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# Experimental investigation of impact on composite laminates with protective layers

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## A B S T R A C T

This paper presents an experimental study of low energy impacts on composite plates covered with a protective layer. In service, composite materials are subjected to low energy impacts. Such impacts can generate damage in the material that results in significant reduction in material strength. In order to reduce the damage severity, one solution is to add a mechanical protection on composite structures. The protection layer is made up of a low density energy absorbent material (hollow spheres) of a certain thickness and a thin layer of composite laminate (Kevlar). Energy absorption ability of these protective layers can be deduced from the load/displacement impact curves. First, two configurations of protection are tested on an aluminium plate in order to identify their performance against impact, then the same are tested on composite plates. Test results from force–displacement curves and C-scan control are compared and discussed and finally a comparison of impact on composite plates with and without protection is made for different configurations.

## Keywords:

B. Impact behaviour  
C. Damage tolerance  
B. Delamination

## 1. Introduction

Composite materials are widely used nowadays in aeronautics. This growing interest is due to the relatively high strength/mass ratio of these materials compared to those of metals. These materials are sometimes subjected to low energy impacts during fabrication and in service as well which can have an influence on the residual mechanical properties of the structure [1]. In the field of aeronautics, depending on the impact detectability, damage tolerance is often the key factor in structure design [2,3]. It is a known fact that damage due to impact reduces the residual compressive strength of a structure to less than 50% of the initial strength. The notion of impact detectability was introduced for aircraft certification needs. The minimum indentation damage that can be detected by visual evaluation is called “Barely Visible Impact Damage” (BVID) [4], and in aeronautical standards, this threshold of detectability after few days of rest and humidity ageing is 0.3 mm depth. In the case of a non-detectable damage (indentation less than BVID), the structure must sustain the ultimate load. Consequently, damage tolerance in composites has been a subject of investigation for many years. Several authors, [5–10] have studied the resistance of composite structures against low velocity impacts.

The use of mechanical protection against impact is one other way of solving the problem of impact on composites. Although

introduction of a mechanical protection against impact induces a non-negligible increase in weight of the structure, it nonetheless avoids or considerably reduces damage in the structure. Furthermore, use of mechanical protection improves the detectability of impact, as the protection is generally more deformable which causes a visible post-impact indentation mark.

Core material covered with skin seems to be a good candidate for protective layers. Core materials (honeycomb, foam, hollow spheres ...) are of significant scientific interest due to their good specific resistance and enhanced energy absorption capabilities and are already used to protect structures against impact. For example, some aircraft cockpits are protected against bird strikes by a layer of aluminium honeycomb covered by an aluminium skin to improve the capacity of energy absorption. Wang [11] showed that the energy absorption tends to increase linearly with the increase in relative density of honeycomb cores. Therefore, increasing the relative density of honeycomb cores can efficiently improve the dynamic cushioning properties of the sandwich panels. Li et al. [12] used different materials in their study on high velocity impacts in which they determined and compared the energy absorption capability of these materials. They concluded that porous silicon carbide materials are best suited for absorbing impact energy. On the other hand, Apetre et al. [13] studied the impact at low velocity on honeycomb sandwich beams with variable density and rigidity in the thickness. They showed that core with graded properties reduces maximum deformation corresponding to maximum impact load. Furthermore, Shin et al. [14] presented impact tests at low velocity on several types of sandwiches. They concluded that glass skin sandwich plates have a better resistance

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against impact compared to aluminium skins. In the same context, Petit et al. [15] showed that a layer of thermal protection (cork) is also a good mechanical protection against impact. The use of such protections increases the residual strength of compression after impact tests. In the same context, Rahmé et al. [16] compared the resistance against impact of three type of cores (foam, honeycomb and hollow spheres) having the same thickness or the same surface density. They concluded that hollow spheres give best efficiency against impact. Moreover, the concept of protective layers, consisting of epoxy filled glass microballoons covered with one or more layers of aluminium gauze was presented by Hart and Ubels [17]. Their work also showed that the resistance to impact damage of a composite structure can be improved by application of a protecting surface layer.

Anyways, the main objective is to obtain a good compromise between the residual strength and the mass of the structure, for a given impact energy (or a given BVID).

In this paper, two configurations of protective layers made of hollow spheres core (HS) and Kevlar skin are tested. Impact tests at low velocity ( $<10$  m/s) and low energy ( $<100$  J) are performed using a 20 mm diameter impactor in a drop weight setup. In the first step, composite plates are impacted without protection, then both configurations of layers are tested on aluminium and composite plates. A comparative study is then carried out based on the results of different configurations. Finally, the results of impact on composite plates with and without protection are compared and discussed. Furthermore, the observations of C-scan controls are also discussed.

## 2. Experimental study

### 2.1. Drop weight device

There are many testing procedures to simulate an impact on a structure; however, the drop weight remains the most used device [1]. Such a device has been used in this study to perform impact tests according to AITM 1-0010 standards [18]. The principle of this drop weight device is to drop a mass guided in a tube on a composite plate. Fig. 1a and b shows impacts on aluminium and composite plates respectively having protective layers.

This device is dedicated to impact tests at low velocity ( $<10$  m/s) and low energy ( $<90$  J). A 4.02 kg impactor with a 20 mm diameter hemispherical head is used. The impactor is instrumented with a load sensor, installed between the impactor head and its

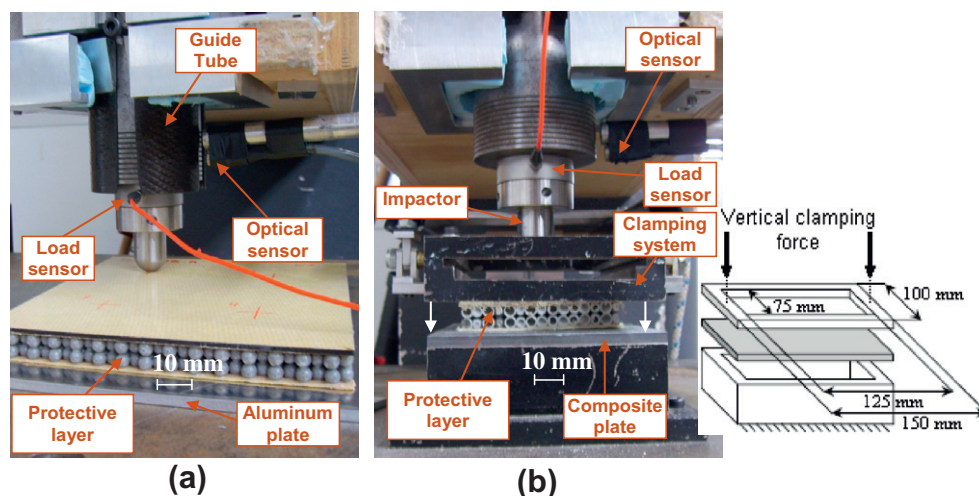
body. This KISTLER piezoelectric sensor having a maximum capacity of 120 kN is calibrated to measure the impact load. An optical sensor (Laser diode, Fig. 1) measures the initial velocity of the impactor before impact. The impactor displacement and velocity histories are obtained by integrating the impactor acceleration resulting from the measured load taking into account the initial velocity [15]. When impacting on composite plate, an additional optical sensor (OptoNCDT50) is used to measure the displacement in the impact direction of the non-impacted face of the composite plate. This displacement due to the bending of the plate helps in determination of indentation of the layers and then the corresponding energy absorption. This allows comparison of the different impact curves when supporting on aluminium and composite plates.

### 2.2. Protective layers and plates

Two configurations of protective layers have been tested. Configuration L1 is designed for 50 J energy impacts (cf. Fig. 2). It is composed of a 1.4 mm thick  $0^\circ/90^\circ$  Kevlar woven fabric skin and of a polymer hollow spheres core made by ATECA Company. Sphere diameter is between 5.4 and 6 mm, and spheres are glued together and also with the skin. In the context of practical application on real world structures, for a simpler installation and an easier maintenance after impact, protective layers will not be glued to the structure. Consequently, an additionally thin  $0^\circ/90^\circ$  ply of Kevlar woven fabric has been added between the hollow spheres and the plates. The patent "Peau amortissante de protection de pièces composites" no. 2 930 478 has been filed about these protective layers of hollow spheres [19]. The mechanical properties of the skin and the hollow spheres cores used are provided in Tables 1 and 2 respectively. For hollow spheres, the properties given in the table are homogenised characteristics, calculated from spheres layers compression tests. The Young's Modulus is the initial slope of the stress-strain curve, whereas the failure stress is the stress reached at the crushing plateau.

Configuration L2 is developed in order to withstand 90 J energy impacts. It consists of a 2.1 mm thick  $0^\circ/90^\circ$  Kevlar woven fabric skin and two layers of hollow spheres core with an additionally thin  $0^\circ/90^\circ$  ply as shown in Fig. 2. The design of this configuration is based on gradual stop of the impactor.

Table 3 gives the global surface density for each configuration of the tested protective layer along with material and geometrical information. In the case of tests on aluminium plates, the plate is



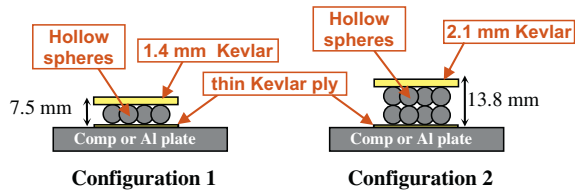


Fig. 2. The two configurations of protective layers.

only resting on a flat rigid foundation. Concerning composite plates: material used is a carbon-epoxy UD prepreg of T700/M21. The stacking sequence for these quasi-isotropic plates is  $[0_2^{\circ}, +45_2^{\circ}, 90_2^{\circ}, -45_2^{\circ}]_s$  according to AIM 1-0010 standards [18]. The thickness of one ply is 0.25 mm which amounts to a total plate thickness of 4 mm. The in-plane dimensions of the composite plate are  $150 \times 100 \text{ mm}^2$ . During tests, composite plates are clamped using the device shown in Fig. 1b. A vertical load is applied on a clamping frame to prevent rebounds of the plate.

### 2.3. Test results

The specimens were impacted at several impact energies. Configuration 1 specimens were tested at 15, 30 and 50 J impact energies and composite plates without protection were also impacted at the same energy (15, 30 and 50 J). Impact energies of 15, 50 and 90 J were used for the thick protection layers (configuration L2). Displacement versus time curve is given in Fig. 3, for A-L1-30 J impact test (aluminium support and protective layer L1). Furthermore, load/displacement impact curves are presented in Fig. 4, for 30 J energy impact on configuration L1 specimen with aluminium support and composite plate. Tests on the other protective layers present similar curves. Both unfiltered and filtered impact forces are presented in Fig. 4a (15 kHz low pass filter), but onwards only filtered impact forces will be presented in his article. The initially measured impact velocity in this test is 3.9 m/s. The maximum displacement of the impactor is then about 6.2 mm in the case of aluminium support. This displacement is lower as compared to the 7.5 mm layer thickness represented on the curve by the vertical line. Hence, the impactor will not touch the aluminium plate in this case and the layer should be able to absorb the total impact energy.

The displacement of the non-impacted face of the composite plate is due to its bending. Using the LASER sensor, this displacement was measured. The indentation of the protective

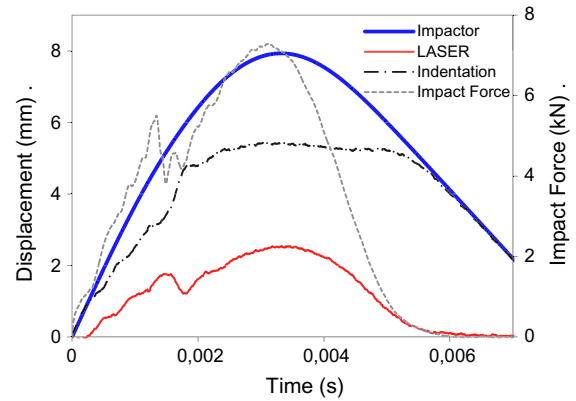


Fig. 3. Force and displacements versus time curves for A-L1-30 J impact test.

layer is then deduced by subtracting the plate bending displacement from the impactor displacement (Fig. 3), with the assumption that the thickness of the composite plate does not change (no local indentation of the plate). In the case of aluminium support, the layer indentation and the impactor displacement are the same. The maximum indentation of the impactor is around 5.4 mm, which appears in the protective layer when supported on composite plate.

The various steps of the impactor displacement through the protective layer can be identified during impact (Fig. 4a). First, there seems a very short elastic behaviour of the protective layer which is then followed by a progressive damage of both the skin and the hollow spheres. A major failure of the skin is then reached, characterised by a significant drop in load. After this break, the skin damage continues and the hollow spheres densification is held up to the maximum load. The indentation curve in Fig. 4b shows the same behaviour of the layer on composite plate. The maximum indentation is smaller than in previous case, due to the transformation of initial energy in damage and in elastic bending in the composite plate.

Fig. 5 shows the non-impacted faces of composite plates impacted at 50 J, with protection L1 (a), and without protection (b). No damage is visible on the first one (even if C-Scan shows internal delaminations: see further), whereas obvious longitudinal failure of the last ply is visible for the non-protected plate.

On the other hand, Fig. 6 shows the different protective layers after impact at maximum impact energy (50 J for L1 layer, 90 J

Table 1  
Skin properties.

Material	Failure stress in compression (MPa)	Failure stress in tension (MPa)	Failure stress in shear (MPa)	Young's modulus (MPa)	Density ( $\text{kg/m}^3$ )
Kevlar (skin)	170	500	150	22,000	1330

Table 2  
Core properties.

Material	Failure stress in compression (MPa)	Young's modulus in compression (MPa)	Density ( $\text{kg/m}^3$ )
Hollow spheres (HS)	0.35	30	166

Table 3  
Characteristics of protective layers.

Configuration	Core	Skins	Thickness (mm)	Surface density ( $\text{g/dm}^2$ )
L1	1 × HS	1.4 mm Kevlar	7.5	55
L2	2 × HS	2.1 mm Kevlar	13.8	92

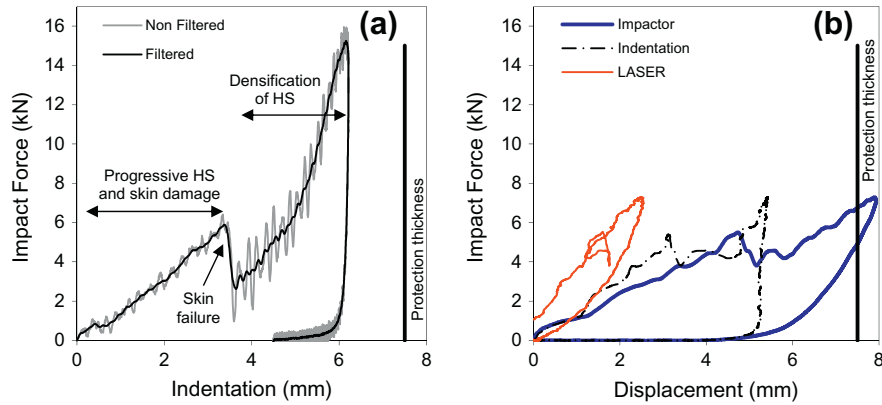


Fig. 4. Load/displacement curves for L1 protection configuration, at 30 J energy impact on aluminium support (a) and composite plate (b).

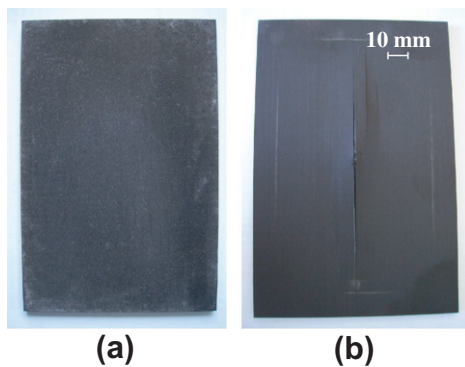


Fig. 5. Composite plates impacted at 50 J: (a) with protective layer L1 – (b) without protective layer.

for L2). Impacts lead to hemispherical indentation marks with cross shaped failure of the skin. As shown on impact curves, the indentation is smaller in the case of impact on composite. The results observed on the different layers are compared and discussed in the next section.

### 3. Comparison and discussion

First, the different impact curves corresponding to protected and non-protected composite plates are presented in Fig. 7. Impact force is drawn as a function of the impactor displacement. For each protection configuration, the superposition of 15 and 50 J impact energy curves indicates good repeatability of the impact tests.

By carefully examining these curves, comparison of the behaviour of composite plates with or without protection can be carried out. The presence of protection reduces the impact force during the first 7 mm of displacement by mechanical fuse effect. Later, when the core layer is totally crushed, the load increases. Paradoxically,

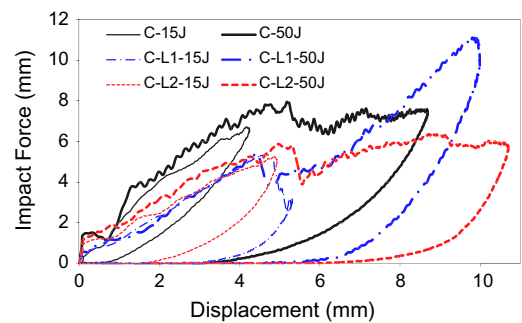


Fig. 7. Comparison of force-displacement curves for composite plates impacted with and without protection.

the load increases more in layer L1 than in the non-protected plate. The reason being that damage in non-protected plate reduces highly the rigidity under the impactor which then reduces the force. In case of protected plates, force spreading due to the protective layer leads to less critical damage due to which there remains a margin in the impact force which can still increase.

Concerning layer L2, at 50 J, the maximum force is not as high as in layer L1 test because the core is not entirely crushed under the impactor.

Fig. 8 compares the impact curves on protected aluminium and composite plates, for different impact energies. Fig. 8a shows the results for configuration L1 at 15 J and 50 J. The impact force is drawn as a function of indentation, that is crushing displacement in the core. In the first phase of the impact, the different curves show almost identical behaviour. Despite bending of the composite plate, the impact force is ruled by the indentation of the protective layer.

However, after 4 mm indentation, the behaviour of the layers becomes different on aluminium and on composite plates during the hollow spheres densification phase. Due to appearance of damage in composites, the force is lower in composite plate tests. For a

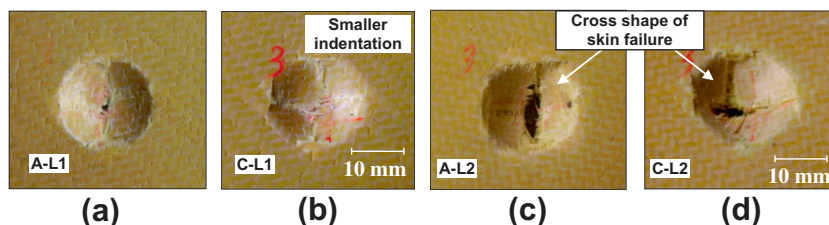
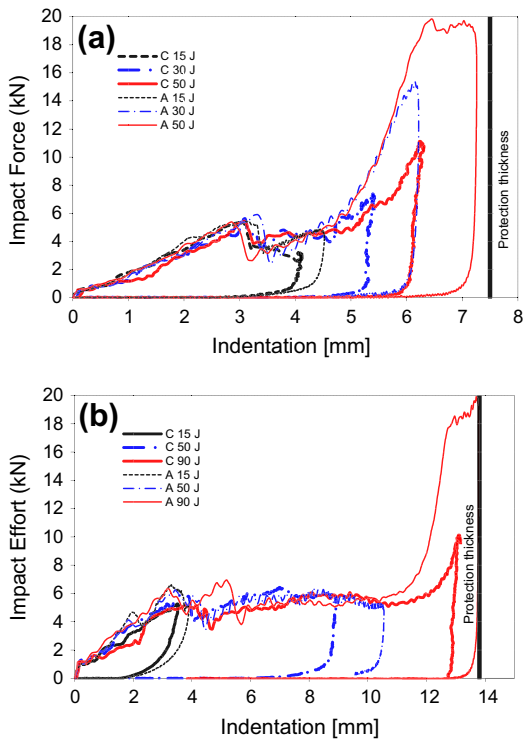


Fig. 6. Protective layers after impact on aluminium support (A) and composite (C): Configuration L1 at 50 J (a and b) and configuration L2 at 90 J (c and d).



**Fig. 8.** Comparison of protective layers impact behaviour between aluminium (A) and composite (C) supports: configuration L1 (a) and configuration L2 (b).

given energy, the maximum indentation is also lower in the case of composite plate, due to absorption of energy due to damage in composites and release of bending energy.

Similarly, Fig. 8b shows the curves of configuration 2 i.e., impact on aluminium and composite plate at different energies (15, 50 and 90 J). The curves are also similar except there is a difference in slopes due to densification of the hollow spheres. Note that the total impact energy is almost absorbed by the protective layer in case of the aluminium support (there is almost no impactor rebound), whereas, in composite plates a part of that energy is transformed into damage.

Table 4 presents the distribution of energies during a test. Impact energy which is the initial energy of the impactor is made up of the following:

- Energy dissipated in the protective layer: calculated from impact force and indentation.

**Table 4**  
Energy repartition in impact tests (A for aluminium and C for composite).

Name	Plate	Protection	Impact energy (J)	Layer absorbed energy (J)	Impactor rebound energy (J)	Plate absorbed energy (J)
A-L1-15 J	A	L1	14.8	13.8	1	–
A-L1-30 J	A	L1	29.9	28.6	1.3	–
A-L1-50 J	A	L1	50	48.7	1.3	–
A-L2-15 J	A	L2	14.2	11.6	2.6	–
A-L2-50 J	A	L2	49.8	48.9	0.9	–
A-L2-90 J	A	L2	88.6	87.5	1.1	–
C-15 J	C	–	15.2	–	9.6	5.6
C-30 J	C	–	30.3	–	10.5	19.8
C-50 J	C	–	50.2	–	11.8	38.4
C-L1-15 J	C	L1	15.5	11.3	2.2	2
C-L1-30 J	C	L1	29.9	18	7.4	4.5
C-L1-50 J	C	L1	49.5	23.3	13.2	13
C-L1-70 J	C	L1	69.8	27.1	21.4	21.3
C-L2-15 J	C	L2	14.6	7.4	5.4	1.8
C-L2-50 J	C	L2	49.7	39.6	5.6	4.5
C-L2-90 J	C	L2	89.7	60.2	13.4	16.1
C-L2-107 J	C	L2	107.1	60.8	19	27.3

- Elastic recovery energy (impactor rebound energy): calculated from force release.
- Energy absorbed in the composite plate by damage: calculated from the subtraction of the two previous energies from impact energy.
- Kinetic energy of the plate and energy dissipated in the test set-up can be neglected in this study.

Up to 50 J for L1 configuration, and 90 J for L2, the energy absorbed by the protective layer reaches about 50% or more, which proves the relevance of the use of such a protection.

To identify the importance of the protective layer C-scan observations are made for all tested composite plates. These C-scan observations help in determining the shape of the different delaminations and their locations in the plates. Fig. 9 presents the different C-scan snapshots at different energies (impacted face). It is clearly visible from these images that while impacting non-protected composite plate, damage is already present at 15 J impact energy. This damage increases with the rise in impact energy. For protected plates with the layers of configuration L1, no defect is seen for 15 and 30 J impacts. The defects appear at 50 J impact energy while nothing was visible with the naked eye on the external surfaces. Similarly, there are no defects on configuration L2 plates until 50 J.

Fig. 10 presents the projected delaminated area of the impacted composite plates as a function of impact energy (a) and the energy absorbed by the composite plate (b). The first curve shows clearly the efficiency of the use of protective layers. The second one also shows that taking into account the only absorbed energy in the plate, behaviour is not the same between protected or non-protected plate.

A detail of delamination surface for composite plate with (L2) and without protection subjected to 30 and 90 J impacts respectively is presented in Fig. 11. The delaminated area in this case is respectively 1972 and 2031 mm<sup>2</sup> and the locations of different delaminations are also indicated in this figure. The differences between the two C-scan shots are clearly visible. In the case of non-protected plates, the damage is symmetrical about the impact point, and the classical delamination form of double helix is obtained. Moreover, every interface delamination is oriented by the fibres direction of the ply located below.

In the case of protected plate, a very asymmetric damage shape is observed on all tested specimen, and the location of delamination in the thickness of the laminate is limited to the central interfaces (3–5), like illustrated in Fig. 12. The first two interfaces of non-impacted face of the protected plates are largely protected, whereas usually it is the most damaged interface. Such observations have already been made in previous works of Petit et al.

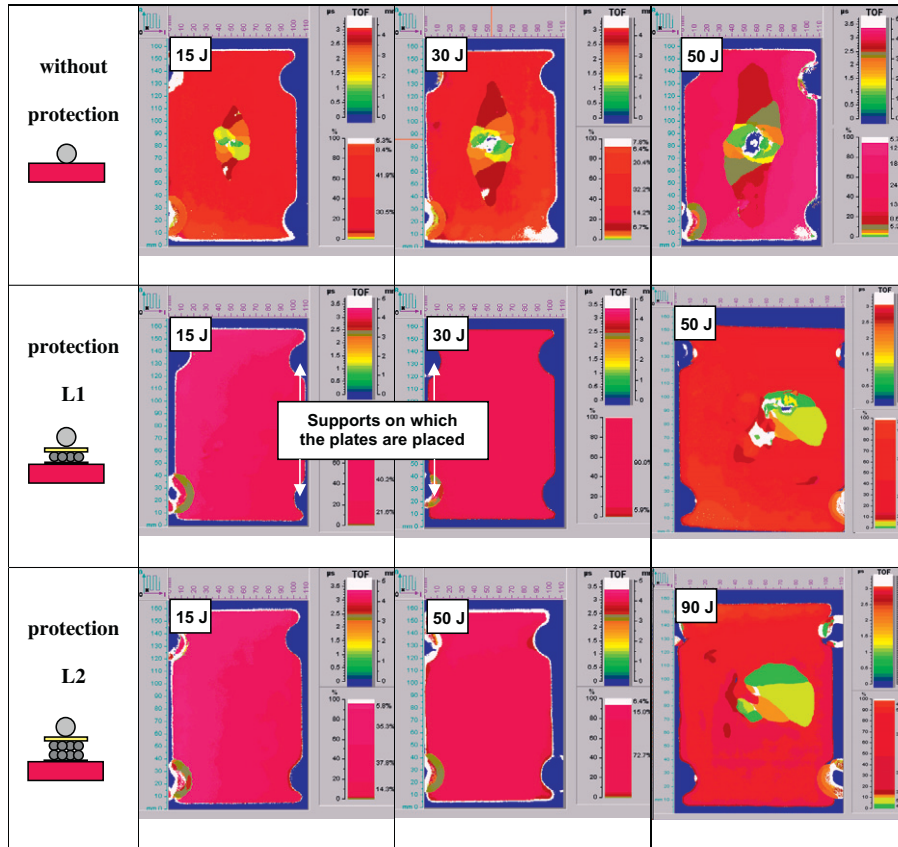


Fig. 9. C-scan control for different tested composite plates (impacted face).

[15]. The physical explanation of the reason behind this specific damage shape is difficult. Some numerical investigations are in progress in order to understand the chronology of damage that leads to this phenomenon.

About the impacted side, by taking into account only indentation in the plate not in the protective layer, it is observed that the permanent indentation is much smaller in the case of the protected plate.

As a result of this study, the proposed protective layers L1 can protect completely the composite structure without any delamination for impact energy lower than 30 J, for a 90% increase in mass. The layer L2 protects it against impacts at energy lower than 50 J, for a 150% increase in mass. The critical protective energies can be

determined experimentally. It is between 30 and 50 J for protection L1 and between 50 and 90 J for protection L2. On the other hand, no damage was visible during visual inspection of the plate for 50 and 90 J corresponding respectively to protective layers L1 and L2. However, delamination at mid-thickness was observed during C-scan control. As observed in [15], mid-thickness delaminations should have less effect on the residual strength. However, in order to identify the exact effect of these defects on the residual resistance of the plates, tests of compression after impact (CAI) will be made in a future study.

Finally, this study shows that layers made of hollow spheres core offer a good candidate for protection of composite structures against impact. It is important to underline that for the purpose of

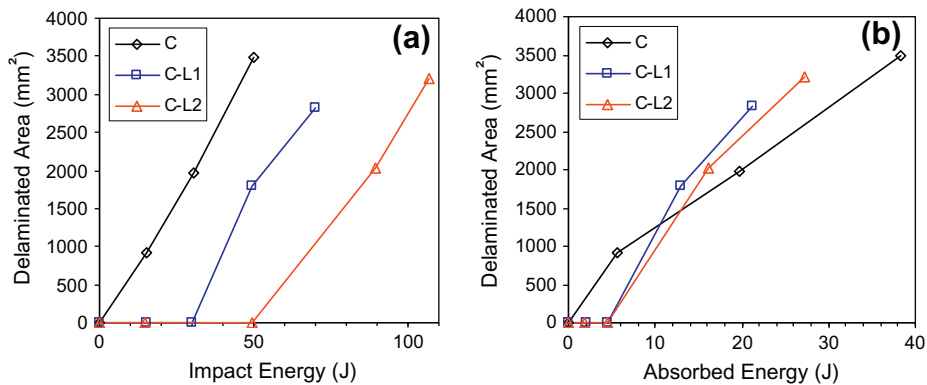


Fig. 10. Delaminated area in composite plate versus impact energy (a) and energy absorbed in the plate (b).



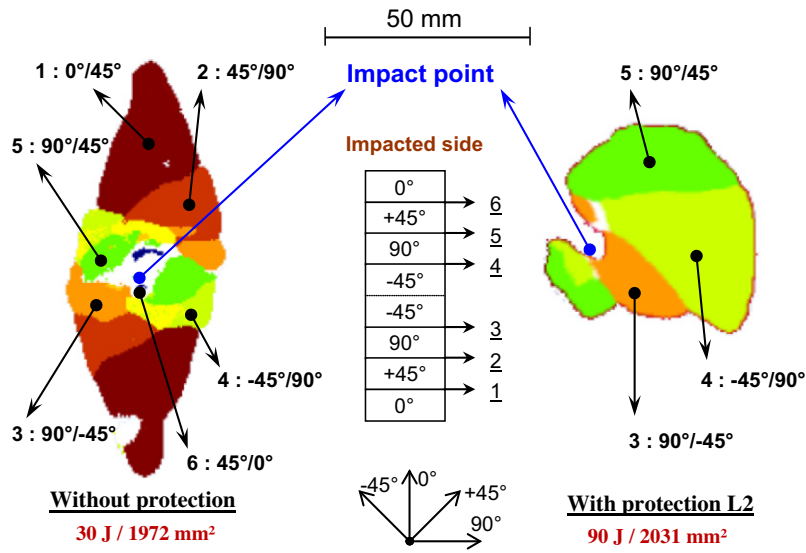


Fig. 11. Focus on delaminated area for impacted composite plates: with protection L2 (90 J) – without protection (30 J).

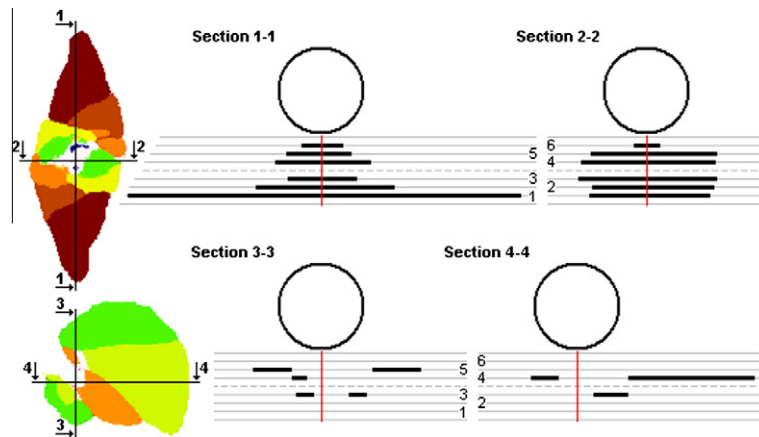


Fig. 12. Location of delamination in the thickness for impacted composite plates: with protection L2 (90 J) – without protection (30 J).

energy absorption hollow spheres have an advantage over other materials (honeycomb, foam...) due to their easy installation on non-flat structures (e.g. cylindrical surfaces).

In a subsequent study, tests of compression after impact will be made on impacted composite plates. These tests allow identification of the resistance/mass gain obtained when adding the protective layers. On the other hand, another study on modelling of impact on protective layers will also be carried out in order to optimise layers in function of given specifications.

#### 4. Conclusions

In this paper, an experimental study of protective layers on composite structures submitted to low energy impacts is made. These layers are made up of hollow spheres core and Kevlar woven fabric skin. Two configurations of protective layers designed for 50 and 90 J have been impacted at several impact energies on aluminium support and on composite plates. The different impact curves show that the impactor does not touch the composite plates at the different impact energies used. Furthermore, no defects were visible during C-scan observations on the composite plates protected by: (i) configuration L1 and subjected to impact

energy lower than 30 J, (ii) configuration L2 and impacted by energy lower than 50 J. However, delamination was observed when impacting plates protected by configuration L1 and L2, subjected to 50 and 90 J impact energies respectively.

Although the use of protective layer involves a significant increase in weight, this study shows the interest of this concept of protective layers made of hollow spheres core and woven fabric Kevlar skin for the protection of composite parts. Industrial applications for such a protective layer concept are aeronautical composite structural parts expensive to repair or replace, or composite structures for which the weight is not a major problem. It is also important to notice that in the field of aeronautics, this kind of protection is a very good indicator of impact, as the visible impact damage is in the layer, and not in the composite laminate.

Moreover, an advantage in the use of hollow spheres is their easier installation on complex shapes such as non-flat surfaces as well as circular ones. These protective layers can also be changed in case of impact, without changing or repairing the protected composite structure below. This shows the interest in using hollow spheres in the protection of structures against impact.

Of course, the authors are aware that currently the additional mass due to the protection is relatively important, and an

optimisation phase of both materials and layer concept is required to obtain a better ratio between protection and weight.

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### References

- [1] Abrate S. Impact on composite structures. Cambridge University press; 1998.
- [2] Coutellier D, Walrick JC, Geoffroy P. Presentation of a methodology for delamination detection within laminated structures. *Compos Sci Technol* 2006;66(6):837–45.
- [3] Alderliesten RC. Damage tolerance of bonded aircraft structures. *Int J Fatigue* 2009;31(6):1024–30.
- [4] Moody RC, Harris JS, Vizzini AJ. Width effects on the compression strength of composite sandwich test specimens after barely visible impact damage. In: AIAA/ASME/ASCE/AHS/ASC 40th structures, structural dynamics, and materials conference, St. Louis, April 1999.
- [5] Mitrevski T, Marshall IH, Thomson R. The influence of impactor shape on damage to composite laminates. *Compos Struct* 2006;76(1–2):116–22.
- [6] Li CF, Hu N, Cheng JG, Fukumaga H, Sekine H. Low-velocity impact-induced damage of continuous fiber-reinforced composite laminates Part II. Verification and numerical investigation. *Compos Part A* 2002;33(8):1063–72.
- [7] Davies GAO, Zhang X. Impact damage prediction in carbon composite structures. *Int J Impact Eng* 1995;16(1):149–70.
- [8] Ballère L, Viot P, Lataillade JL, Guillaumat L, Cloutet S. Damage tolerance of impacted curved panels. *Int J Impact Eng* 2009;36(2):243–53.
- [9] Abi Abdallah E, Bouvet C, Rivallant S, Broll B, Barrau JJ. Experimental analysis of damage creation and permanent indentation on highly oriented plates. *Compos Sci Technol* 2009;69(7–8):1238–45.
- [10] Bouvet C, Castanié B, Bizeul M, Barrau JJ. Low velocity impact modelling in laminate composite panels with discrete interface elements. *Int J Solids Struct* 2009;46(14–15):2809–21.
- [11] Wang D. Impact behavior and energy absorption of paper honeycomb sandwich panels. *Int J Impact Eng* 2009;36(1):110–4.
- [12] Li Y, Li JB, Zhang R. Energy-absorption performance of porous materials in sandwich composites under hypervelocity impact loading. *Compos Struct* 2004;64(1):71–8.
- [13] Apetre NA, Sankar BV, Ambur DR. Low-velocity impact response of sandwich beams with functionally graded core. *Int J Solids Struct* 2006;43(9):2479–96.
- [14] Shin KB, Lee JY, Cho SH. An experimental study of low-velocity impact responses of sandwich panels for Korean low floor bus. *Compos Struct* 2008;84(3):228–40.
- [15] Petit S, Bouvet C, Bergerot A, Barrau JJ. Impact and compression after impact experimental study of a composite laminate with a cork thermal shield. *Compos Sci Technol* 2007;67(15–16):3286–99.
- [16] Rahmé P, Bouvet C, Rivallant S, Fascio V, Valembois G. Mechanical protection for composite structures submitted to low energy impact. In: 14th European conference on composite materials, Budapest, June 2010.
- [17] Hart 't WGJ, Ubels LC. Impact energy absorbing surface layers for protection of composite aircraft structures. In: 8th European conference on composite materials, Naples, June 1998.
- [18] Airbus Industrie Test Method: AITM 1-0010: Determination of compression strength after impact.
- [19] Patent no. 2 930 478. Peau amortissante de protection de pièces composites, by ATECA (<http://www.ateca-fr.com>) and Conseil et technique (<http://conseil-et-technique.com>).