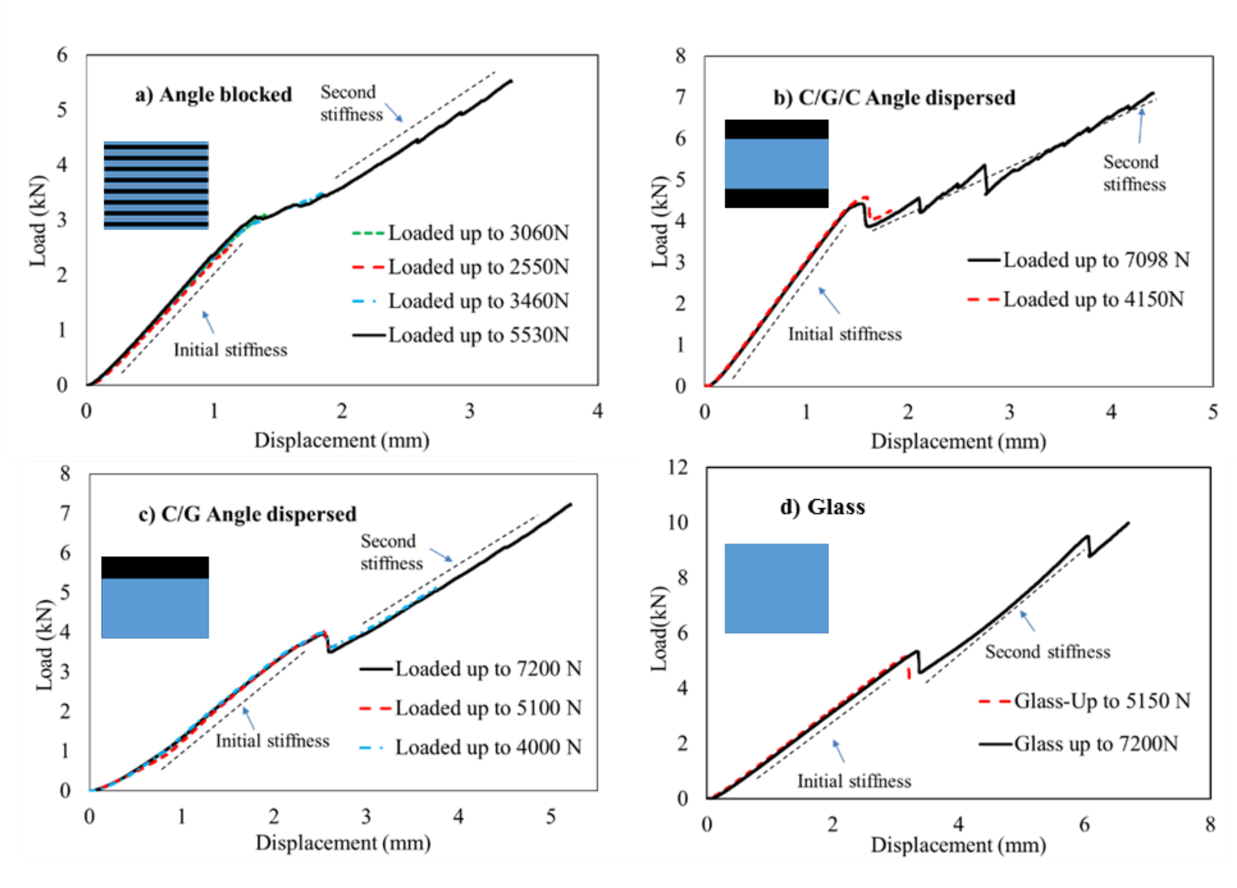

Figure 3. Load–displacement curves for the investigated specimens.

Representative global load–displacement curves and images from the indented side of the specimens are illustrated in Figure 4. In contrast to the conventional composite laminates, for the hybrid laminates, the damage appeared on the indented side from the early stage of the loading and was easily detectable by the naked eye. For the angle blocked laminates, delamination of the glass/carbon interfaces and fracture of the glass layer are visible in Figure 4 (a). In both types of the angle-dispersed laminates an overall fracture in the top carbon layers is observable just after the load drop which was then followed by further extension of the crack and delamination in the fibre direction, Figure 4 (b) and (c). For the Glass laminates, a conventional localized damage pattern (delamination) is observed after the load drop which then extended with increasing load, Figure 4 (d).

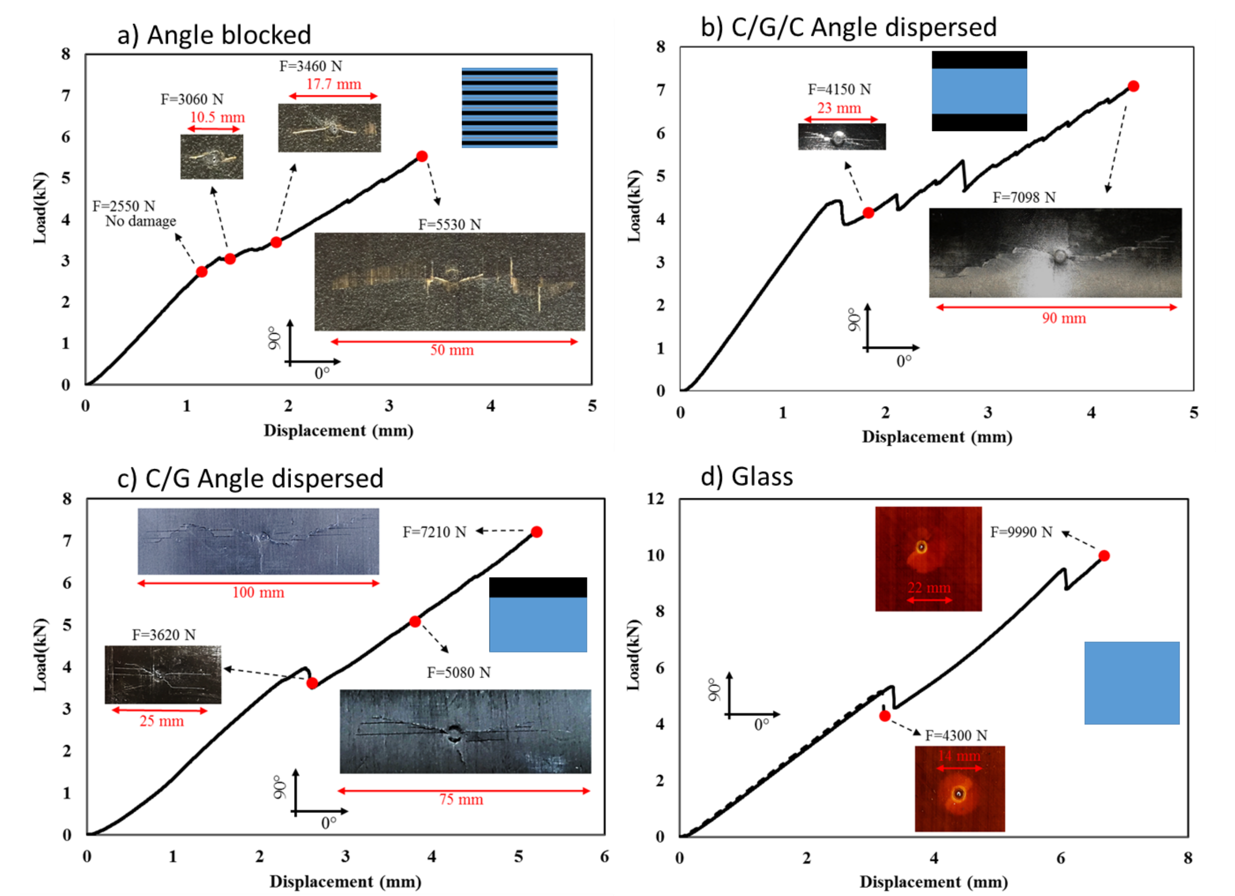

Figure 4. Representative global load–displacement curve and an image from the indented side for all the considered layups.

In order to have a better knowledge of the evolution of the damage, CT-scanning was used as a non-destructive technique to extract detailed information. Zinc-iodide penetrant was introduced to the plates by a small hole drilled at the centre of the local permanent indentation.

Images from the CT scan taken parallel to the short side of the specimens, at three different depths defined adjacent to the centre of the specimens, are illustrated in Figures 5 and 6. Comparing the damage extent and its location for all the hybrid configurations, a larger damage was observed under the indenter and the delaminations were smaller in the middle plies compared to the upper plies. This is in contrast to the Glass laminates (Figure 6 c and d) and the conventional QI laminates fabricated from Hexcel IM7/8552 [12] where the delaminations were larger in the middle plies compared to the upper plies. The unconventional behaviour of the hybrid laminates was due to the new introduced damage mechanisms, i.e. compressive fracture of the carbon fibre plies and delamination between the glass/carbon layers that had a lower load threshold for initiation compared with the load threshold for the initiation of delamination as suggested by the equation of Davies et al [13]. As a result, these damage mechanisms occurred earlier and/or at the same time as the conventional delaminations.

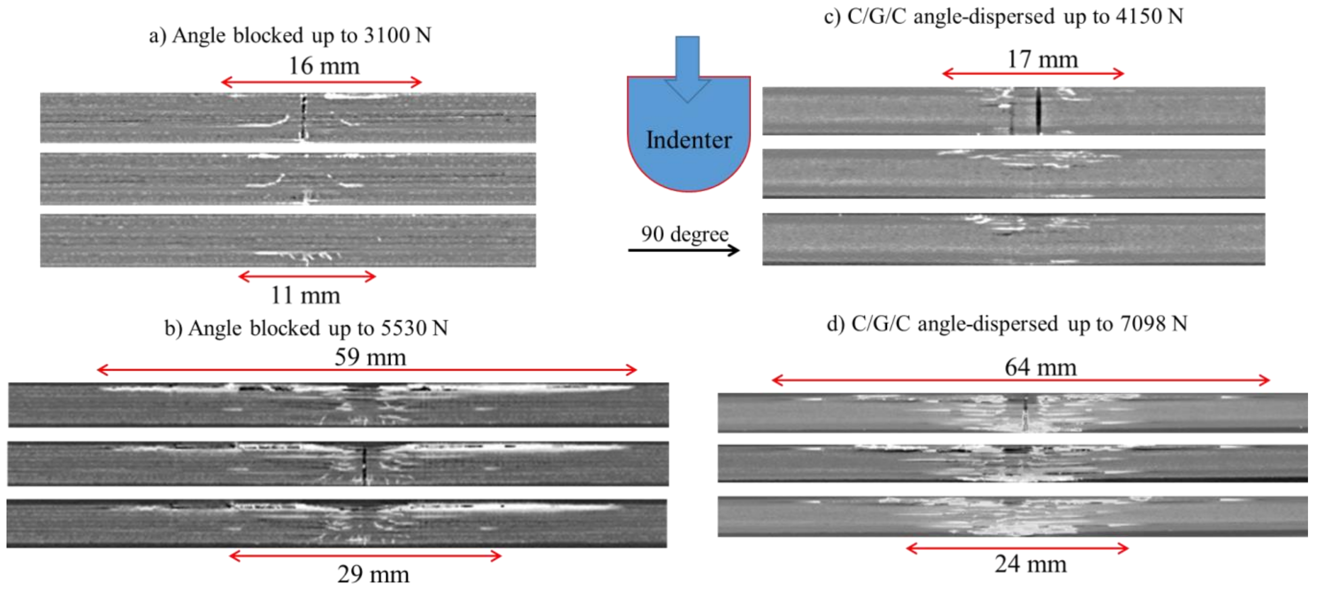

Figure 5. CT-Scan results for the angle blocked and C/G/C angle-dispersed laminates (view direction is parallel to the short side of the plate).

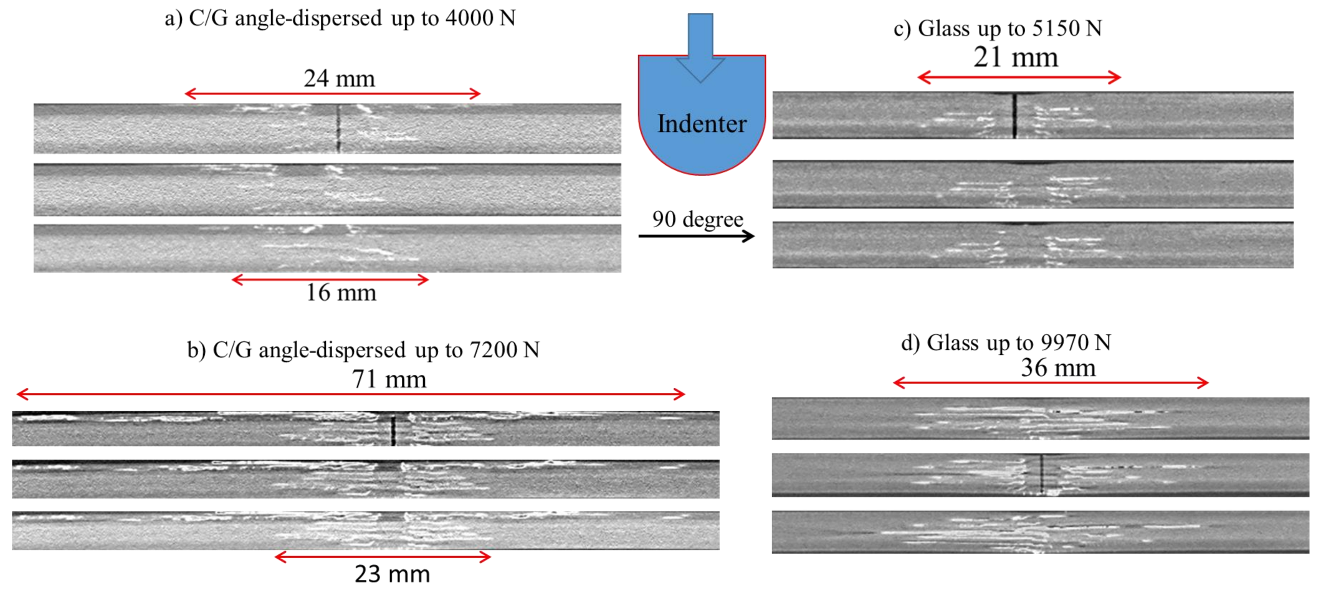

Figure 6. CT-Scan results for the C/G angle-dispersed and Glass laminates (view direction is parallel to the short side of the plate).

4. Conclusions

In this paper, thin ply carbon/glass hybrid laminates were designed and investigated experimentally with the aim to activate new types of damage mechanisms under indentation (quasi-static impact) that

are more gradual and easier to detect. Three different types of Carbon/glass hybrid laminates were used: a material dispersed angle blocked laminate (4.16 mm thick), a material blocked C/G/C angle-dispersed laminate and a material blocked C/G angle-dispersed laminate. The hybrids were compared with an all glass laminate. The mechanical and CT-scan results from the hybrid configurations showed different damage mechanisms from the glass laminates, i.e. carbon ply fibre fracture and delamination under the indenter, with larger deformations and less damage to the inner layers, largely due to low compressive strain of the carbon fibres. For the angle dispersed hybrid laminates, the first observable load drops in the global load–displacement curves were found to correspond to the upper carbon ply fibre fracture and delamination under the indenter, followed by delaminations in the inner layers. In the angle blocked laminate, instead, the damage started from the lower half of the laminate, initiated by matrix cracking and then followed by delamination. After matrix cracking and slight delamination in the lower half of the laminate, delamination in the upper layer under the indenter occurred. In the glass laminate, the damage started with significant delamination at different interfaces, larger in the middle plies compared to the other plies. In addition, in all the hybrids the damage was easily detectable from the impacted surface that can enable easier inspection procedures.
The results of this work can be used in future research activities to design high performance hybrid laminates to trigger specific damage mechanisms under low-velocity impact loading condition.

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