Threshold identification and damage characterization of GF/CF composites under low-velocity impact

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ABSTRACT

A significant factor affecting the widespread use of carbon fibre and glass fibre reinforced laminates is the detrimental effect of low-velocity impact damage during manufacture and while in service. Various damage mechanisms can be involved under low velocity impact of composite materials. For unidirectional composites the identification of the Delamination Threshold Load is performed considering the sudden drop in the force-time history curve under low velocity impact. For the woven composite the failure mechanisms seem to be different and the current literature is not providing any clear procedure regarding the identification of the delamination as well as the evolution of the failure mechanisms associated with it. In this paper, experimental data have been produced using glass and carbon fibres composites. The results have been analysed in terms of force-time and force-displacement history curves. Although delamination and other damages were clearly observed using C-scan, the analysis of the results is not showing any change in the trend of the curves that can be associated with the incipient nucleation of the delamination. A preliminary discussion regarding the nature of the mechanisms through which the delamination propagates in woven composite and a justification for the absence of a sudden variation of the stiffness is made.

KEYWORDS: *Low velocity impact, woven composite, delamination, Threshold identification,*

1 INTRODUCTION

Composite laminates are often subjected to low-velocity impacts while in-service and during manufacture. Barely visible impact damage (BVID) is a perception which often neglects the underlying damage introduced within the laminate. Impact energy can be absorbed at any point of the laminate, sometimes far from the impact site due to the inherent material characteristics and brittle nature of fibres and matrix. Although impacting at low energy, there can be various levels of laminate failure mechanisms during energy absorption, including, front face indentation, interlaminar delamination, back face splitting and fibre peeling [1]. The latter mechanisms are in some cases un-inspectable during service and often difficult to detect. These mechanisms are able to interact and coalesce, leading to considerable reductions in stiffness, strength and load-carrying capability of the structure [2]. To support the detection of non-visible damage as well as identify suitable parameters to be used during the design, the existence and validity of threshold load values have been investigated [3-7]. The threshold has been defined either in terms of energy or impact force. The delamination threshold load (DTL) [8-10] and the F_h (Hertzian Contact Force) [1, 6, 7] describe a specific damage condition, being the significant damage by delamination (DTL) and energy absorption other than by matrix cracking.
Identifying a significant damage event would be by means of detecting a significant load decrease in the force-displacement history before approaching F_{Peak}. A significant load drop would indicate a drastic loss of stiffness within the laminate indicating large magnitude matrix cracking and delamination. Evidence of difficulties in identifying the DTL and F_h have often led to composite designers to use F_{Peak} as a substitute, which careful consideration shows detrimental to the life of the component if future loading is considered.
For unidirectional (UD) materials, the identification of the DTL is performed using a method which is robust and reliable. However, for woven materials, it is not as clear as for the UD. Over the years different approaches have been reported in the literature in order to overcome the difficulties in identifying the DTL when dealing with woven. Yasunobu Hirai et al. [11] reported the distribution of different damage types due to low-velocity impact classifying 4 main regions, each of them with a different type of damage. The central region is mainly delamination, whilst the external areas mainly have interface deboning. The force-displacement curves used in the discussion of the results do not have any evident drop and the "incipient load" is detected as a variation in the slope of the force-displacement curves. In order to shed light on the existence and methods to identify the different type of damages, Schoeppner G.A. and Abrate S. [7] have analysed 500 tests results. The composite tested were only unidirectional and the samples tested had a lay-up ranging from 9 to 96 plies. The analysis of the load time history and the load displacement history highlighted that the variation in the slope of the force-displacement history curves, as well as the drop in the force-time history curves, can be correlated to the matrix cracking and the delamination respectively. The DTL values for the different configurations are identified using different approaches. M.S. Sohn et al. [12] carried out tests on prepreg carbon fibre with interlayer materials. The analysis of the force-time history curves is done considering the force value in correspondence of which the impact load drops due to the first failure. This value is defined as P_i and is called incipient load. In particular, it is shown that with increasing the impact energy the incipient load values increase almost linearly. Although the physical meaning of P_i is equivalent to the DTL it is depended on the impact energy. Lopes at al. [13] studied the effects of the stacking sequence on the low-velocity impact behaviour of composites. Evci and Gulgec [8] have studied the impact response of two different types of E-Glass fabrics. The results reported are referring to UD material as well as to woven samples. The Hertzian failure is identified as the first drop in force time history. The force-time history curves have a linear trend up to the first drop, after which the second linear path is followed up by the maximum load. The threshold load value for the woven is higher than that of the UD as well as the damaged area. In order to identify a single threshold parameter with which the damage assessment can be performed, energy levels are used and compared with the existing model. Quaresimin et al. [6] have reported energy absorption characteristics of different composite layup manufactured using carbon woven fabrics. The work is presenting a generalized approach that correlates the absorption energy with the impact intensity coefficient. Considerations regarding the delamination threshold load are drawn although the force-time history curves are not shown and the identification of the DTL value is carried out considering the first drop. The delamination threshold load and the associated energy are matrix-controlled. Zabala et al. [14] have studied the

effects of the impact velocity on the delamination of woven carbon-epoxy plates. The identification of the DTL is performed firstly considering three different curve patterns. With no damage induced, the curve looks like a sinusoidal shape. The presence of "oscillations" would point out the presence of delamination. Moreover, the damage is related to the energy levels. In particular, sub critical impact, below 1 J, does not induce any damage, the first delamination appear beyond 3 J and fibre fracture is the dominant failure mode above 10 J. Boumbimba et al. [15] reported the low-velocity impact response and damage of laminate composite glass fibre/epoxy. The effect of Nano strength on the impact behaviour is assessed in terms of type and evolution of damages as well as energy and force. The force-time history curves reported are different than the typical curves since there is not drop before the maximum load value. The noise observed in the force time history is used to identify the starting point for the delamination. Evci [3] is reporting the results of low-velocity impact tests performed on laminated composites and the effects of the thickness on the energy dissipation characteristics. The threshold is considered in this case as the first drop in the load time history curve. The Hertzian failure is the failure which initiated the delamination and increasing impact load causes further delamination growth. The threshold condition is defined as multiple stage condition where the Hertzian failure force represents the onset of delamination and the second damage threshold is responsible for the main damage in the form of fibre breakage and laminate failure. Giannopoulos et al [4] have recently reported some results of low-velocity impact and compression after impact test results on a woven fibre composite having a fire retardant, syntactic core, two phase epoxy matrix. The first peak point in the force-time history curve indicates damage initiation. In this study, even with filtered impact force versus time results a clear picture providing with the first load drop was not able to be produced. Instead, following Schoeppner and Abrate [7], the impact force versus deflection diagram was further processed by removing the high-frequency components from it, since the change in slope in the force-time history curve may be associated with the introduction of interplay transverse matrix cracking or localized indentation of the specimen. From the analysis of some of the selected papers dealing with DTL, it is evident that the experimental identification of the threshold condition at the onset of delamination in woven composites is controversial and a robust and reliable method has not yet been found. In the present paper the results of an experimental investigation carried out the testing glass and carbon woven composites are presented in order to highlight the issues encountered in the identification of the DTL through either the force-time or the force-displacement history curves. In particular, the delamination observed through the use of C-Scan and thermal imaging was correlated with the trend in the force-time history with the aim of finding clear evidence that could help in finding a robust and reliable method.

2 MATERIALS AND SPECIMEN COMPOSITIONS

The main objective of this paper is to discuss the issues encountered in the identification of the DTL in woven composites. In order to pursue the above aim, experimental results have been collected testing glass and carbon composite plates under low-velocity impact. 24 specimens for each type of fibre have been manufactured by autoclave. The carbon composite plates are composed by 11 balanced and symmetric laminae arranged in a layup that is $[0/90]_{11}$. In particular, E720/T300 is a multiple preg manufactured by TenCate. TenCate E720 is a toughened epoxy resin system for cures at 120°C (248°F), pre-impregnated into high-performance fibres such as carbon and glass. T300 is a woven carbon fibre ply, with a fabric density of 280 GSM, twilled in 2 x 2 weave style. Regarding the glass composite plates, each plate is composed by 11 Texipreg EE300/EF452 laminae arranged in a layup that is $[0_3\ 90_3]_s$. EF452 is a fire retardant, self-adhesive prepreg system which contains no halogenated flame retardants. It is suitable for sandwich panels or solid laminates. EE300 is a plain weave glass fibre ply, with a fabric density of 300 GSM. The final range of thickness values for the carbon and glass composite plates manufactured with the materials above discussed is 4.6 ± 0.06 mm and 3.42 ± 0.02 mm for the carbon and glass composite respectively. The mechanical properties of the two systems are reported in Tables 1 and 2. For each type of fibres, the 24 plates were cut out from a single panel. Low-velocity impact tests have been performed according to the ASTM D7136/D7136M [16]. The energy is controlled by the drop height. The total mass of the striker was 2.464 kg and the diameter of the projectile was 25 mm. The specimens were 100x150mm^2 supported on a rectangular plate and hold with a mechanical clamping apparatus. Time histories of the impact force, velocity, acceleration, displacement were measured. Impact tests have been performed at six impact energy levels (5J ÷ 30J). Prior to impact tests, C-Scan and Infrared analysis have been performed before testing in order to assess that no damages or delamination were present. The damage produced by the impact has been assessed after impact by means of the same two non-destructive methods.

Table 1 Mechanical Properties of Carbon Fibre.

Property	Condition	Method	Results	
Tensile Strength	RTD	EN ISO 524-4	621	MPa
Tensile Modulus	RTD	EN ISO 524-4	58.4	GPa
Poisson's Ratio	0.05			
Compression Strength	RTD	EN 2850	488	MPa
Compression Modulus	RTD	EN 2850	70	GPa
In-Plane Shear Strength	RTD	EN ISO 14129	99	MPa
In-Plane Shear Modulus	RTD	EN ISO 14129	3.5	GPa
Flexural Strength	RTD	EN ISO 14125	801	MPa
Flexural Modulus	RTD	EN ISO 14125	52.4	GPa
ILSS	RTD	EN ISO 14130	62.1	MPa

Table 2 - Mechanical Properties of Glass Fibre.

Cured Material Properties (*)	Unit	Typical Value	Standard Method
Cured Ply Thickness	mm	0.22	
Tensile Strength	MPa	450	ASTM D 3039
Tensile Modulus	GPa	22	ASTM D 3039
Flexural Strength	MPa	480	ASTM D 790
Flexural Modulus	GPa	24	ASTM D 790
Compressive Strength	MPa	N/A	Modified ASTM D695 (SACMA SRM 1-88)
I.L.S.S.	MPa	35	ASTM D 2344
(*) The tests were carried out @ 23°C and 60% R.H. on specimens cured in std conditions (dwell @150° for 1 hour in hot plate press. External pressure applied: 3 bar). The tests were performed along the warp direction.			

3 IMPACT TESTS

The low-velocity impact testing was carried out in accordance with ASTM/D7136M−15 [16] for all samples using an Imatek drop weight tower (Fig. 1) from variable heights to provide an impact energy equivalent of 5J, 7.5J, 10J, 15J, 20J & 30J. The Load cell used was a calibrated Kistler 9331B in-line load cell connected by a gold plated coaxial cable attached to a Kistler analyser and Imatek C3008 signal amplifier. The Software used to record the raw data was developed by Imatek Version:3.3.24. A secondary strike arrestor being built into the Imatek drop tower was also employed and was triggered by a laser guided gate trigger and pneumatic actuator pressure of 70 psig.

Figure 1 - Drop tower and details of the acquisition system used for the testing.

4 IMPACT TESTS RESULTS AND DISCUSSION

The main objective of this paper is to assess the possibility of identifying the DTL in woven composite materials through the force-time history curve. Tests have been performed on glass and carbon composite plates in order to collect the experimental data to be analysed. The results are presented gathering together glass and carbon composite plate. Ultrasound scanning techniques using a Sonatest Veo 16:64 with a 45° probe in a water tank have been used in this paper for the identification of the post-impact damage area. The identification of the pine tree fracture pattern [17] is visible in the B-scan at the impact site location. The calibration method used to identify this internal damage was by accurately measuring the indentation size of each impact site, and use this to identify the colour contour scaling. It is worth noting that the use of a 45° probe for ultrasonic scanning is not ideal for scanning thick laminates however for this purpose, the results have been verified by a thermographic method on a number of samples for comparison. The damaged area has been observed to be circular on the surface however it is worth noting that elliptical measurements have also been recorded. Considering the impactor was a hemispherical shape with 25mm diameter, the damage shape would indeed be conical [18]. Higher energies of 30J would appear to give an elongated conical shape with an elliptical cross. The B-scan measurements have therefore been taken to the semi-major axis of the ellipse (x=150mm direction) for a conservative comparison (Fig. 2 and 3).

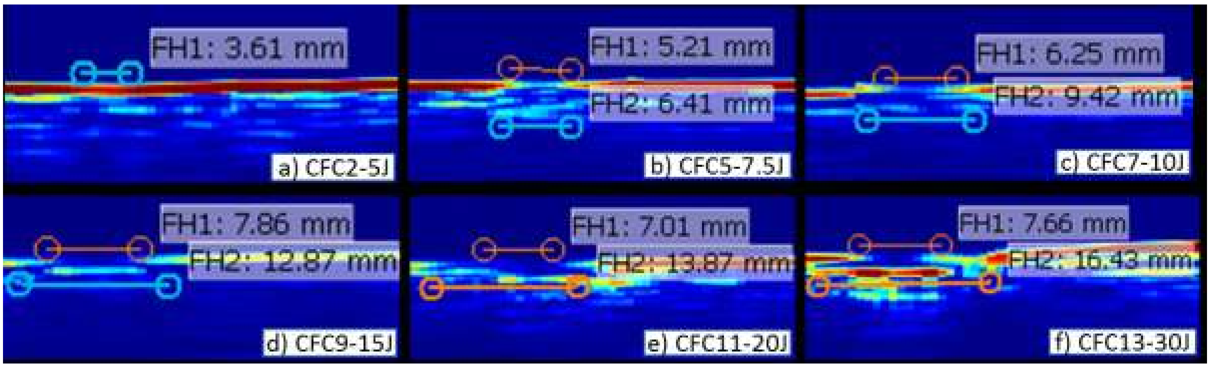

Figure 2 - Damage characterisation B-Scans – Carbon Fibre - 5J to 30J (a-f).

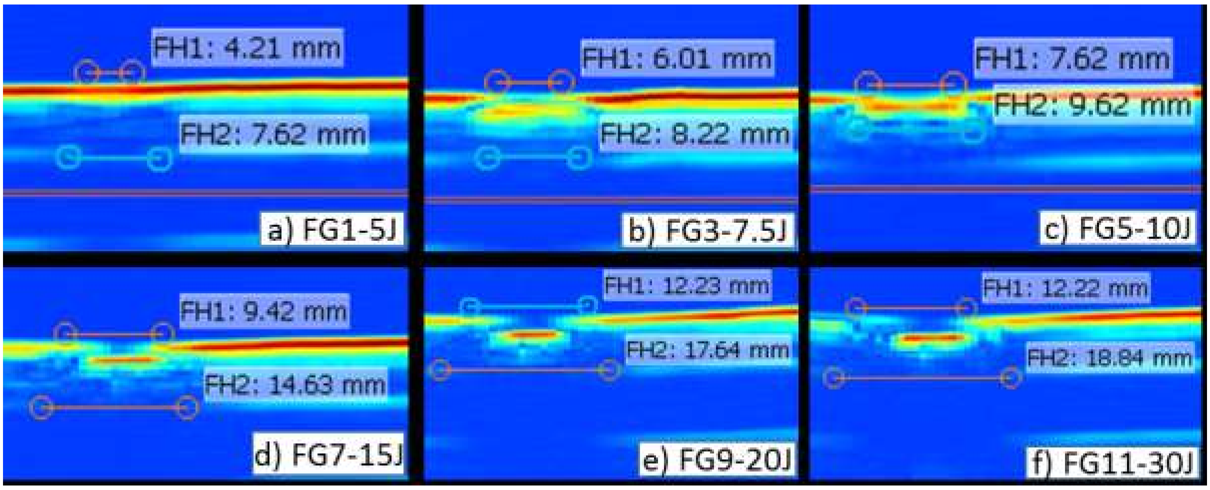

Figure 3 - Damage characterization B-Scans – Glass Fibre - 5J to 30J (a-f).

The force-time history curves are shown for carbon and glass composite plates in Fig. 4. As reported by other authors [2, 19] the curves exhibit oscillations that are due to the resonance effects produced in the sample by the impact load. This phenomenon has been observed in UD and woven materials. As discussed by [4] even with filtered impact force time history is not possible to analyse the curve in order to identify the peak force and the DTL. It is also possible to identify an initial region where an initial drop can be observed for the lower energy impact levels. However, increasing the impact energy the first drop for the carbon fibres disappears, which means that it cannot be linked to the DTL since it should be evident at any higher energy level. For the glass fibres, an increase in the impact energy amplifies the oscillations in the force-time history curves, which can be explained with the excitation of the vibration modes of the samples.

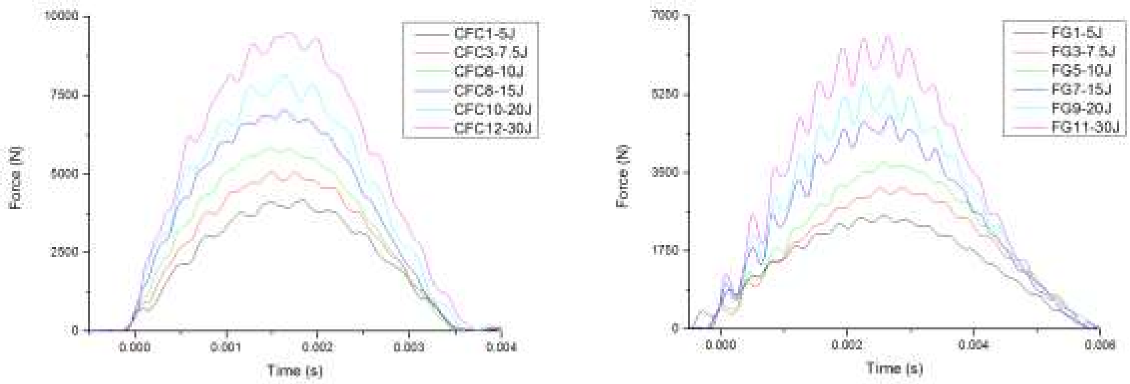

Figure 4 - Force time history for Carbon (left) and Glass (right) fibres tested.

The use of the force-time history curves is controversial since as reported by Abrate [2] if the effective mass of the plate is taken into account in the solution of the energy balance problem, strong oscillations in the contact force history are observed. This oscillation has the same frequencies as the mode shape of the impacted plate. For the samples investigated in this paper, natural frequencies have been derived for the carbon and glass composites and by means of the FFT, the force-time history curves have been filtered. In Fig. 5 two examples, one of the carbon and one for the glass composite, are shown. In both cases the signal has been filtered with the 4th mode (m=2 and n=2), since it the mode shape closer to the deformed configuration for the centre impact.

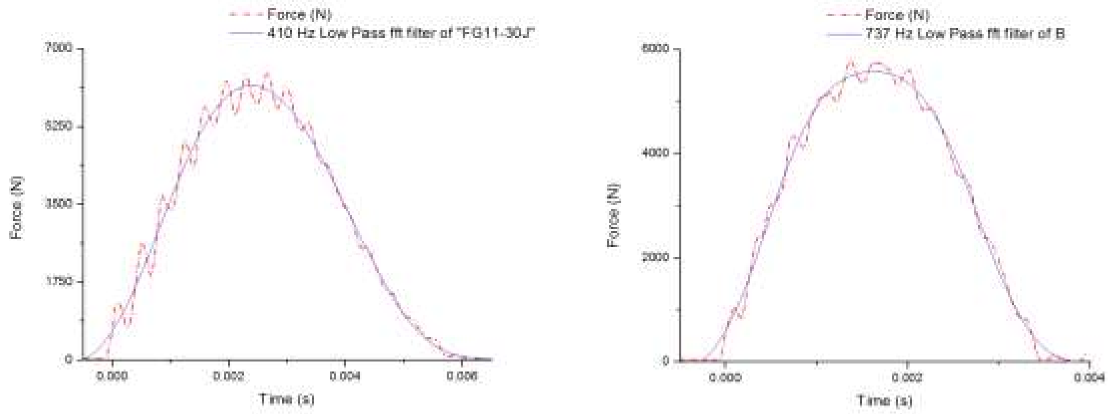

Figure 5 - Comparison between the as acquired and low pass filtered curves.

The filtered curves are smooth and it is not present any drop which could be related to the onset of the damage in the composite plate. It can be argued that the low pass filter adopted in this case has a cut-off frequency which is too low cutting away any sign of drop linked to the threshold. However, if the drop corresponding to the DTL is comparable to the noise produced by the sample undergoing resonance, it is not possible to clearly identify which drop is the DTL and which one is due to the samples vibrating.
As suggested by Abrate [2], the assessment of the damage after impact in the composite can also be done considering the slope of the force-displacement curve. This is based on the assumption that the presence of damage has the direct effect of changing the stiffness. The force-displacement history curves for the carbon (left) and the glass (right) fibre are reported in Fig. 6.

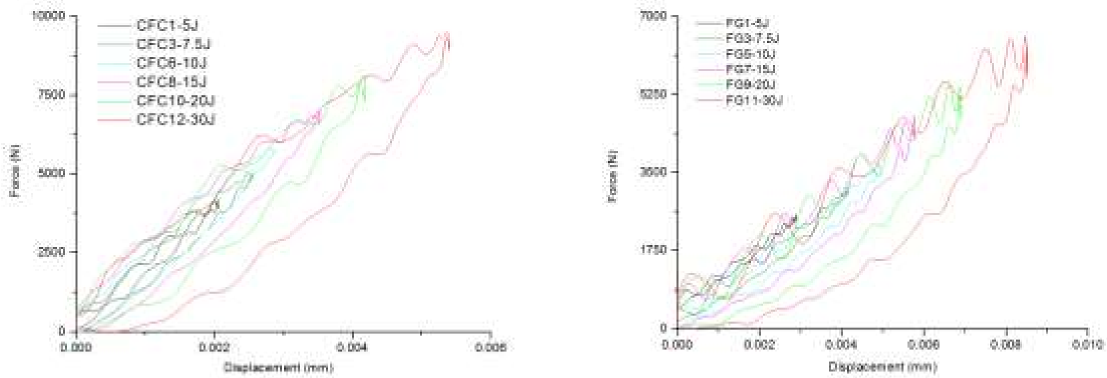

Figure 6 - Force displacement curves for carbon fibres (left) and glass fibres (right).

It can be seen that for the carbon composite there is a variation in slope corresponding to a variation in stiffness at high impact energy. The same behaviour is not present in the glass composite, although the investigation after the test has highlighted delamination and damage. The analysis performed for the carbon composite allowed to identify the force value in correspondence of the change in slope. Although it is a variation in stiffness and as reported by [4] it represents a variation in stiffness along the transversal direction, it can be due to a combination of interlaminar and intralaminar damages, fibre fractures as well as delamination. The analysis of the above graphs highlights two main limitations. On one hand, the threshold cannot be identified for glass composite, whilst on the other hand, it seems possible for carbon composite for higher energy. For this latter, damages without delamination are observed under 5 J impact energy, but there is not evident variation in the slope. Moreover, the value of the force in correspondence of which the slope change under 7.5 J is lower than the value observed at the higher energy levels. As proven by other authors [1, 6, 20] the DTL is constant with impact energy, which means that either the values reported is measuring overall effects and it is not only related to the delamination or the DTL is not constant with the impact energy. Moreover, as reported by Zabala [14], the delamination is usually the dominant failure mechanism at lower impact energy, whilst at higher energy level matrix cracking and fibre fracture play the major role. The above observation seems to encourage the authors to consider the variation in slope more as a measure of the overall damage rather than the value at which the delamination starts to propagate.

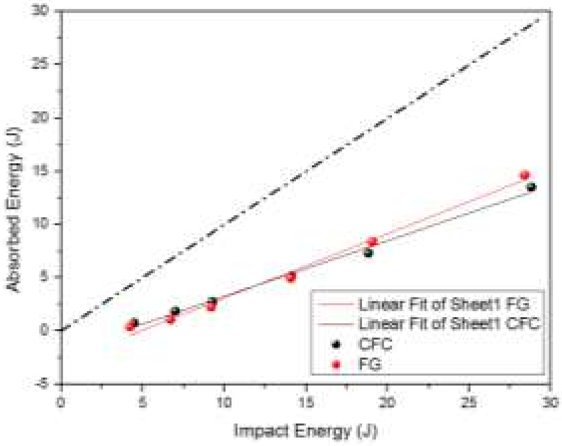

Figure 7 - Energy profile with the equal energy curve.

The absorbed energy has been computed as the area under the force-displacement curve. In Fig. 7 the energy profile diagram is shown together with the equal energy curve. All data points are above the equal curve since the penetration energy was never reached [21]. In terms of comparison between the glass and carbon fibres shows that at lower impact energy the carbon composite plates absorb more energy compared to the glass composite. Increasing the impact energy glass fibres absorb more energy. The absorbed energy is the results of several damages produced in different ways. On the different mechanisms, the matrix and the fibres play a different role. According to [22], the fibres with higher strain at failure perform better at higher impact energy. Moreover, the matrix, which plays a major role in the interlaminar damages since the damage initiation is matrix-dominant [23], used for the carbon and glass composite plates is different. Yang et al. [10] have used the value of the peak force as the force to initiate damage. It is also observed that the rapid drop in the impact force has not been observed. The onset of damage is detected visually by inspecting the samples after impact. According to Belingardi and Vadori [24], the value of the peak force increases with the impact energy. The use of the maximum peak as a threshold for the delamination is in contrast with the definition of DTL since it is a function of the impact energy and cannot be considered as material properties.

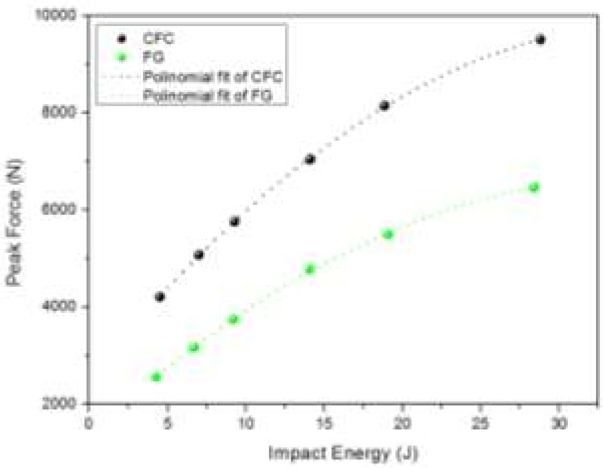

Figure 8 - Peak force as a function of the impact energy for the carbon fibres (black) and glass fibres (green).

As already reported by [25], low velocity impact tests performed on woven composites didn't show neither load drop nor slope changes until the load reached the maximum. The first failure event can be represented by the incipient load drop or the sudden change in slope, depending on the type of woven. However, the major role is played by the matrix since the higher its ductility the higher the possibility of initial damage being a load drop. For the particular composite investigated in this paper the combination of matrix ductility, the strength of the fibre-matrix bonding and the interlaminar fracture toughness (G_{IIC}) are responsible for the shape of the force-time history curve in which load drop is not shown. The initial damage should occur at the maximum load P_m. However, the mechanisms by which the damage should growth is not fully explained. A possible explanation could be that the damage is induced while loading and the growth of the delamination is sustained by the increasing load. The stiffness of the samples would not be affected due to the delamination not reaching the critical toughness, which implies that the "crack" would not become unstable and the force-time history would not have any drop. The above hypothesis requires further experimental tests in order to assess the failure mechanisms.

5 CONCLUSION

The DTL for UD material is the load value at the first drop occurring in the force-time history curve under low-velocity impact. In this paper, the possibility of adopting the same approach for woven composites has been discussed. The damage detection through the change in slope of the force displacement curve was also discussed. It was observed that although the damage is identified through C-scan there is no change in the slope for the woven composites, as it is usually observed in UD materials. This different behaviour has been justified with a difference in the mechanisms involved in the nucleation and propagation of the delamination in the case of woven composite. For the type of layup and material investigated in this paper, the interlaminar damage induced by the impact is growing progressively without causing any sudden change of the stiffness. The combination of matrix ductility, strength of the fibre-matrix bonding and the interlaminar fracture toughness (G_{IIC}) are responsible for the shape of the force-time history curve in which a sudden load drop is not shown. The preliminary results presented in this paper represent a first step in the understanding of the delamination under low-velocity impact. More tests and analysis are required in order to validate the approach here presented.

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