Development of Orbital Debris Impact Protection Panels

Authors:

Marco ANGHILERI*
Luigi-M L CASTELLETTI*
Fabio INVERNIZZI*
Marco MASCHERONI*
Francesco PIGOLI*

Affiliation for all the authors: Department of Aerospace Engineering
Politecnico di Milano
via La Masa 34, 20156 Milano, Italy

Correspondence:

Fabio INVERNIZZI

Telephone: 00 39 02 2399 7155
Fax: 00 39 02 2399 7153
E-mail address: invernizzi@aero.polimi.it

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ABSTRACT

The presence of debris in the orbits used by artificial satellites represents an actual threat for space operations – as such an event is likely to cause the failure of the satellite. Spacecraft hulls are in general built with honeycomb-cored sandwich panels made of Aluminium alloys - which are not effective as a protection in case of medium size debris impact. Using LS-Dyna 970, the benefits (from a mechanical standpoint) coming from the use of materials such as polymeric foams or aramidic fibres in manufacturing hull panels were investigated. Indeed, these materials are frequently used in common applications for their excellent ballistic characteristics and low weight. Initially, a reliable numerical model was developed referring to experimental tests consisting of the impact of medium size debris against sandwich panels with honeycomb core. Hence, using the same impact scenario of the tests, the impact behaviour of different panel typologies obtained using a polymeric foam core or using aramidic fibres as reinforcement was evaluated. As a result, it was possible to highlight the advantages coming from the use of these materials in order to have lightweight and debris-proof structures.

INTRODUCTION

The presence of debris in the orbits used by artificial satellites represents an actual threat for space operations [1]. The impact between orbital debris and satellites, in fact, is likely to cause damages that range from a simple malfunctioning due to the damages of one or more systems to the loss of the satellite and then to the failure of the mission.

Different methods are currently used to avoid that threat. Among those, *active protection systems* are particularly effective for large debris, whilst *passive safety devices* (such as external protection panels) are useful to minimise the damages caused by medium and small debris. In particular, the shield-panels have to withstand the impact avoiding penetration.

The structures of satellites are usually manufactured using sandwich panels of aluminium alloys with a honeycomb core [2]. This panel typology combines a high bending strength with a lightweight and does not require particular care in manufacturing. Unfortunately, it is not equally effective as a protection from the impact of medium size debris.

The aim of this research work is to find an alternative to the usual aluminium sandwich panel: a different panel typology able to stop the debris without increasing the overall weight of the structure or affecting the structural stiffness. In particular, the benefits in using sandwich panels with polymeric foams [3] or panels reinforced with aramidic fibres [4] in the manufacture of satellite structures were investigated. Indeed, polymeric foam and aramidic fibres, due to their excellent ballistic capabilities and lightweight, are widely diffused as means to absorb impact energy.

Initially, a reliable numerical model was developed and validated referring to experimental tests [5] that reproduced the impact of medium debris onto a sandwich panel typically used in the manufacture of satellite structures. After obtaining a good numerical-experimental correlation, the same impact scenario was used to evaluate the behaviour of panels built using a polymeric foam core and panels built using aramidic fibres.

Advantages and disadvantages of the different shield-panel typologies were outlined in view of the obtained results. In that, it was observed that the aluminium sandwich panels are not optimized to withstand debris impacts. Furthermore, it was possible to appreciate the benefits deriving from the use of polymeric foams and aramidic fibres.

1. SANDWICH PANELS WITH HONEYCOMB CORE: NUMERICAL MODEL VALIDATION

The numerical model to investigate the consequences of a medium debris impact was developed and validated referring to tests carried out at the *Kurzzeidynamik Ernest Mach Institut* in Freeburg [5] – and here only briefly described. This model was subsequently used to investigate the effectiveness of new panel typologies as a protection against the medium debris impact.

1.1 Experimental tests

The tests used to develop the model were part of a program carried out to characterise the behaviour of sandwich panels of aluminium alloy with (aluminium) honeycomb core when impacted by orbital debris.
Using a gas cannon [5], spheres in (cast) aluminium of different sizes were shot with different velocities against a target – a square panel with 150 mm edge.
Two different impact scenarios were considered (typical in geostationary orbit). The first, here indicated as *low impact velocity test*, characterised by a debris of 3.5 mm diameter and an impact velocity of 494 m/s. The second, here indicated as *high impact velocity test*, characterised by a debris of 2.0 mm diameter and an impact velocity of 1800 m/s.
The panels used in both test typologies were sandwich panels made of two 1.0 mm thick aluminium alloy (Al 2024-T6) plates and a 47.0 mm thick aluminium honeycomb core (Figure 6a).

Low impact velocity tests. The impact of the projectile on the first plate caused the formation of a crater and the separation of part of the plate (plug). The projectile passed through the panel (without impacting the honeycomb) and finally was stopped by the second plate.

High impact velocity tests. The impact of the projectile on the first plate caused the complete perforation of the panels. The holes in the plates were sharp: no craters were observed.

The scarce contribution of the honeycomb was a feature that both the test typologies shared. In that, sandwich panels with a different core were deemed to be more effective as a protection against medium debris impact.

1.2 Numerical model

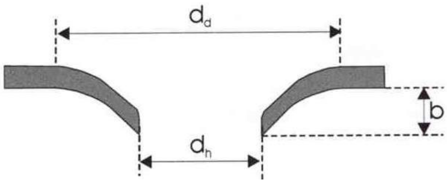
The numerical model was developed to reproduce the experimental tests [3] in detail. Also, great care was devoted in posing the proper *boundary* and *initial* conditions.
Only a small portion of the panel (25 mm x 25 mm) was considered. The mesh of the plates, finer in the impact region, consisted of ten layers of 42160 eight-nodes solid elements. The mesh of the honeycomb, finer next to the plates, consisted of 29580 four-nodes shell elements.
The FE mesh of the projectiles was built on the geometry of a sphere for both the projectiles (used in low and high impact velocity tests). The number of the element was the same: 3456 eight-nodes solid elements.
The elastic piecewise plastic constitutive law (*MAT_24 in [7, 8]) was used for all the materials in the model. Cowper-Simond coefficients were used to take into account strain-rate effects.

1.3 Numerical-experimental correlation

The results of the numerical simulations were compared qualitatively and quantitatively with the experimental data collected during *low* and *high* impact velocity tests.

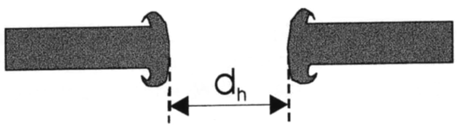
Low impact velocity tests. In Table 1, experimental data and numerical results for the low velocity impact are compared referring to characteristic parameters [9]: diameter of the impact hole, diameter and depth of the crater in the first plate. Images of the panel after the impact and results from the simulation are shown in Figure 1.

High impact velocity tests. In Table 2, experimental data and numerical results for the high velocity impact are compared referring to characteristic parameter [9]: the diameter of the impact hole. Images of the panel after the impact and results from the simulation are shown in Figure 2.



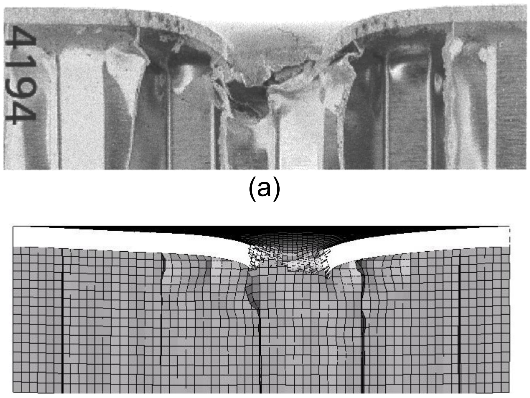
	Experimental test	Numerical simulation
dh (mm)	3,5	3,7
Dd (mm)	20,0	21,3
b (mm)	2,3	1,9

Table 1 – Experimental-numerical correlation – Low velocity impact



	Experimental test	Numerical simulation
dh (mm)	2,9	2.89

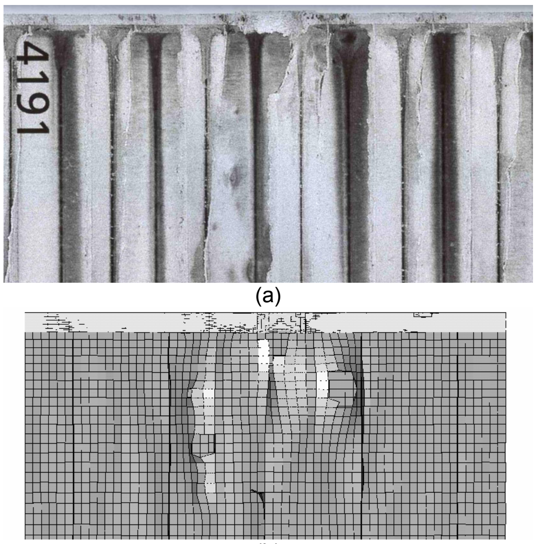
Table 2 – Experimental-numerical correlation – High velocity impact



(a)

(b)

Figure 1 – Low velocity impact test: qualitative comparison between (a) experimental data and (b) numerical results



(a)

(b)

Figure 2 – High velocity impact test: qualitative comparison between (a) experimental data and (b) numerical results

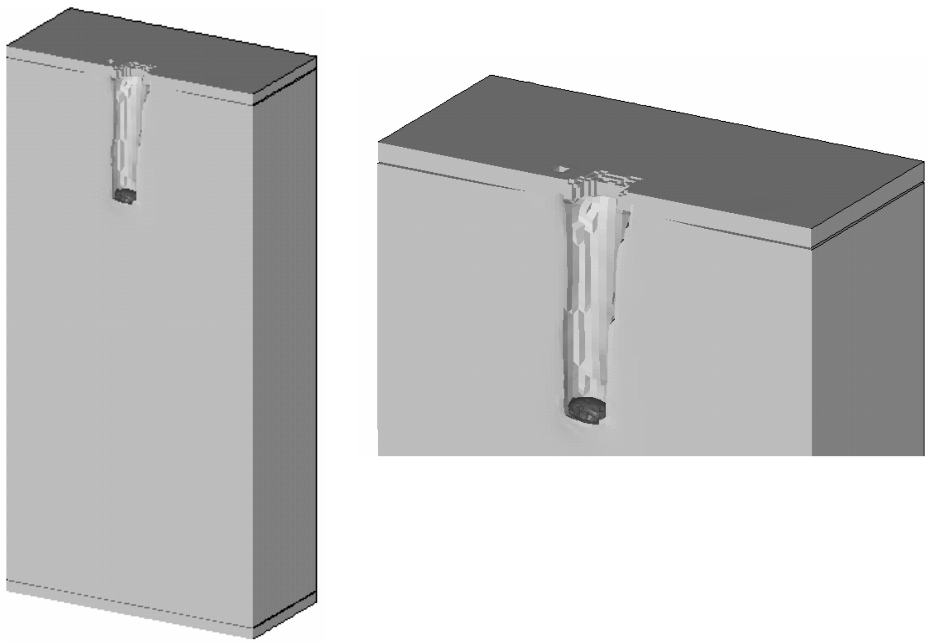
2. SANDWICH PANELS WITH POLYMERIC FOAM CORE

Honeycomb core gives a scarce contribution against medium-size debris impact. Therefore, since polymeric foams are known for the high proficiency in absorbing impact energy [10-12], the effectiveness of a sandwich panel with a polymeric foam core [3] as a protection against medium debris impact was investigated.
Before considering polymeric foams, the benefit coming from the use of aluminium foams were investigated. Unfortunately, with regard to the aluminium foam considered, the average size of the cells was greater than the size of the debris and therefore the contribution of the core was negligible.

Numerical model. The numerical model of the panel was obtained from the one previously described changing the honeycomb with the foam (Figure 6b). The mesh of the foam consisted of 218636 eight-nodes solid elements. A material

model developed to characterise the behaviour of foams with high impact energy absorption capability was used (MAT_126 in [7, 8]).
The impact scenario was the one of the high velocity tests.

Results obtained and remarks. The simulations carried out demonstrated that a sandwich panel with a polymeric foam core is an effective protection against the impact of a medium debris impact. The debris, in fact, was stopped just after breaking through the first plate (Figure 3) and, in that, the results obtained were deemed encouraging. On the other hand, the weight of such a shield-panel is about one third higher than the one of the panel with a honeycomb core (Table 3).



(A) (B)

Figure 3 –Orbital debris impact against a sandwich panel with polymeric foam core.

3. SHIELD-PANELS REINFORCED WITH ARAMIDIC FIBRES

A polymeric foam cored-sandwich panel is more effective than a honeycomb-cored sandwich panel as a protection against medium debris impact, but also heavier. Therefore, the behaviour of a panel reinforced with aramidic fibres was considered.
The aramidic fibres were, initially, used in combination with aluminium alloy plates and, then, combined with carbon fibre reinforced plastic (CFRP) woven plies. Benefits and drawbacks of these two different panel typologies were evaluated in view of the results of the simulations carried out.

3.1 Aluminium alloy panel reinforced with aramidic fibres

The aramidic fibres show excellent ballistic behaviour. Unfortunately, aramid (i.e. *aromatic polyamide*) is a hygroscopic material. Regardless, in this research work, the aramidic fibres were regarded only from a mechanical standpoint.

Numerical model. The panel was obtained inserting ten layers of aramidic fibres (±45° symmetric, 0.2 mm thick) between two aluminium alloy plates (0.4 mm thick). Both the aluminium alloy plates and the aramidic fibres layers were modelled using eight-nodes solid elements. The whole mesh consisted of 118048 elements.
The behaviour of the aramidic fibres under dynamic loads was modelled using a material model developed for composite material and validated referring to experimental crush test carried out at the *Department of Aerospace Engineering* of the *Politecnico di Milano* [6]. The model of the projectile and the impact scenario were the same of the high velocity tests.

Results obtained and remarks. The simulations showed the excellent ballistic behaviour of the aluminium alloy plates reinforced with aramidic fibres. The debris was stopped before it reached the second plate (Figure 4) and, therefore, it was shown that such a panel is able to avoid penetration when used as a part of the structure of a satellite. Furthermore, it allows a relevant saving in weight: the weight of this panel typology, in fact, is about half the one of the sandwich panel with a honeycomb core.
On the other hand, it is straightforward realising that such a panel has a flexural stiffness much lower than the ones of the panels previously considered.
A greater flexural stiffness could be easily obtained by using this panel as external skins of a sandwich panel (Figure 6c). Such a sandwich panel, with a honeycomb core, 23.5 mm in thickness (i.e. half the thickness of the reference honeycomb-cored sandwich panel), would have the same flexural stiffness and the same weight, but would also provide a complete protection against the impact of medium size orbital debris (Table 3).

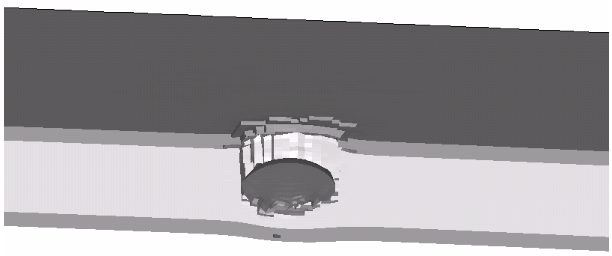


Figure 4 – Orbital debris impact against an Aluminium/aramidic-fibres/Aluminium panel

3.2 Carbon fibres and aramidic fibres reinforced plastic panel

Carbon fibres exhibit high stiffness-to-weight and strength-to-weight ratio. Furthermore, since carbon fibres are an orthotropic material, they allow optimising the design of the structure. The recourse to this material (supported by new and more accurate numerical tools able to model its static and dynamic behaviour) is constantly increasing in all the fields of the industry. Indeed, a laminated panel made of carbon and aramidic fibres reinforcement was here considered as a shield against orbital debris impacts.

Numerical model. The panel was obtained inserting ten layers of aramidic fibres (±45° symmetric, 0.2 mm thick) between four layers of carbon fibres (±45° symmetric, 0.2 mm thick). Both carbon and aramidic fibres layers were modelled

using eight-nodes solid elements. The whole mesh consisted of 118048 elements.
The behaviour of both carbon fibres and aramidic fibres under dynamic loads was modelled using a material model developed for composite material and validated referring to experimental crush test carried out at the *Department of Aerospace Engineering* of the *Politecnico di Milano* [6, 13]. The model of the projectile and the impact scenario were the same of the high velocity tests.

Results obtained and remarks. The simulations showed that the panel, after the impact, reaches its *ballistic limit*: the debris perforated the panel (Figure 5) – althought the velocity of the debris at the end of the simulation was slowed almost to zero.
The perforation could be avoided by adding two additional layers of aramidic fibres.
Besides, a sandwich panel obtained using this panel typology after adding (Figure 6d) two further plies and a honeycomb core, 23.5 mm in thickness (i.e. half the thickness of the reference honeycomb cored sandwich panel), would have the same flexural stiffness, but would be one tenth lighter and, in addition, would also provide a complete protection against the impact of medium size orbital debris (Table 3).

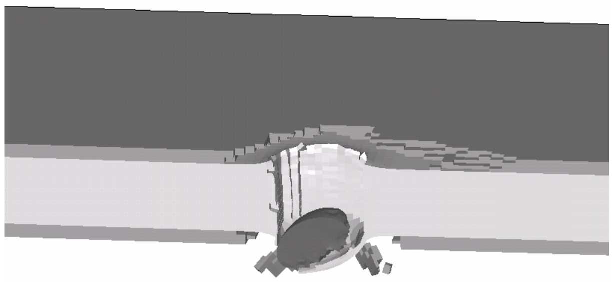


Figure 5 – Orbital debris impact against a CRFP/aramidic-fibres/CRFP panel

4. SUMMARY AND REMARKS

The different panel typologies considered and presented in this work is shown in Figure 6. The comparison among their characteristics is reported in Table 3.
In particular, it is worth noticing that the sandwich panel consisting of external skins of CFRP woven plus aramidic fibres and aluminium-cell honeycomb core (Figure 6-d) not only represents a good compromise between lightness and flexural stiffness but also provide a satisfactory orbital debris protection.

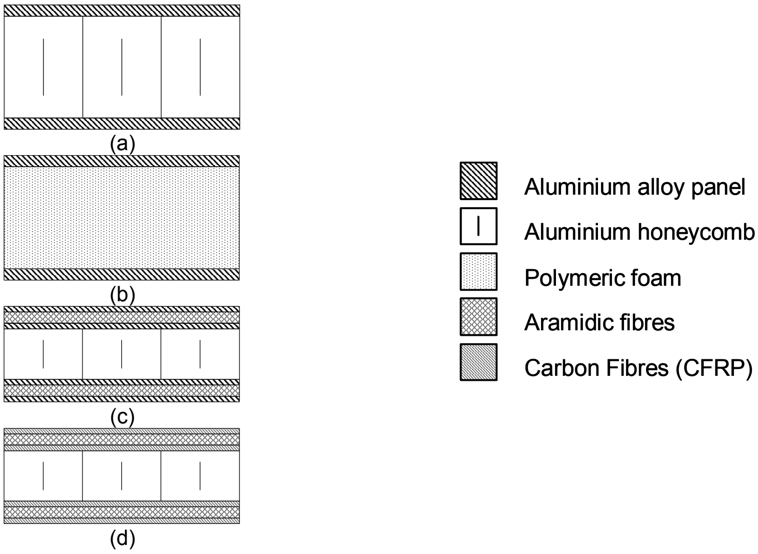


Figure 6 – Panel typologies scheme.

Sandwich panel typology	Relative weight *	Relative flexural stiffness **	Orbital debris protection
Figure 6-a	1.0	1.0	NOT EFFECTIVE
Figure 6-b	1.3	1.0	EFFECTIVE
Figure 6-c	1.0	1.0	EFFECTIVE
Figure 6-d	0.9	1.0	EFFECTIVE

** Weight referred to the weight of the panel in Figure 6-a*
*** Flexural stiffness referred to the flexural stiffness of the panel in Figure 6-a*

Table 3 – Summary of the different panel typology performances.

CONCLUSIONS

The presence of debris in the orbits used by artificial satellites is an actual menace for the space mission. In particular, the impact of medium debris is likely to cause serious damages.
In satellite manufacture, aluminium alloy sandwich panels with a honeycomb core are customary used. Unfortunately, these panels are not particularly effective as a protection against debris impact. Therefore, in this research work, the benefits of using different typologies of shield-panels were investigated.
Initially, a numerical model to analyse the event was developed and validated referring to specific tests carried out considering two different impact scenarios – which are typical in the geostationary orbit. Subsequently, the worthiness of sandwich panels with polymeric foams or panels reinforced with aramidic fibres was investigated.
As a result, it was shown that these panels are able to successfully contrast the menace of medium debris impact without increasing the overall weight of the structure or affecting its flexural stiffness. In view of that, further researches to investigate the effectiveness of these panels with regard to other load conditions and to develop the technology to produce these panels are recommendable.

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