Low Velocity Impact Response of Composite Panels for Aeronautical Applications

M. Grasso, F. Penta, G.P. Pucillo, F. Ricci, V. Rosiello

***Abstract* — The present experimental work analyses the impact behaviour of thermosetting composite materials for aeronautic applications. The main goal of the experimental activity was to identify the energy level in correspondence of which penetration occurs. The initial values of the impact energy were estimated according to analytical correlations found in literature. Tests were performed on three types of composite panels: carbon fibre laminated panels, fibreglass laminated panels and hybrid panels. The technology of lamina is that of prepeg fabric with twill sequence and fibres weaving at 0°-90° and ± 45°. The fixture used for tests is a Charpy impact test machine, which was conveniently equipped to evaluate the angular variation and the acceleration of the impacting mass. Preliminarily, non-destructive ultrasonic controls were performed to check that the specimens were not damaged before impacts tests. The interesting results of the tests were identification of the energy absorbed and the impact force for each specimen. Moreover, for each energy and force level, it was possible to associate a different fracture state. Comparisons among the results obtained for specimens made up of just one type of reinforcement (glass or carbon) and the results obtained with hybrid specimens were performed.**

***Index Terms*— hybrid composite, low-velocity impact, delamination, non-destructive testing, polymer-matrix composites.**

I. INTRODUCTION

Among the problems regarding the structural behaviour of composite materials the low-velocity impacts response represents one of the most significant. These impacts basically produce three types of damages: delamination, matrix cracking and indentation. Literature regarding the study of composite materials behaviour for low-velocity impacts is wide and it is possible to find several analytical formulations which may give different results and which might also differ quite a lot from experimental results. Another gap in the literature dealing with low-velocity impacts is represented by limited information and studies regarding hybrid configurations.

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Aktas et al. [1 - 2] studied the impact response of glass composite laminates with epoxy resin, considering the energy profile associated to the load-deflection curves. An alternative method is presented which is based on the analysis of the variation of the exceeding energy (E_e) in comparison with the impact energy (E_i), so that to determine the threshold value of the penetration Energy (P_n).
C. Atas et al. [4] carried out an experimental activity on the repeated impact behaviour of E-Glass fabric composite material. The perforation energy in function of laminate thickness together with the absorbed energy in function of the number of repeated impacts was derived. The ratio of the perforation energy over the impact energy associated with a single impact is a linear function of the laminate thickness. The aforementioned correlation is useful for the determination of the number of impacts (N_r) needed to fully penetrate the thickness of a given specimen. F. Aymerich et al. [5] investigated the influence of the weaving on the damage produced in thin laminates reinforced with carbon fibres under low velocity impacts. Test results shown that the response of weaving and unweaving panels was very similar in terms of impact force and absorbed energy. However, the delamination extent for weaving panels was smaller than that produced in unweaving panel. Caprino et al. [6] carried out static tests on carbon fibre circular plates having different thicknesses. The specimens were loaded in the center using a spherical head. The static load was increased up to the total perforation of the specimen using different head diameters. The experimental findings were compared to data achieved during previous researches on low-velocity impact in order to validate the existing models and acquire useful data for the derivation of empirical laws able to identify the indentation. Empirical laws for the identification of the indentation associated with a given value of the impact energy were also found in literature [7]. The experimental activity reported in [7] was carried out testing specimens with different thickness made of fibreglass. The absorbed energy and the damage produced in correspondence of different values of the impact energy were reported. G. Caprino and V. Lopresto [8] studied the estimation of the penetration energy for thermosetting composites subject to low-velocity impacts. On the basis of these studies they suggested a prevision formula of the Up penetration energy for composites in CFRP carbon fiber. Energy is mainly function of some characteristic parameters such as: panel thickness, the weight percentage of V_f fibres, the diameter of the D_t impactor and two experimental constants (K, α). A similar study had already been

performed by the same authors for GFRP fibreglass composites [9 - 10].

W. A. de Morais et al. [11 - 12] studied the effect of thickness variation on the resistance of carbon, glass and aramid composites fabric under repeated impacts at low velocity. The authors have developed a quadratic equation with correlation coefficients related to the degree of freedom of the composite, to the variation ratio of the properties of the composite due to impact events, and to the change of the damage mechanism. The achieved results show that under a certain energy level, the cross section is the most significant variable affecting the impact resistance. When the energy level of the impact increases, fibre characteristics begin to be significant. Further investigations were carried out in order to understand the effects produced by the stacking sequence and the panel thickness on the absorbed energy, type of damage and impact force [13]. The common finding is that up to certain values of the panel thickness the stacking sequence becomes significant since it affects the evolution of the impact phenomenon. Sayer et al. [14] studied the impact behaviour of hybrid composite plates until a complete penetration. Tests were performed on two main configurations of hybrid composite laminates (glass-carbon and carbon-glass, in epoxy resin). The analysis and comparison of the load-deflection curves and the damage mechanisms, for different impact energies, showed that the perforation limit of hybrids with upper carbon fibres (impact side) shows a 30% higher perforation limit in comparison with hybrids with upper fibreglass. S. Xiao et al [15] on the basis of the shear strength of the undamaged panel, which is based on the Eshlby micromechanical approach, developed an analytical model able to predict the damage induced by low-velocity impacts.

II. TEST PANELS

The list of panels used for the experimental campaign which is being analyzed is reported below.

- Panels made up of carbon fibre;
- Panels made up of fiberglass;
- Panels with hybrid composition;

Panels made up of carbon fiber and those made up of fiberglass are subdivided in woven fibre panels at 0°-90° and woven at a ± 45°. The hybrid panels are made up of carbon fiber and fiberglass according to the following stacking sequence:

$$[(\mathrm{G0}) + (\mathrm{C90/C0}) + (\mathrm{G90/G0/\overline{G90}})]_S$$

Layup:

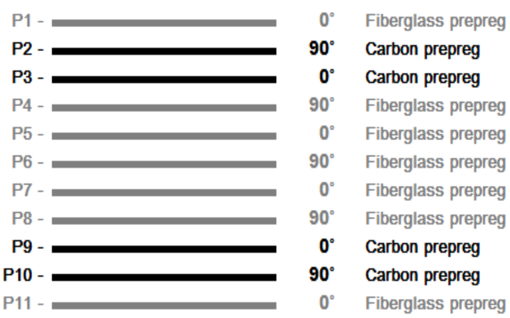

Fig. 1. Stratification of the hybrid panel.

All panels are balanced and symmetrical and are made up of eleven laminas. The laminas used to build the panels have the following commercial reference:

- fiberglass-reinforced fabric:
  SAATI – TEXIPREG EE300 EF452
- carbon fibre-reinforced fabric:
  AMBER COMPOSITES – MULTIPREPREG
  E720 T300 (3K) 280 GSM 5HS 55% V_f

The above described test panels were made through autoclave (vacuum bag). Specimens extrapolated from each panel have the size 105 x 160 mm^2, such sizes were chosen according to the impact opening window on the specimens housing plate.

III. IMPACT TESTING

The testing machines usually adopted for this type of experimental activities are the modified Charpy impact test and the drop tower. By counter rotating the pendulum hammer it is possible to install a cylindrical block having different sizes and shapes, usually a hemispherical head. Plates are located, through threaded bolts for specimens housing, on the vertical surfaces of the supporting bases of the pendulum, at the height of the notched plane of the hammer (0° angle). The electromagnetic brake limits the phenomenon of bouncing. In addition, drop tower uses a couple of steel columns which drive the falling crossbeam. The drop masses have different geometries and weight according to the different energy level and damage required for the test. The tower can be equipped with an anti-bouncing system to allow the development of single impact or bouncing tests. For the present experimental study the modified Charpy impact test machine with digital indicator and manual lifting was used.

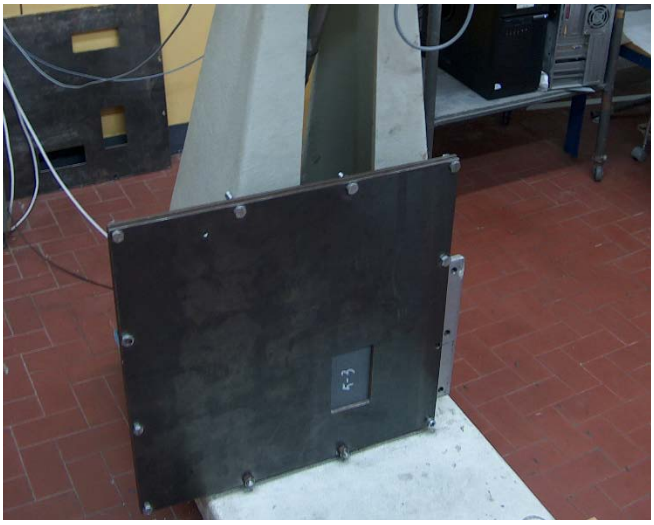

Fig. 2. Modified Charpy impact test machine.

Before each impact test it was decided to perform non-destructive tests on specimens, in this way it was possible to check the integrity of each specimen. The OmniScan SX, based on the phased array technique, was used to perform the ultrasonic controls. Ultrasound scans did not show the presence of serious inner imperfections, connected to the production process or to damages due to possible external hits. The only specimens showing some defects are those in both glass and carbon with woven fibres at 45°. In particular, it can be noted that in some areas there are spots which follow the contour of some fibres, these colours indicate that in that area the resin content is lower. As this dryness affects the more external laminas, delamination can propagate according to its traditional scheme (pine tree).

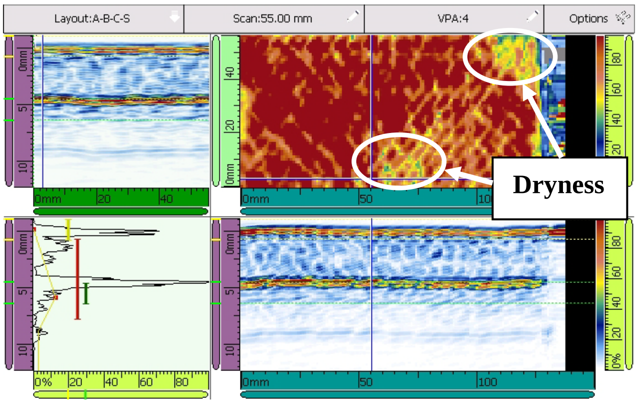

Fig. 3. Example of ultrasound scans with the phased array probe.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

The outputs acquired during the tests are angular variation and acceleration. The angular variation is obtained by acquiring the signal of an angular potentiometer installed on the axis of rotation of the pendulum. The acceleration is derived from a uniaxial accelerometer (BK DeltaTron type 4395) installed in line on the axis of the impactor having an acceleration range ±7500 ms^{-2}. From the acceleration values it was possible to determine the values of the impact force [2].

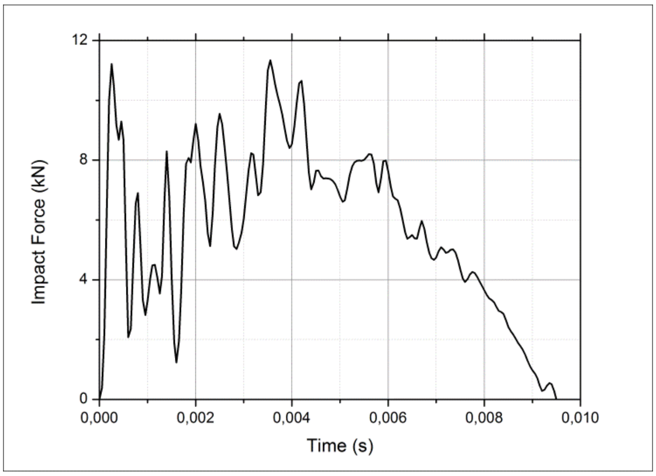

Fig. 4. Example of an impact force diagram.

A. *Energy Levels*

Impact energy levels adopted in the experimental activities here discussed were determined from correlations available in literature and discussed in the following [9 - 11 - 14].

For fibreglass specimens, both for those with woven fibres at 0°- 90° (specimens code _0_) than for those with woven at ± 45° (specimens code _45_), a very high absorbed energy was detected with a limited elastic energy associated with the impactor rebound [1]. These specimens have the highest absorption ratio (U/U_a) over the whole experimental campaign (about 94 - 95 %).

Carbon-fibre specimens have an absorbed energy which is definitely lower than fibreglass counterpart, with a consequent higher elastic energy. This laminated has the lower percentage of absorbed energy among all tested specimens (between 47 and 52 %) [7 - 13].

Hybrid specimens show a high value of absorbed energy for high levels of potential energy (about 93 %), and a low level of absorbed energy for low levels of potential energy (about 41%) [14]. From the latter results, it is clear that for low levels of impact energy the hybrid laminated tend to behave, from energy pointy of view, as a carbon-only laminated, while for high energy levels absorption can be compared to a glass specimen.

TABLE I
ENERGY LEVELS OF IMPACT TESTS

Type	Specimen Code	E_p [J]	E_a [J]	E_e [J]	U / U_a
Glass	*F.G._0°_1*	*85,32*	*80,48*	*4,84*	*0,94*
	F.G._0°_2	*85,32*	*80,41*	*4,91*	*0,94*
	F.G._0°_3	*55,47*	*52,39*	*3,08*	*0,94*
	F.G._0°_4	*30,5*	*16,96*	*13,54*	*0,56*
	F.G._45°_1	*55,47*	*52,75*	*2,72*	*0,95*
	F.G._45°_2	*55,47*	*52,06*	*3,41*	*0,94*
	F.G._45°_3	*55,47*	*51,2*	*4,27*	*0,92*
Carbon	*C.F.C._0°_1*	*87,77*	*45,67*	*42,1*	*0,52*
	C.F.C._0°_2	*87,77*	*44,71*	*43,06*	*0,51*
	C.F.C._0°_3	*105,46*	*54,91*	*50,56*	*0,52*
	C.F.C._45°_1	*71,03*	*33,14*	*37,89*	*0,47*
	C.F.C._45°_2	*71,03*	*34,27*	*36,76*	*0,48*
	C.F.C._45°_3	*71,03*	*34,53*	*36,49*	*0,49*
Hybrid	*H._0°_1*	*90,25*	*84,58*	*5,67*	*0,93*
	H._0°_2	*30,5*	*12,54*	*17,96*	*0,41*
	H._0°_3	*90,25*	*83,75*	*6,5*	*0,93*
	H._0°_4	*80,47*	*80,48*	*5,51*	*0,93*

B. *Energy Profile Method*

The analysis of energy profiles gives information on the threshold value of the penetration energy for different materials.

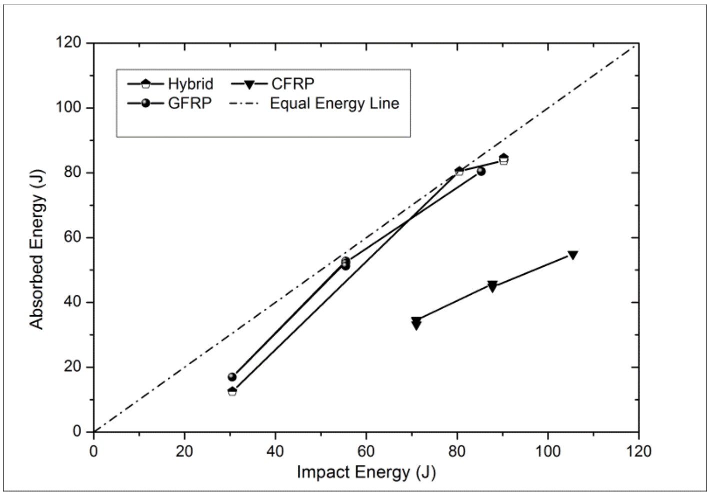

Fig. 5. Energy profile diagrams (EPM).

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For carbon-fibre specimens (CFRP) the experimental values of absorbed energy, for all the types of reinforcement, shows that in no case it was possible to get close to the penetration value placed on the balance energy line, where Ep = Ea. In particular it can be noted that the elastic energy, given by the difference between the absorbed energy and the penetration energy, for this type of material, is the highest observed in the whole campaign.

In the case of fibreglass laminates (GRFP) the absorbed energy is extremely higher and close to the penetration value, in comparison with the counterpart specimen in carbon fibre. In this way elastic energy thus take very low levels.

Hybrid laminates have a mixed behaviour in relation to the impact energy. For high values of the impact energy, the absorbed energy increases but, unlike fibreglass laminates, they present a higher penetration limit. For low levels of the impact energy, the absorbed energy is lower; in this case hybrid laminates show a behaviour which is similar to carbon-fibre specimens, with a higher elastic energy in respect to the absorbed one [14].

C. Load vs Deflection Curves

The load-deflection diagram (F-s) is made up of a rising part, which is function of the stiffness, whose maximum value represents the maximum strength. The descending part represents the unloading phase. This latter part corresponds to the bouncing and it is function of the absorbed energy.

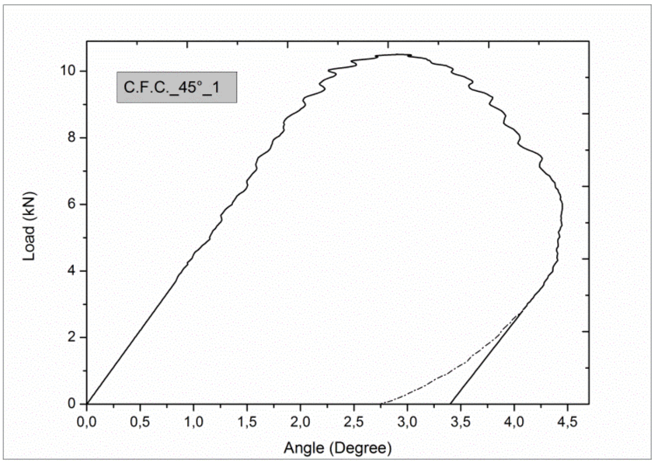

Fig. 6. Example of a load vs deflection curve for a carbon fibre specimen.

The load-deflection diagram acquired during an impact test on a carbon fibre specimen is reported in fig. 6. The main damage is the indentation induced by the matrix cracking. These phenomena are produced during the loading phase up to the maximum force value. During the descending part of the loading curve, the splitting damage, which corresponds to a sudden reduction of the impact load, takes place followed by the rebound of the impactor [8]. The zeroing of the load is reached in correspondence of a displacement which represents the indentation. The visual inspection of the specimen highlight the presence of intralaminari cracking on the impacted surface whilst on the back-face fibre-fracture occurs.

The load-deflection diagram acquired during an impact test on fibreglass specimen is reported in Fig. 7. Even if the impact energy was lower than that used for the carbon fibre specimens, the absorbed energy is greater than that registered during the previous tests. The greater absorbed energy in respect to the carbon fibre one is related to the brittle behaviour associated with the fibreglass. The stiffness of panels made of this kind of reinforcement is lower than that of similar panel made of carbon fibre [7].

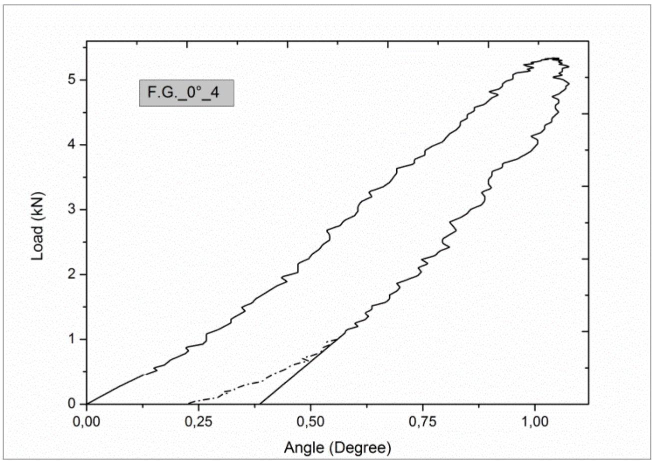

Fig. 7. Example of a load vs deflection curve for a fibreglass diagram.

Up to the maximum value of the impact force bending of the whole panel and indentation produce fibre fracture in correspondence of the impactor. Since in this case the penetration is greater than the previous tests, limited rebound occurs and the residual displacement in correspondence of the zeroing of the load is greater too. Pull-out on the surface opposite to the impact one occurs.

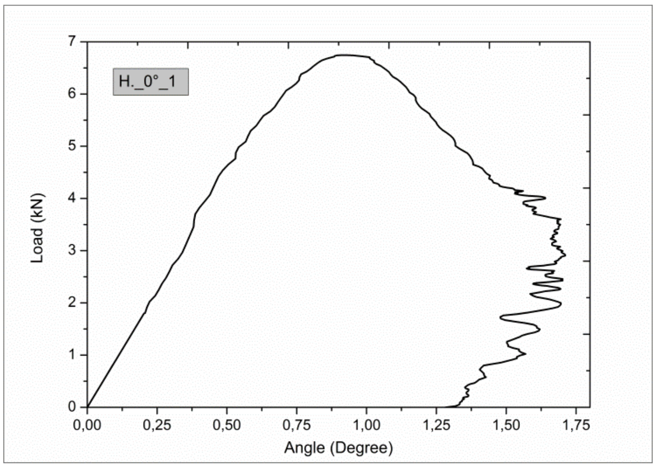

Fig. 8. Example of a load vs deflection curve for a hybrid specimen.

A load deflection curve representative of the impact response of hybrid specimens is reported in Fig. 8. The high values of the impact energy (90,25 J) produced perforation in all tested specimens. During the loading phase all fibres were damaged by the cracking propagating through the thickness, until the maximum load value is reached. The damage produced in this type of specimen is similar to the fibreglass plates whilst, as it can be seen in Fig. 5, the impact energy needed to perforate the panel is higher in accordance with [14]. Moreover, intralaminari cracking occurred on the impact surface whilst fibre fracture takes places on the back-side.

D. Damages and Features

The results obtained in terms of contact force and absorbed energy together with the type and extension of the damage, may be used to compare the behaviour of single type fibre laminate with the hybrid ones. In this way, it is possible to understand the evolution of the damage resulting from the impact. In particular, in fibreglass laminate it can be observed that while the impact energy rises the extension of delamination reduces with consequent indentation increase. Moreover, a much extended fibre fracture on the surface which is opposite to the impact surface was observed when complete penetration is reached.

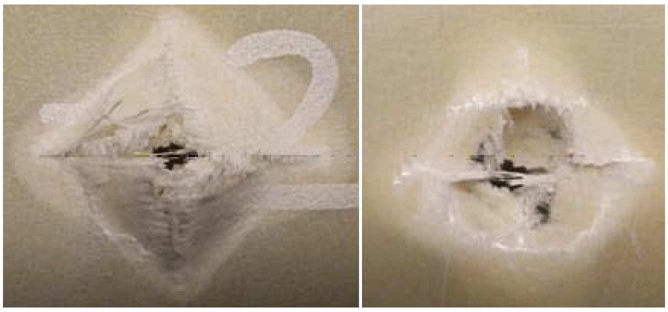

Fig. 9. Damages produced on a fiberglass specimen - back-side (left) front side (right).

In the case of carbon fibre laminate, the absorbed energy is lower than fibreglass laminate, with an increase of the elastic component and a consequent reduction of indentation extent. The considered energy levels did not allow to reach the complete penetration for carbon fibre laminate. Within the range of impact energies here considered, by comparing the damage induced in all tested carbon specimens a significant delamination on the back side was observed, which turns into a significant splitting for energy levels higher than 90 J.

In the hybrid laminates the impact response highlights the concurred presence of the two contributions, with values of absorbed energy which may be compared to the ones of glassier laminates and values of the impact force which may be compared to the ones of carbon fibre laminates.

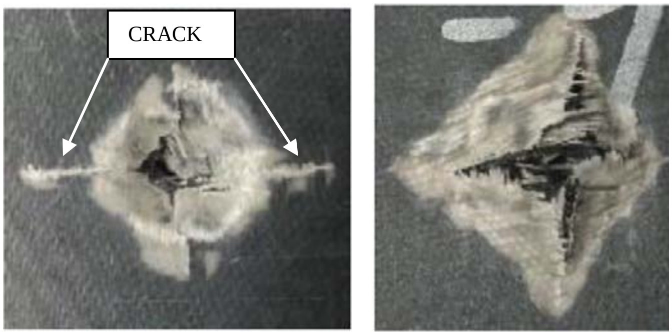

Fig. 10. Damages induced on a hybrid specimen - front side (left) back side(right).

For increasing values of the impact energy it was possible to observe the damage evolution, unlikely the case of fibreglass panels, where the penetration limit is definitely lower.

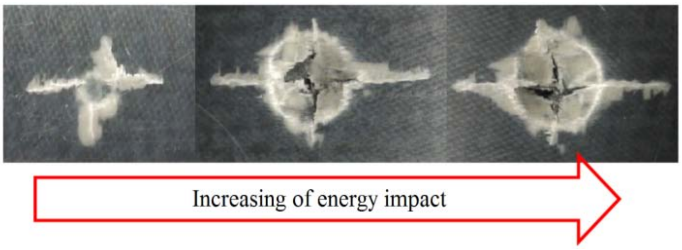

Fig. 11. Damages induced at the increasing of the potential energy.

Moreover, the presence of carbon fibres also effects the impact duration, which is comparable to the duration of the impact on carbon fibre panels.

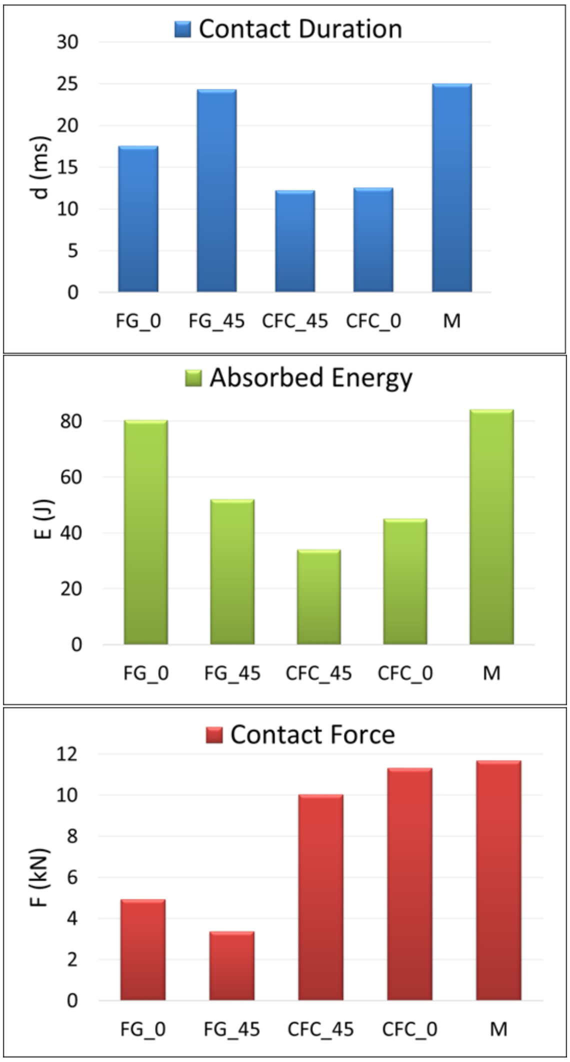

Fig. 12. Comparison among the different stacking sequences.

The results of impact tests allowed to identify the penetration energy absorbed for the hybrid laminate (84,16 J), as well as the average value of the maximum impact force (11,67 kN).

V. CONCLUSIONS

The present work is about the study of low-velocity impact behaviour of hybrid panels produced by combining fibreglass laminates with carbon fibre laminates. In order to have all information needed to understand the damage mechanisms which appear in hybrid panels, impact tests on

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panels made up of only fibreglass reinforced laminate and panels made up of only carbon fibres laminate were performed.

For the impact tests on laminates with just one type of fibre, the energy levels were determined using Caprino and de Morais analytical formula, while for hybrid panels the authors could not find in literature any analytical formula useful for the definition of penetration energy levels. For such a reason, for a preliminary evaluation of the impact energy, experimental significant data observed on tested specimens during the preliminary phase were cross-checked with those reported in literature [15] concerning the experimental activities carried out on hybrid panels having a different stacking sequence and made of same composite materials.

From the analysis of experimental results it was possible to observe that carbon fibre reinforced specimens present a lower absorbed energy in comparison with the fibreglass reinforced ones and therefore a higher level of elastic energy. Laminates made up of the same type of reinforcement, with woven fibre at ± 45°, present a lower absorption of impact energy in comparison with the counterparts with woven fibre at 0° - 90°. Such differences may also be observed in the contact force values, however the difference is not as significant. For hybrid laminates the absorbed energy may be compared with that of glass reinforced laminates, while the impact force has the same order of magnitude than that of carbon fibre laminates.

In terms of the damage analysis it was observed that in glass fibres-only laminates delamination reduces with the increasing of the impact energy. On the surface which is opposite to the impact surface an extended fibre fracture is produced for energies which induce a complete penetration. In carbon fibre laminates it was not possible to reach the complete penetration in the considered field of impact energy. The comparison between the two kinds of failure shows that on the back-side a significant delamination which turns into a splitting for high energetic levels (greater than 90 J) is observed. From the analysis of damages induced in hybrid specimens it is evident that for low impact energy levels, the characteristics of the damage produced are similar to the ones produced in carbon panels, as a matter of fact the same damage types may be observed: indentation, intralaminar crack and splitting. For increasing values of the impact energy (for example 90 J) the main hybrid characteristic is that of fibreglass laminate.

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