# INFLUENCE OF A THERMAL SHIELD ON THE DAMAGE TOLERANCE FOR COMPOSITE STRUCTURES OF LAUNCHERS

***S. Petit*/** - C. Bouvet*** - A. Bergerot** - J.J. Barrau******

* IGM – ENSAE – LMS
10 av. E. Belin 31055 Toulouse Cedex - France

** EADS Space Transportation
B.P. 11 - 33165 Saint Médard en Jalles Cedex - France

*** IGM – LGMT – UPS
118 Rte de Narbonne, Bât 3PN 31062 Toulouse Cedex - France

## ABSTRACT

This study presents the characterisation works performed on laminates used for launchers fairing considering damage tolerance demonstration. An experimental investigation concerning the low velocity impact response of shielded composite structures are conducted. Static indentation tests are also carried out. The main studied material is a high modulus carbon fiber composite : M46J/M18. The results are also compared to a classical aeronautical material, T300/914, which impact behaviour is well known. The shield is a thermal protection made with natural cork pellets agglomerated; this composition justifies the name of Norcoat Liège. The degradations created are examined by ultrasonic non destructive inspections, and also by micrographic observations. Those analysis show that the damage threshold is lower on M46J/M18 than on T300/914. The thermal shield appears to be a good mechanical protection towards impact as well as a good impact revelator. Nevertheless, the damage survey shows that the nature of the delamination changes if the panel is shielded.

*Keywords* : damage tolerance ; low velocity impact ; thermal shield; delamination

## 1. INTRODUCTION

Composite materials have been increasingly introduced in airframe and spatial applications in the last decade. These materials have interesting characteristics:

- A low specific weight;
- An enhanced mechanical strenght;
- A high stiffness.

Nevertheless, damage induced in these materials by impacts by foreign objects during the life of the structure can cause drastic reductions in the strength of the structure and, for this reason, the problem of impact on laminated structures has been a subject of intense research efforts. Aeronautical and spatial structures are often subjected to accidental damages. Consequently, it is essential to define a damage tolerance demonstration as soon as a new project begins.

Damage tolerance was introduced at the end of 1978 for aircraft structures [1]. It is intended to ensure that, with serious fatigue, corrosion, or accidental damage occuring within the operational life of the airplane, the remaining structure can withstand reasonable loads without failure or excessive structural deformation until the damage is detected [2]. In the military and spatial launchers fields, the damage tolerance concept only begins to appear.

The purpose of the study is to characterise composite laminates used for the launchers' fairing considering damage tolerance demonstration. An experimental investigation of low velocity impact to laminates is conducted. Damage phenomena are examined on composite panels and the influence of a thermal shield on the laminate damage is analysed.

# 2. EXPERIMENTAL INVESTIGATIONS

## 2.1. Materials and specimens

Two different fibrous materials are used in this investigation :

- a high modulus material, used in the manufacture of civil and military launchers' fairing : M46J/M18, with a thickness of 210 µm per ply, a modulus of 250 GPa and a compression failure stress of 610 MPa;
- a high strength material, T300/914 with a thickness of 130 µm per ply, a modulus of 130 GPa and a compression failure stress of 1000 MPa, which makes possible to have a comparison with a well-known reference in the aeronautical world.

Three M46J/M18 panels of 350 x 350 mm² are manufactured with 18 unidirectional plies with a stacking sequence of 0°/±60°/90° fixed by EADS Space Transportation. The total thickness of the plate is 3.8 mm.

Three T300/914 panels of 350 x 350 mm² are manufactured with 28 unidirectional plies in order to have a thickness as close as possible to M46J/M18 panels' one. With 28 plies of T300/914, the total thickness of the plate is 3.64 mm. The number of layers of 0°, 60°, -60° and 90°, as well as the stacking sequence of the plies, are determined in order to respect as far as possible the percentages and the stacking sequence defined for the M46J/M18 panels. The characteristics of the plates are given in a general way in the table 1.

| | M46J/M18<br>210 µm/ply | | T300/914<br>130 µm/ply | |
|---|---|---|---|---|
| Stacking sequence | Number | Percentage | Number | Percentage |
| 0° | 8 | 44.4 | 12 | 42.85 |
| 60° | 4 | 22.2 | 6 | 21.43 |
| -60° | 4 | 22.2 | 6 | 21.43 |
| 90° | 2 | 11.1 | 4 | 14.28 |
| TOTAL | 18 | 99.9 | 28 | 99.9 |

*Table 1 : characteristics of the M46J/M18 and the T300/914 panels*

The studied thermal protection is made with natural cork pellets agglomerated by impregnation and polymerisation of a phenolic nitrile resin. This composition justifies the name of "Norcoat Liège". Two Norcoat Liège thicknesses are tested:

- 3.5 mm, thickness designed to cover launchers' fairing;
- 6.5 mm in order to analyse the influence of the thermal shield thickness during an impact.

The type of specimens are described in the table 2.

| Type | Material | Thermal shield |
|---|---|---|
| I | T300/914 | None |
| II | T300/914 | 3.5 mm |
| III | T300/914 | 6.5 mm |
| IV | M46J/M18 | None |
| V | M46J/M18 | 3.5 mm |
| VI | M46J/M18 | 6.5 mm |

*Table 2 : test matrix*

### 2.2. Static indentation test system

The static indentation test system is given schematically in Fig. 1 [3]. The principal features are : (1) a stiff crosshead driven down by precisely controlled screws ; (2) a stiff 10 kN load cell ; (3) a 16 mm diameter indentor between the crosshead and the specimen; (4) a stiff clamp system to hold the specimen; (5) two displacement sensors mounted under the crosshead, which measure the global displacement of the indentor; (6) a displacement sensor mounted under the specimen which measure the displacement induced by the specimen bending; (7) an analogical data acquisition system.

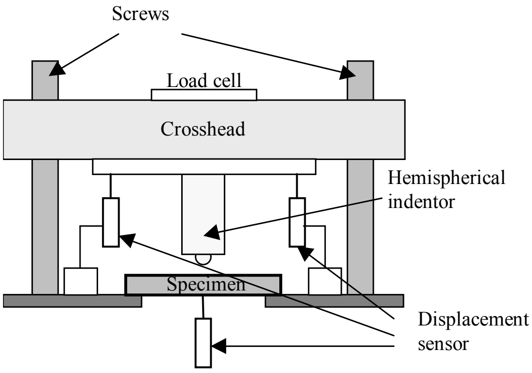


*Fig. 1: Schematic of static indentation test system*

### 2.3. Dynamic impact test system

The dynamic impact test system is given schematically in Fig. 2 and 3. The apparatus used to impact the composite coupons is the drop weight system. It consists in dropping an impactor, equipped with a load cell, on a laminate panel, clamped by a 125 x 75 mm² window. Its principal features are : (1) a guided near free falling mass of 2 kg; (2) a load cell mounted under the mass, which measures the force between the mass and the specimen; (3) a spherical 16 mm diameter impactor; (4) an optical sensor to measure the velocity just before impact; (5) a clamp system to hold the specimen; (6) a control system preventing multiple hits on the specimen; (7) an analogical data acquisition system.

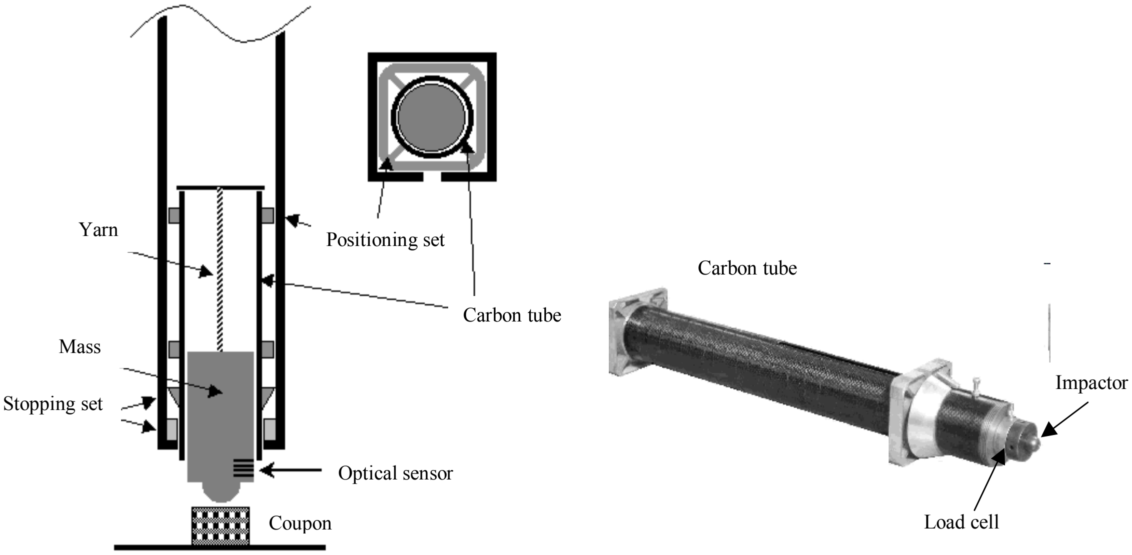


*Fig 2 and 3 : Drop weight test system*

## 2.4. Test results

### 2.4.1. “Norcoat Liège” impact behaviour

Preliminary tests are carried out on the thermal shield in order to understand the impact behaviour of this material. Graphs of the fig. 4 and 5 show the strength evolution (kN) versus the displacement for the two thickness and for various impact energy levels.

A non-linear behaviour of the Norcoat Liège thermal shield is observed whatever its thickness. At the cycle beginning, the material is elastic non-linear. As the strength increases, the cavities contained in the material close gradually, and the cork rigidifies (visible with the increasing slope on the curves fig. 4 and 5). An important hysteresis is observed in each case : it corresponds to the consummated energy in the shield.

The Norcoat Liège degradation seems to appear for impact energies above than 6.5J for the 3.5 mm shield and between 14J and 19J for the 6.5 mm shield (curves saturation). Besides, the surface quality of the thermal protection presents a detachment of the cork grains in the bottom of the impact (Cf. Fig. 6). Cracks are visible on the opposite side, they tend to propagate from the centre to the outside of the impact zone (Cf. Fig. 7).

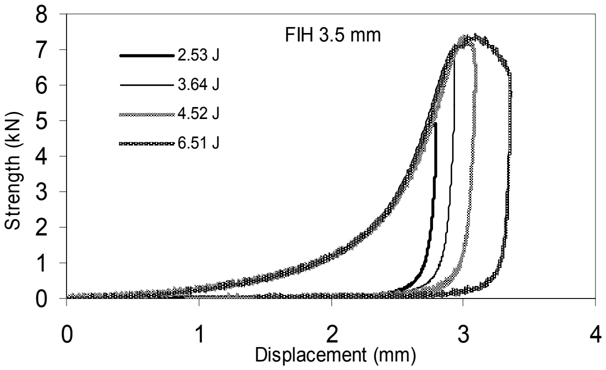


*Fig. 4 : Strength versus displacement for a 3.5 mm TS panel*

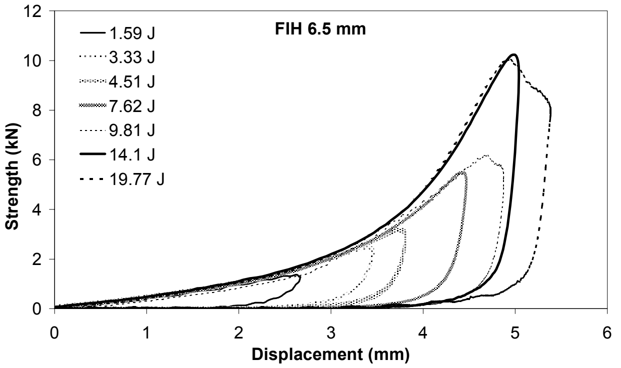


*Fig. 5 : Strength versus displacement for a 6.5 mm TS panel*

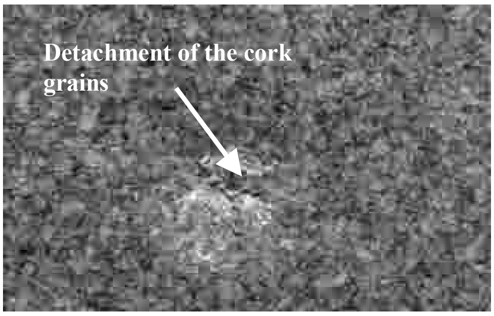


*Fig 6 : damaged TS panel – impacted side*

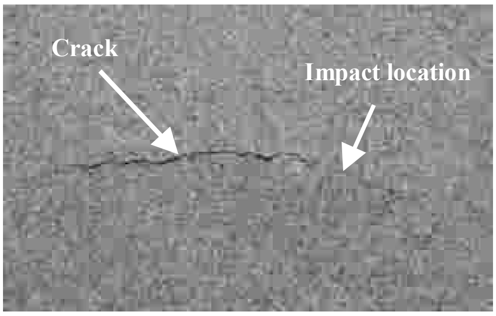


*Fig 7 : damaged TS panel – non impacted side*

Static tests are also carried out with the same impactor. Fig. 8 compares the dynamic results to the static ones with the load versus displacement curves and shows that the thermal shield's behaviour barely changes. Thus, the load versus displacement curves seem to be independent of the speed at which the load is applied. For the same thickness of thermal shield, low velocity impact and static indentation seem to be equivalent. However, the thermal shield surface quality in indentation static tests is different from the one observed during an impact : in static tests, the thermal shield presents a sort of roll around the indentor contact area (cf. Fig 9).

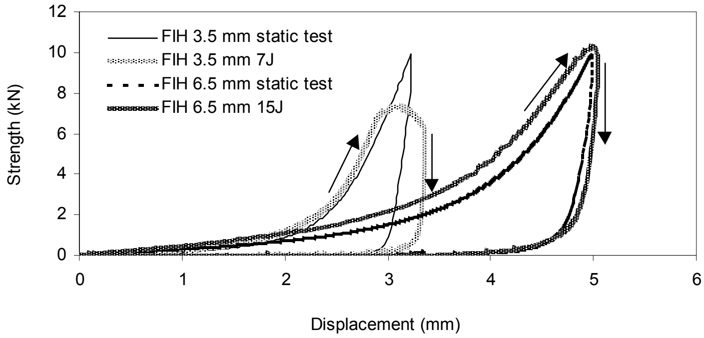


*Fig 8 : comparison between static indentation tests and impact tests*

*Fig 9 : observation of a roll around the indentor contact area*

### *2.4.2. Shielded composite panels impact behaviour*

#### **2.4.2.1. Impact tests results**

Impact tests are carried out for each type of specimens at different levels of impact energies. After every test, the following operations are proceeded:
- Indentation depth measurement and evolution in time;
- C-scan views of the impacted panels in order to define the delaminated areas.

The impact depths are measured just after the test and again after 10 days. An indentation depth decrease is noted for each type of specimens. The following reductions are noted :
- 25% on average for types I and IV;
- 20 to 25% on average for types II and V;
- 10% on average for type III and VI.

Thus, to cover the time effects (resin viscoelasticity / Norcoat Liege relieving), and in order to be sure to have the expected detectability threshold after a few days of storage (0.3 mm according to Airbus certifications), it is necessary to increase the penetration depth of 25% at the moment of the impact. This coefficient does not cover the effects of wet ageing, the thermal effects and the fatigue effects. In our study, it is decided to take 0.6 mm of penetration depth as detectability criterion at the impact moment, which corresponds to the usual aeronautic criterion.

The relation between the delaminated area and the impact energy is shown in Fig. 10. The data, from tests on shielded and unshielded M46J/M18 and T300/914 laminates, indicates that the M46J/M18 material seems to damage more easily than the T300/914 material. The delaminated area evolution versus the impact energy is overall linear for an unshielded composite laminate until the laminate perforation. Then, when the laminate begins to be perforated, delaminated areas reach a saturation point and the curves tend towards an asymptote. For shielded laminates with Norcoat Liège, the composite degradation appears for higher energies : actually, for an impact energy below 10J, there is no damage in the M46J/M18 laminate with 3.5 mm thermal shield whereas the composite damage appears at 0.8 J for the same specimen without thermal shield. Besides, the thermal shield's thickness seems to have an influence on the composite degradation . The tests show an increasing protection versus the thickness until a certain energy threshold : the damage of M46J/M18 composite with 6.5 mm thermal shield begins at 17.5 J whereas the damage appears at 10J on M46J/M18 laminates with 3.5 mm. Once the damage threshold reached, the delaminated area grows more quickly as a function of the impact energy than for unshielded specimens. Then, at high impact energies (near the laminate perforation), delaminated areas are more important for shielded panels than for unshielded ones.

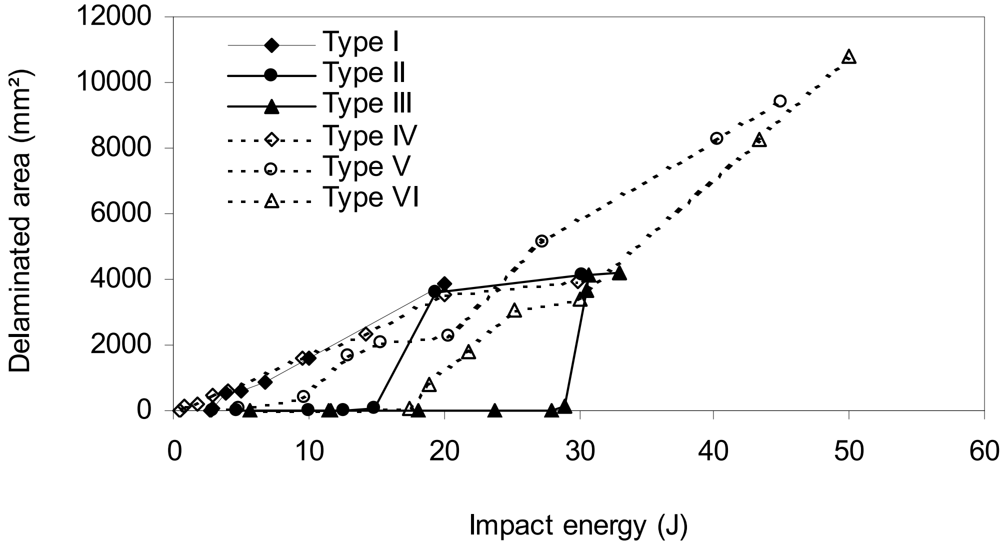


*Fig. 10 : delaminated area versus impact energy*

The Fig. 11 gives the delaminated area evolution versus the permanent indentation depth. The curves show that the composite degradation appears well before having a visible depth on the unshielded composite panels. Besides, on the unshielded panels, for equivalent delaminated areas, the penetration depth is more significant on the M46J/M18 laminate. This indicates a more important damage for the unshielded M46J/M18 laminate than for the unshielded T300/914 laminate. Unlike unshielded panels, the print caused by the impact on the thermal shield is visible before having a degradation in the composite. Thus, the thermal protection has a shock revealing role and allows detection of impacts not involving composite damage.

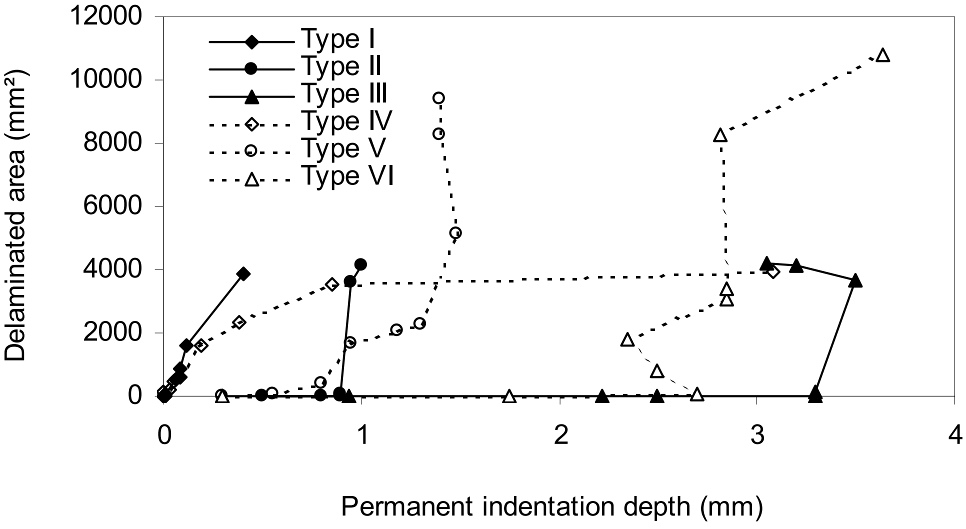


*Fig 11 : delaminated area versus permanent indentation depth*

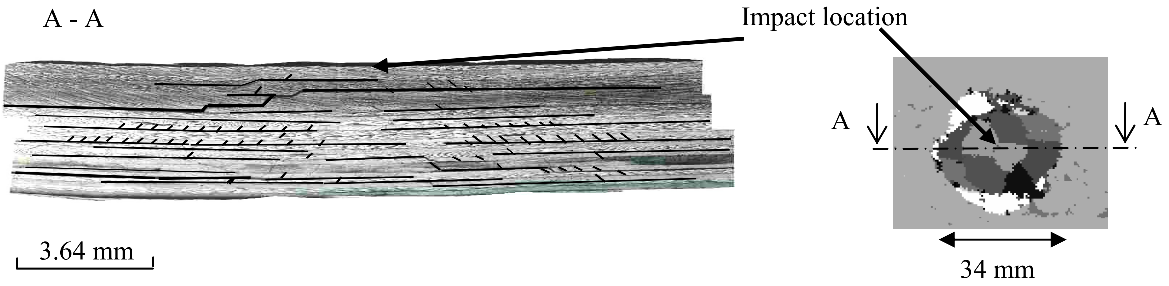
### 2.4.2.2. Post-impact C-scan and photomicrographs

For impacts that do not result in complete penetration of the target, experiments indicate that damage consists of delaminations, matrix cracking and fibre failures [4]. Investigators have observed that the typical impact damage shape for laminate composites was a conical shape in the thickness direction with the in-plane damage area increased from the impact surface to the backside [5]. Nevertheless, the post-impact C-scan views and the microscope observations of T300/914 and M46J/M18 laminate coupons show three kinds of impact behaviour (Cf. Fig 12 a-b-c):

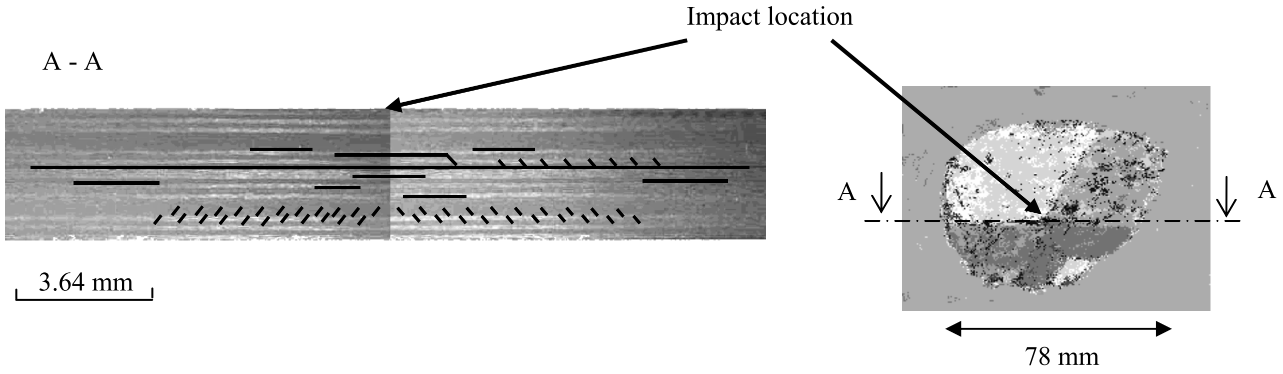
- for unshielded impacted composite panels, each interface is delaminated. C-scan views show that pairs of twin-triangles develop at each interface. With the rotation of fibres from one ply to the other one, the scheme depicts a typical “double-helix” when repeated through all the thickness. Increasing from the impacted side to the free side of the plate, delaminations are wrapped in a conical shaped envelope, well-known result in the literature [6].

- for shielded impacted composite panels and below a certain level of impact energy $E_0$, delamination is only located in the middle of the specimen thickness and its shape is indefinite. Matrix cracking are visible in the free side of the impacted plate;

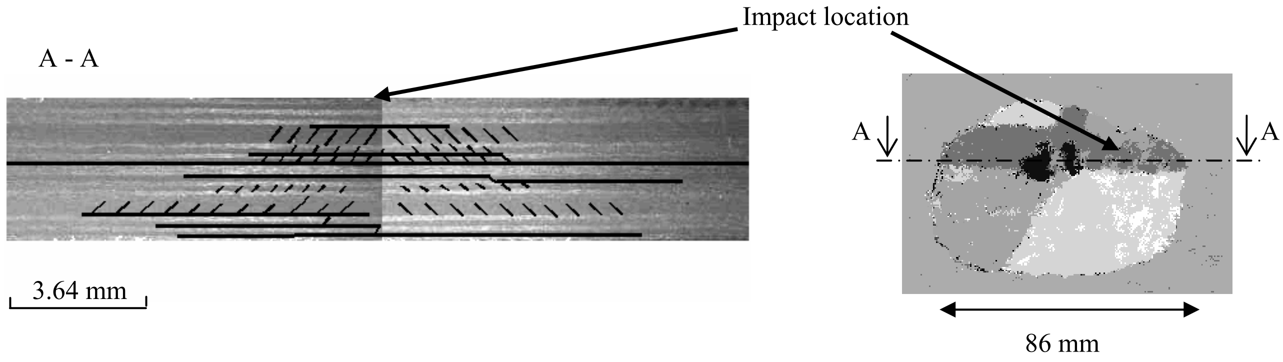
- for shielded impacted composite panels and above a certain level of impact energy $E_0$, the main delamination is still located in the middle of the coupon thickness, but the delamination shape seems to tend again towards a conic form.



*(a) T300/914 laminate panel without thermal shield - 7J*



*(b) T300/914 laminate panel with 3.5 mm thermal shield - 20J*

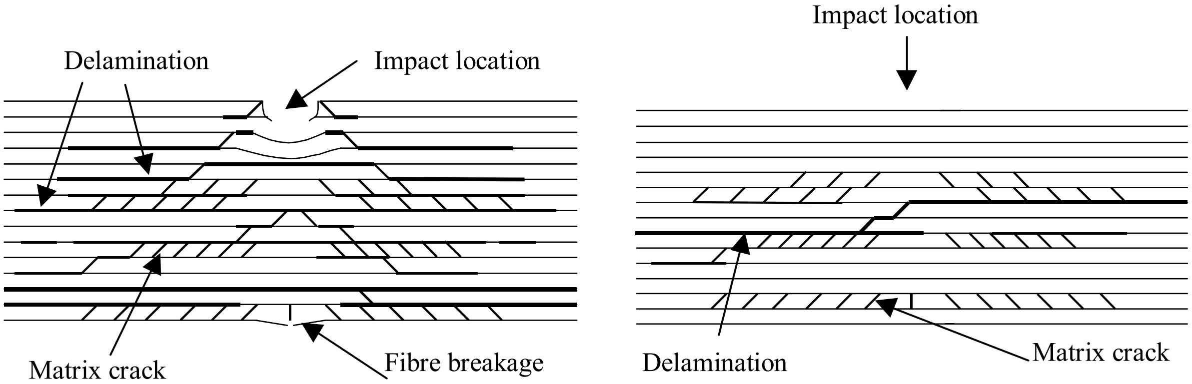


*(c) T300/914 laminate panel with 3.5 mm thermal shield - 30J*

*Fig. 12 : microscope observations and C-scan views of different T300/914 laminate panels*

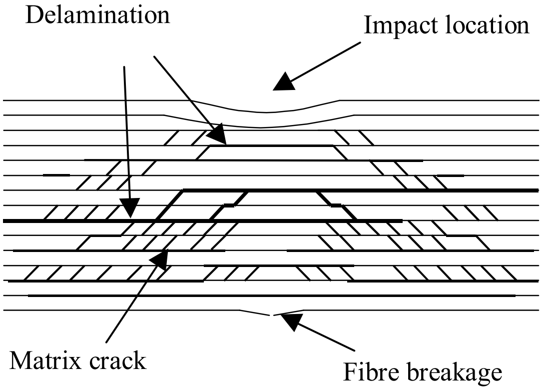
With reference to these observations, a typical impact damage mode is depicted for each case in the schematic representations shown in the Fig. 13.

The previously mentioned impact energy threshold $E_0$ is different for each material and each thermal shield thickness. The different values are given in the table 3 and has been determined by analysing the C-scan views and the photomicrographs.



(a) Impact damage on unshielded composite laminate

(b) Impact damage on shielded composite laminate for E < $E_0$



(c) Impact damage on shielded composite laminate for E > $E_0$

*Fig. 13 : schematic representations of different typical impact damages on composite laminates*

| | 3.5 mm thermal shield | 6.5 mm thermal shield |
|---|---|---|
| T300/914 | ≈ 30 J | ≈ 35 J |
| M46J/M18 | ≈ 20 J | > 25 J |

*Table 3 : $E_0$ values*

## 3. CONCLUSIONS

This study attempted to understand the impact behaviour and damage characteristics in two fibrous composite materials with thermal protection. Low velocity impact tests were carried out on shielded and unshielded panels in order to analyse the thermal protection influence on impacted damaged monolithic panels and to define the behaviour laws of shielded composite structures used for launchers fairing versus impact damages. The detectability criterion and the delaminated areas were determined, the degradations were examined by ultrasonic non destructive inspections, and also by micrographic observations. Results allow the following conclusions :

- The M46J/M18 material seems to damage more rapidly than the T300/914 material;
- The delaminated area evolution versus impact energy is overall linear for an unshielded composite laminate until panel perforation. Then, when the laminate begins to be perforated, delaminated areas reach a saturation point and the curves tend towards an asymptote;
- The thermal protection has an impact revealing role : the print due to the impact of the thermal shield is visible well before damaging the composite. However, above a certain indentation depth, delamination area suddenly increases and it is impossible to estimate the damage size at a given indentation depth;
- The thermal protection has also a mechanical protection function : composite damage appears at higher impact energies for shielded laminates, which is favourable for damage tolerance justification. However, above a certain impact energy threshold, delaminated areas reach a saturation point for unshielded panels (composite laminates tend toward perforation), whereas those concerning shielded panels go on increasing. Thus, for impact energies above this threshold, it is possible to have more important delaminated areas for shielded panels than for unshielded ones;
- The thermal protection modifies the impact behaviour of the composite : the delamination distribution in the laminate thickness changes when specimen are shielded.

Post-Impact Compression Loading tests are being conducted in order to define the residual strength and the allowable damages for impacted composite structures.

Numerical analyses are in progress. The purpose is to be able to foresee a damage on an impacted shielded structure without having to realise costly experimental tests. Finally, from simple numerical models of impacted shielded laminate coupons, the engineer should be able to comprehend the damage phenomena on a more complex impacted structure (a launcher fairing for example).

## ACKNOWLEDGEMENTS

This work was funded by EADS Space Transportation, Saint Médard en Jalles, France. The authors would also like to thank CEAT and the laboratory of ENSICA for their assistance in the post-impact C-scan.

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