COMPARISON OF THE IMPACT RESISTANCE OF CARBON/EPOXY AND CARBON/PEEK COMPOSITE LAMINATES

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Keywords: polymer matrix composites, carbon fibres, impact behaviour, energy absorption.

Abstract
This study deals with the impact resistance of usual composite materials. Numerous results available in the open literature concern damage tolerance studies of thermoset laminates reinforced with unidirectional carbon fibre plies, as they are today mainly used in aeronautical structures. However, thermoplastic composites represent a growing interest with the aim of future structural applications.
The influence of the composite matrix and the reinforcing carbon armour on the impact behaviour of composite laminates was then analysed over a wide range of impact energy: drop weight test, Charpy test and gas gun test. Dissipative mechanisms were analysed (delamination, elastic energy storage and fibre breakage) and related to the armour architecture and polymer matrix. The results show that UD plies favour delamination and therefore energy dissipation. However, the effect of composite matrix was not observed.

1 Introduction
Next generation aircraft may introduce contra-rotative propulsion systems for energy saving purposes. This introduces new requirements on fuselage related to the open rotor configuration, which pale rupture may generate high velocity small fragments. This problematic is particularly delicate since organic composite materials are envisaged for the next generation fuselages.
Nevertheless, the current design of composite aircraft structures, as regards to impact resistance, only consider compression resistance after low speed / low energy impact for fatigue life prediction of damaged laminates; and laminates impact energy absorption is still relatively unknown.
The aim of this study was therefore to evaluate the impact behaviour of various carbon fibre composite laminates as regards to the reinforcing armour, the polymer matrix and the impact energy.

2 Materials and testing methods
In order to analyse the influence of the matrix nature on the impact behaviour, i.e. thermoset vs. thermoplastic, three different resins were tested: M21 (epoxy thermoset), PEEK and PPS (semi-crystalline thermoplastics). The influence of the carbon armour was also evaluated by comparing unidirectional reinforcements to carbon 3k satin 5H fabrics.

Quasi-isotropic 5 mm thick laminates of 200 mm x 200 mm dimensions were manufactured from different semi-finished carbon fibre products (table 1). A conventional processing cycle in autoclave, as recommended by Hexcel, was used to process T700/M21 UD prepregs. Cytec AS4/APC-2 prepregs were consolidated in an electrically heated press at 395°C during 35 minutes with a constant pressure of 7 bars. Finally, PEEK and PPS carbon fabrics, provided by Porcher Composites were processed with the Cage System® inductive moulding technology developed by Roctool using a short consolidation cycle [1].

Material designation	T700/M21	AS4/APC-2	PEEK Porcher	PPS Porcher
Resin	Epoxy	PEEK		PPS
Reinforcing armour	UD		Satin 5	
Number of plies	24	40	16	
Stacking sequence	$[90°,+45°,0°,-45°]_{3S}$	$[90°,+45°,0°,-45°]_{5S}$	$[90°,+45°,0°,-45°]_{2S}$	
Thickness (mm)	5,8	5,4	4,9	4,6
Fibre content in vol. (%)	62	60	51	55

Table 1. Material characteristics

Three different impact tests were performed on laminates so as to characterize the influence of impact energy on the composite resistance and energy absorption: drop weight test, Charpy test and gas gun test. Sample dimensions and test specifications are listed in table 2 and table 3.

Test	Length (mm)	Width (mm)	Thickness
Drop weight	150	100	
Charpy	70	10	Laminate thickness
Gas gun	200	200	

Table 2. Sample characteristics

Test	Impactor mass (g)	Impact velocity ($m.s^{-1}$)	Impact energy (J)
Drop weight	2079	7,27	55
Charpy	21900	5,23	299,5
Gas gun	64	121-124	468-491

Table 3. Test specifications

Drop weight testing was performed on 100 mm x 150 mm laminates supported by a 75 mm x 125 mm frame according to the AITM 1-10010 testing method [2]. An impact energy of 55 J was obtained with a spherical impactor of 25 mm diameter and the impact load was recorded during the impact thanks to a load cell mounted on the impactor.

Charpy tests were performed on unnotched samples of 10 mm x 70 mm dimensions with an impact energy of about 300 J. According to the ISO 179 standard method, the samples were struck through laminate thickness by the hammer and the impact force was measured.

Gas gun tests consisted in propelling a bearing ball of 25 mm diameter on 200 mm x 200 mm composite plates with a gas gun. The plates were only supported by a 170 mm x 170 mm frame and the maximum ball velocity was 124 $m.s^{-1}$ as recorded before impact by a high-speed camera. Residual ball speed after perforation was also recorded with a second high-speed camera.

3 3 Results and discussion

3.1 Drop weight tests

The variation of the measured load during drop weight tests is displayed in figure 1a for the different laminates. The curves first exhibit a linear elastic domain but rapidly followed by a

slight decrease of rigidity depicted by oscillations. Then, because of the low impact energy imposed in drop weight tests the curves exhibit a loop shape characteristic of elastic energy restitution (bounce of the impactor) [3].
Thanks to the load measurement during impact, the projectile velocity and therefore the energy variation can be determined by a double integration (figure 1b) [4]. The residual energy corresponds to the absorbed energy by damaging.

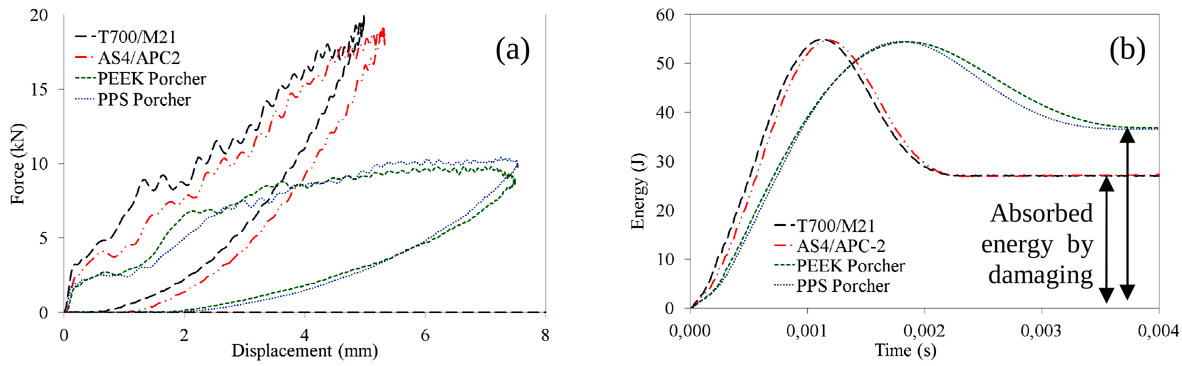

Figure 1. Curves of force versus displacement (a) and energy versus time (b) obtained experimentally

The graphs of figure 1 clearly show the influence of the reinforcing armour on the impact behaviour of composite laminates. Indeed, the force-displacement curve as well as the energy curve is similar for T700/M21 and AS4/APC2 but visibly different from the PEEK and PPS fabric laminates, which exhibit a similar behaviour.
This distinct behaviour of both populations is noticeable on the force-displacement curves (figure 1a). T700/M21 and AS4/APC2 curves exhibit oscillations with large amplitude that are characteristic of delamination, while woven laminates oscillations show evidence of fibre breakage. Moreover, as displayed in figure 1b, woven laminates mainly absorbed the 55J energy of the drop weight test by damaging, while unidirectional prepreg laminates can store about 50% of the impact energy by elasticity. This result is confirmed by the resulting permanent indentation that was measured with a dial comparator 48 hours after the impact (figure 2b). Woven laminates exhibit a large permanent indentation of about 1.5mm in comparison to the 0.5mm of the UD prepreg laminates.

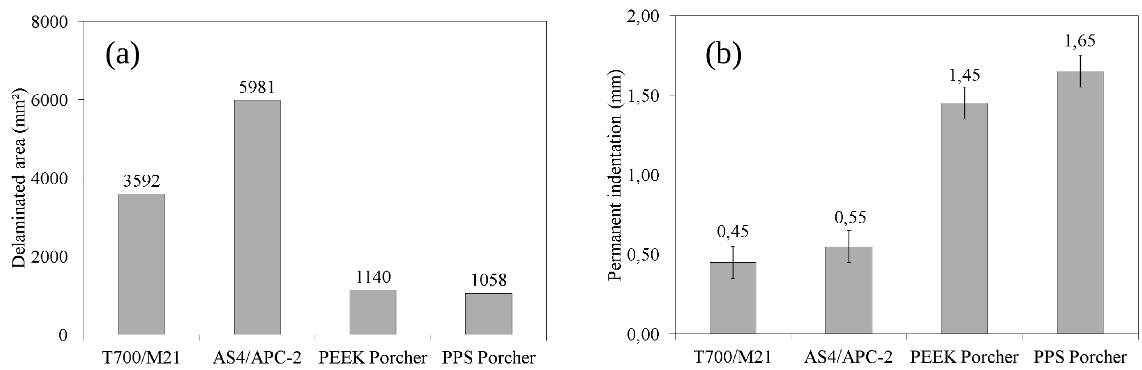

Figure 2. Delaminated areas (a) and permanent indentations (b) after impact

C-scan analyses were performed after impact to observe the damages through the thickness of the samples [5]. The measured delaminated interfaces are compared in figure 2a. The results show that T700/M21 and AS4/APC-2 are delaminated on a much larger area than PEEK and

PPS Porcher, which confirms the influence of the reinforcement structure on composite impact behaviour. The difference between T700/M21 and AS4/APC-2 may be explained by the different number of plies of these laminates (table 1). According to the literature, the delaminated area increases at each interface from the impacted side to the opposite side and lead to a damage cone [6]. In the present study, dividing the total delaminated area by the number of interface lead to the same value for both laminates.

3.2 Charpy tests

The variation of the measured load during Charpy tests is drawn in figure 3 for each material. The area under the force curve is proportional to the energy absorbed by damaging. In this way, the advantages of this test form are immediately apparent. Where the traditional test results only in a measurement of total absorbed energy and a fractured specimen, the instrumented test provides a measure of the specimen response which can be interpreted in terms of events.

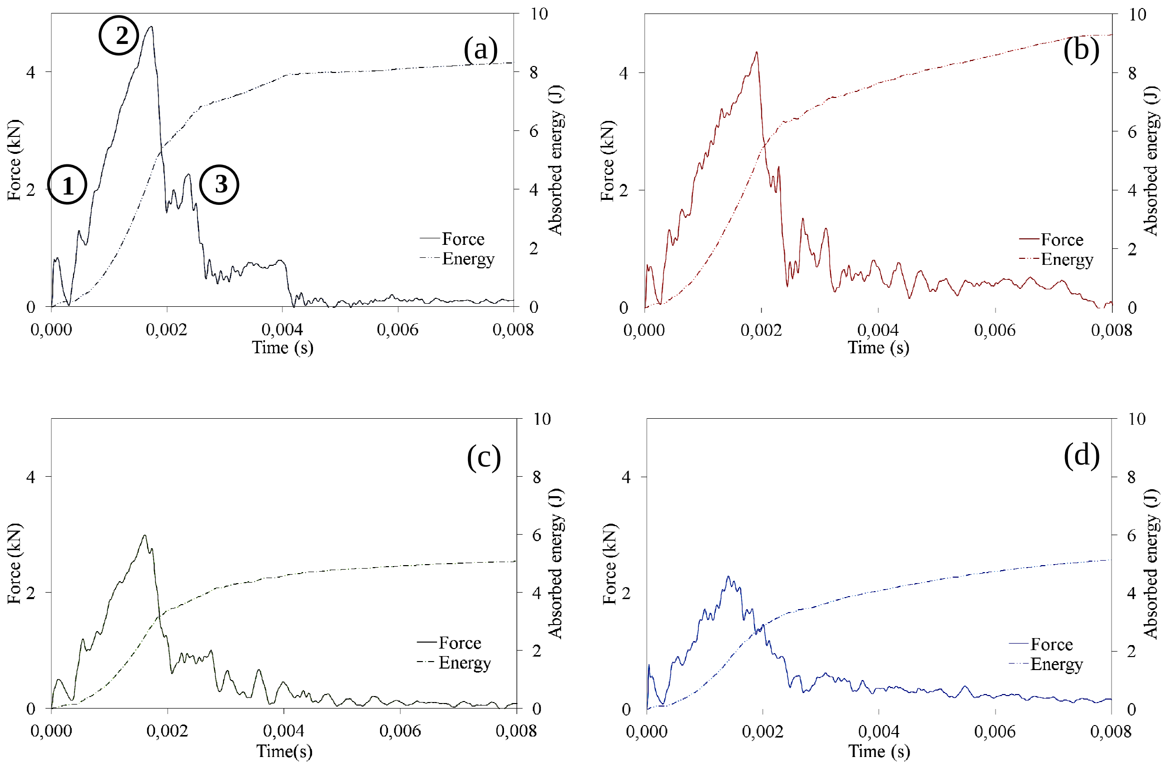

Figure 3. Curves of force and energy absorbed versus time for T700/M21 (a), AS4/APC-2 (b), PEEK Porcher (c) and PPS Porcher (d)

As illustrated in figure 3a, the response of a typical composite Charpy impact specimen exhibits three distinct regions: pre-initial fracture (1), initial fracture (2), and post-initial fracture (3) [7]. The region (1) corresponds to the elastic response of the composite beam and precedes the fracture (2) that occurs subsequently by fibre breaking (small oscillations in the load curve) or interply shear delamination (large subsequent oscillations). Integration of these curves then allows to quantify the distribution of the impact energy through these three mechanisms. The result is displayed in figure 4 as a bar diagram.

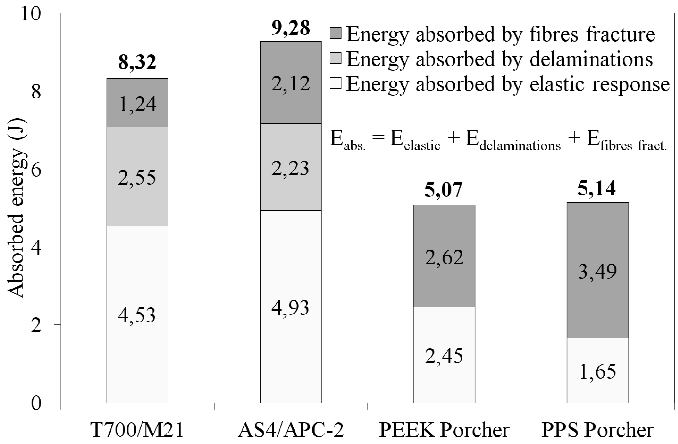

Figure 4. Comparison between energy absorbed by the various mechanisms

As displayed in figure 4, the influence of the reinforcing armour is marked: unidirectional laminates absorb about 8 to 9.3J while woven composites only dissipate 5J. Similar to drop weight tests, a large part of the impact energy is stored by elasticity. It represents more than 50% of the dissipated energy for both prepreg laminates. Nevertheless, woven laminates then only dissipate energy by fibre fracture while UD laminates exhibit in addition delamination process which contribution can account for more than fibre fracture dissipation.

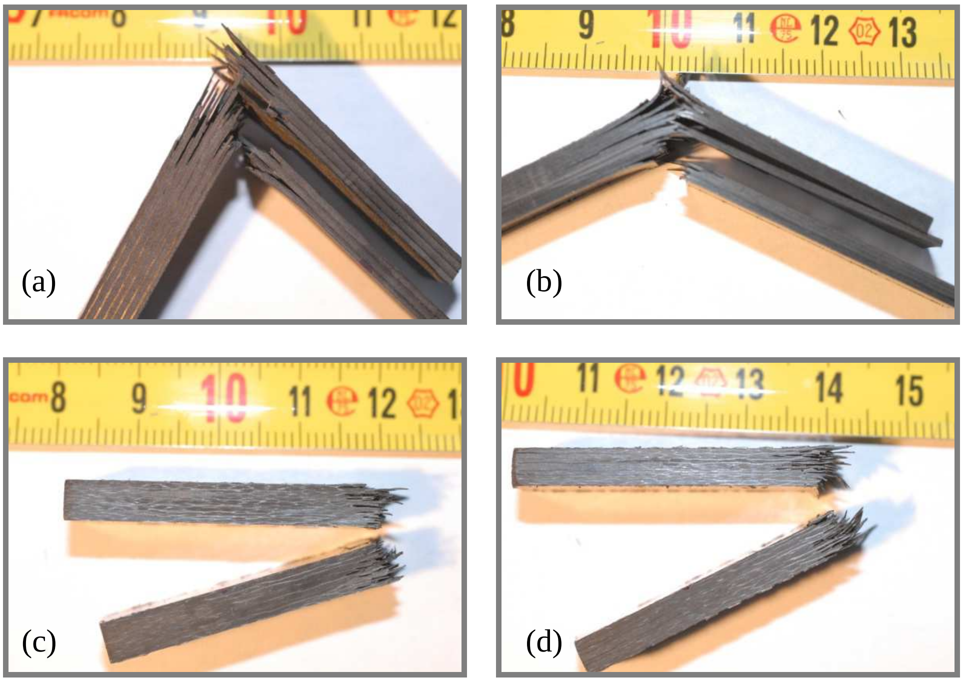

Figure 5. Fractured Charpy specimens for T700/M21 (a), AS4/APC-2 (b), PEEK Porcher (c) and PPS Porcher (d)

The below observations of fractured specimens confirm the previous conclusions (figure 5). Delamination is clearly visible on T700/M21 and AS4/APC2 specimens and in particular on the picture of AS4/APC2 specimen: delamination occurred on the entire length of the Charpy specimen. It leads to a diffuse fracture for these materials. On the contrary, PEEK and PPS woven laminates exhibit a straight fracture and fibre breakage is concentrated in the centre of the specimen.

3.3 Gas gun impact tests

For all different materials, gas gun tests led systematically to perforation. Thanks to the high-speed cameras, impact and residual velocities after perforation were measured and the absorbed energy was calculated with equation 1. E_{impact} corresponds to the incident impact energy and $E_{residual}$ is the residual energy after perforation, both determined from the steel ball velocity with equation 2. m_{ball} corresponds to the mass of the steel ball and v(t) is the velocity of the ball at the instant t.

$$E_{absorbed} = E_{impact} - E_{residual} \quad (1)$$

$$E(t) = \frac{1}{2} m_{ball} \cdot v_{ball}^2(t) \quad (2)$$

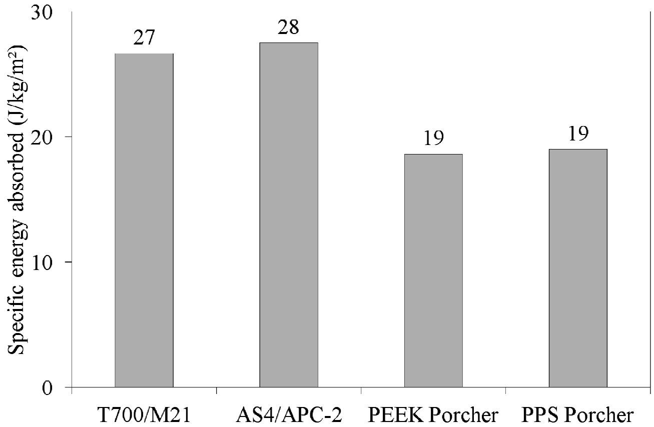

Figure 6. Comparison between specific energies absorbed

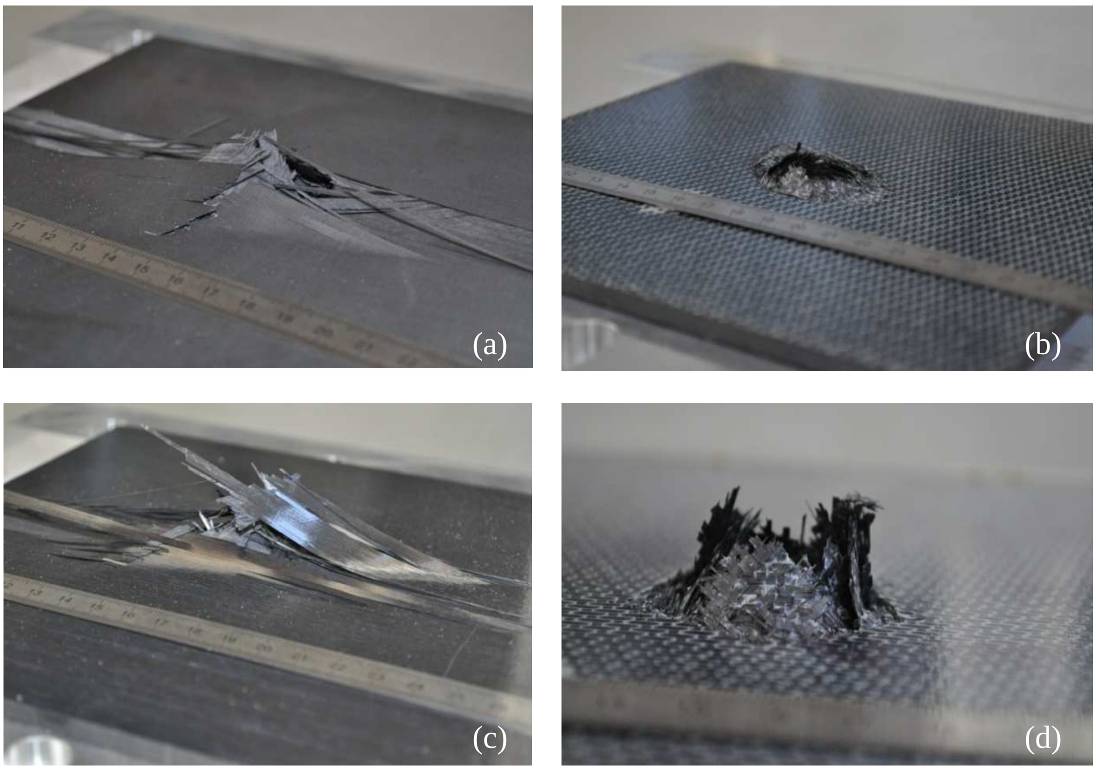

Figure 7. Visual observations of the rear side of the plates after perforation for T700/M21 (a), AS4/APC-2 (b), PEEK Porcher (c) and PPS Porcher (d)

The specific energy of each material is depicted in figure 6. The results show similar dissipated energy for materials with similar armours. Indeed, T700/M21 and AS4/APC-2 absorb 30 % more energy than PEEK and PPS Porcher.

Pictures of the damaged laminates confirm again the relation between the armour and the damage mechanism (figure 7). T700/M21 and AS4/APC2 exhibit a rear face with a wider damaged area than PEEK and PPS woven composites, and the main damage mechanism of UD laminates is inter-plies delamination as already observed for drop weight tests and Charpy tests. On woven laminates, the perforation is mainly due to out-of-plane shear that induced local fibre facture around the impactor.

4 Conclusions

The influence of the composite matrix and the reinforcing carbon armour on the impact behaviour of composite laminates was analysed through three different tests ranging from 55J to 500J. The results obtained for prepreg laminates are systematically better than the woven composites. The fractured samples as well as the measurements show that unidirectional plies favour delamination and the activation of this mechanism may be beneficial to dissipate impact energy. Elasticity also appeared as an important mechanism of energy storage and a high strength may then be advantageous to enhance impact properties of laminates. However, PEEK and PPS woven laminates exhibit similar impact resistance. The different tests were then not conclusive to evaluate the influence of matrix nature on the impact performances.

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