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Comparative Studies on the Impact Behavior of Two Sandwich Structures

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Abstract

The purpose of this paper is to evaluate the impact behavior of two sandwich structures with different cores – polyurethane foam and expanded polystyrene foam coated with a thin metallic layer made of steel and aluminum. Moreover, the contact phenomenon which occurs between a rigid impactor and a sandwich structure is discussed in detail since it is very important to take into consideration the local deformation in the contact zone, in order to create a numerical model for predicting the contact force history. Also, in this paper is presented the rupture of the expanded polystyrene during the impact. The authors have chosen those configurations due to the different mechanical properties and energy absorption observed and measured on polyurethane and polystyrene foams.

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Keywords: sandwich; impact; polyurethane foam; polystyrene

1. Introduction

Nowadays, there is strong interest in the effects of impact induced damage to composite structures as evidenced by the large number of papers on this topic that have appeared in the scientific literature in last years. The sandwich composite structures are often subjected to object impacts that are expected to occur during the life of the structure.

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In most cases these collisions can introduce damages, often difficult to be detected reducing significantly the strength of the structure. Research studies were concentrated on monolithic laminates while sandwich structures with laminated skins, widely also used in aeronautics and aerospace industry, received less attention.

The use of sandwich structures has gained an important place, due to their important role in the structural components of the aircraft industry and not only. Advances in polymer science and manufacturing processes have extended their use in a wide range of applications (automotive industry, civil engineering, sport, leisure etc.), since these materials, while arranged in different combinations, bring a series of advantages focused on the mechanical performances and forms of design.

Over the past few years, the range of applications of different types of foam became increasingly larger because design engineers insisted on changing the microstructure of materials, in order to obtain improved mechanical properties.

Given that the collision with various objects represent a frequently factor which occurs in the exploitation of different sandwich components, the authors considered that the impact energy absorbed by the structure as well as the damage mitigation represent two essential aspects to be taken into consideration.

Since the polyurethane (PU) and the expanded polystyrene (EPS) are two of the most widely foams used as core materials in sandwich structures and due to the fact that some authors performed experimental studies on such materials, in the present paper the authors focused their work on the numerical modelling of these materials behaviour.

As most representative skins used in the aeronautic and automotive industry are steel and aluminium layers, the authors performed this study on several sandwich configurations with different combinations of skins and core materials.

2. Critical overview on the impact behavior of sandwich structures

Depending on the kinetic energy of the collider, impact tests can be classified into three main categories: low speed impact (up to 50 m/s), impact at high speed (50 m/s < v < 1.5 km/s) and in the latter, a hyper-velocity impact (> 1.5 km/s), for example, ballistic impact. However, until now there is not a clear transition between these categories and authors of these studies have not agreed on the definition of these thresholds.

Sjoblom et. al. [1], Shivakumar et. al. [2] defined as "low speed impact" the impact where the dynamic response of the tested sample is negligible. Depending on the specimen stiffness and material properties and the collider mass and rigidity, the upper limit speeds can vary by a few tens of m/s.

For higher speeds, the structure does not have enough time to respond to the impact phenomenon. Consequently, the impact response is dominated by strain wave propagation. In addition, the elastic strain energy decreases and a part of the initial impact energy is thus transferred to create damages in the vicinity of the impact.

However, for low-speed impact, as the contact time is sufficient to permit the entire structure to respond to impact, the structural dynamic response of the sample is of the outmost importance, and consequently, a large part of the incident energy is absorbed as elastic deformation.

Cantwell and Morton [3] proposed a classification based on the test media used in the experimental simulations of the impact (a mass falling from a certain height). According to these authors' views, a low speed impact test is considered the one where the kinetic speed does not exceed 10 m/s.

Other authors have chosen to classify impact tests according to the damage mechanisms induced during a dynamic loading. We can cite for example the works of Liu and Malvern and [4], Joshi and Sun [5].

Finally, Davies and Robinson [6] defined the low-speed impact as the impact where the shock waves have a significant influence on stress distribution. In addition, the authors proposed a simple model to define the transition phase from a low-speed impact to a high-speed impact.

3. Comparative study on the impact behavior of polyurethane foam and expanded polystyrene

When using expanded polystyrene foam, according to some studies on the energy absorption capacity of these materials it has been proven that this capacity can be controlled both on a macroscopic scale - by choosing density foam able to minimize the load transferred and the acceleration in relation to the volume of available absorber, as on a microscopic scale - by changing the internal structure of expanded polystyrene grains according to the size and wall thickness.

In Fig. 1 and 2 are presented two samples of polyurethane foam respectively expanded polystyrene used in the numerical modeling. The foam specimens have a cylindrical shape, with a diameter of 10,6 mm and a height of 7,6 mm.

Fig. 1. Polyurethane foam specimen.

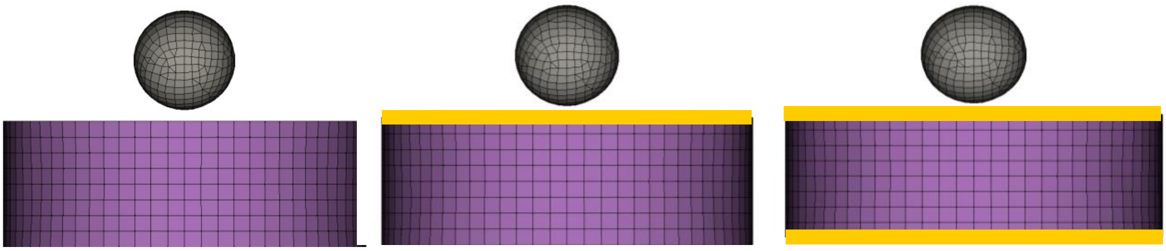
Fig. 2. Expanded polystyrene foam specimen.

When using expanded polystyrene foam, according to some studies on the energy absorption capacity of these materials it has been proven that this capacity can be controlled both on a macroscopic scale - by choosing density foam able to minimize the load transferred and the acceleration in relation to the volume of available absorber, as on a microscopic scale - by changing the internal structure of expanded polystyrene grains according to the size and wall thickness.

The modelling of these samples was carried out in five different configurations using FEM, through ANSA pre-processor, LS-DYNA processor and META-POST post-processor:

- Simple impact test sample (without skins) on PU and EPS foam;
- Impact test on a steel layer applied on the upper surface of PU and EPS foam;
- The impact testing of two steel layers applied on both surfaces of the PU and EPS foam;
- The impact testing of aluminium layer applied on the upper surface of PU and EPS foam;

The impact testing of two aluminium layers applied on both surfaces (top and bottom) of the PU and EPS foam. The five configurations are shown in Fig. 3 a, b, c.



a) without layer　b) with one top layer　c) with two top und bottom layers

Fig. 3. Configurations of impact tests.

For the numerical modelling of the foam there have been used effectively first order (single node of integration) tetrahedral solid elements with great accuracy in case of dynamic stresses, working with a high accuracy even in case of large deformations. For better contact definition and to get the stress on the outside face of the foam, the solid was ‘coated’ with thin shell elements sharing the same material as solid. In addition to these advantages the use of tetrahedral element reduces also the computation time. Using this type of element can lead to zero energy deformation modes, known also as "hourglass energy modes” that must be eliminated. Hourglass modes are nonphysical, zero-energy modes of deformation that produce zero strain and no stress. Hourglass modes occur only in under-integrated (single integration point) solid, shell, and thick shell elements. LS-DYNA has various algorithms for inhibiting hourglass modes.

The thickness of the layer(s) of the metal coating was 0,2 mm, and 7,6 mm thick core. Samples were subjected to impact through spherical rigid projectile with a diameter of 2,5 mm, having a mass of 2,4 g at a speed of 120 km / h (33.3 m / s). The samples were simply supported on a perforated circular plate of 18 mm diameter.

The selection of a perforated plate was motivated by the fact that the phenomenon of the shock wave transmission, followed by the material breaking can be better observed in this case.

In Fig. 4 a) and b) are depicted the support plate used for the abutment of the specimens.

a) Perspective drawing of the configuration b) Bottom view of the configuration

Fig. 4. Support plate for the abutment of the specimens.

4. Obtained results

4.1. Comparative study between impact behaviour of polyurethane foam - polystyrene without layers

In Fig. 5 is represented the time - displacement variation in (Oz) direction for the polyurethane foam.

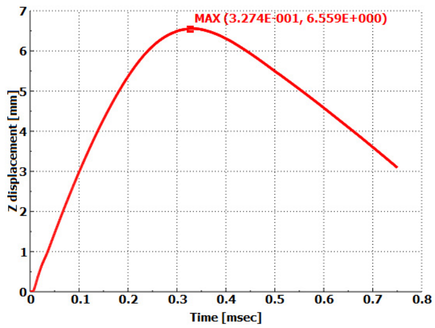


Fig. 5. Time-displacement variation for the PU foam without metallic layers.

In this study it was found that the polystyrene sample does not withstand to impact, producing a perforation of the material. This phenomenon can be seen in Fig. 6. Unlike polyurethane foam which absorbs all the projectile energy, the polystyrene foam crumbles, leaving the projectile to pass through it.

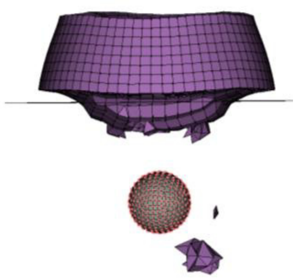


Fig. 6. Perforation of polystyrene specimen.

To avoid the numerical problems like penetrations between the impactor and the skins which conduct to an unrealistic behaviour, the authors have chosen to use ‘node to surface’ contact type, to define the contact between the impactor and the samples.

Node-to-surface contact is a contact type which is established when a contacting node penetrates a target surface. This type of contact is commonly used for general contact between two surfaces and it also been used to define the contact between the samples and the fixed support.

The eroding contact options were used to define the contact between the impactor and interior elements form the foam core. That kind of contact options are used when the elements forming one or both exterior surfaces experience material failure during contact. Contact is allowed to continue with the remaining interior elements from the EPS foam.

In Fig.7 is presented the deformed shape of the polyurethane foam specimen.

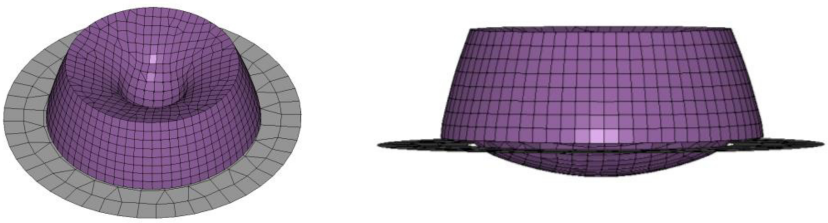
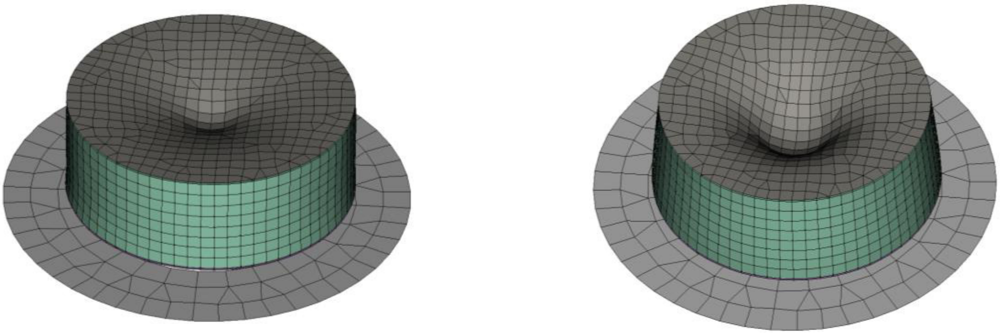


Fig. 7. Deformed shape of polyurethane foam specimen.

4.2 Comparative study between the impact behaviour of a sandwich structure made of polyurethane foam core and steel/ aluminium skins

In Fig. 8 are depicted the deformed shapes of two different sandwich samples:

a) polyurethane foam (as core material) embedded in two steel layers;
b) polyurethane foam (as core material) embedded in two aluminium layers.

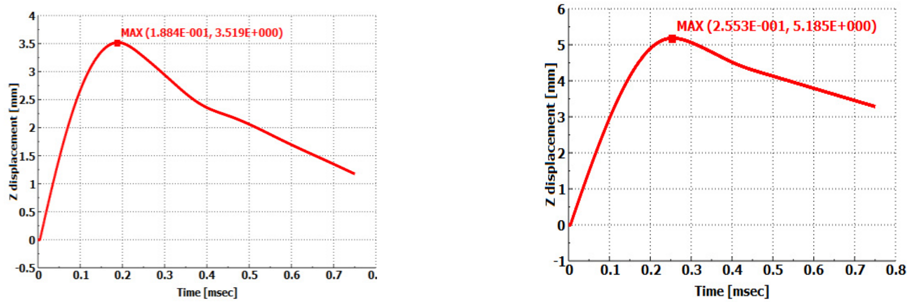


a) b)

Fig. 8. Deformed shapes of two polyurethane foam sandwich specimens
a) with steel layers; b) with aluminium layers.

After running the program, it was found that the maximum deformations in the two materials were: 3.519 mm for the steel layered sandwich structure, respectively 5.185 mm for the aluminium one. As a remark, the authors performed also a study on a sandwich structure equipped with only one layer fixed in the upper part of the sample. They conclude that the maximum deformation of the specimen with two layers of steel is higher than for the single-layer (2.939 mm). This is due to the fact that, when the impactor strikes the first layer, the shock wave is retained by the second layer and then reflected in the mass of the polyurethane foam. In the case of double-layered aluminium specimen, due to the malleability of the aluminium, the phenomenon will not repeat as in the first case, since a part of the impact energy has been absorbed by the first skin, the shock wave being far smaller than that of the steel layered specimen.

In Fig. 9 is presented the displacement versus time variation law for the two configurations.



a) b)

Fig. 9. Displacement – time variation for steel (a) and aluminium (b) sandwich configurations.

4.3 Comparative study between the impact behaviour of a sandwich structure made of expanded polystyrene foam core and steel/ aluminium skins

In Fig. 10 is shown the deformed shape of the two steel (a) and aluminium (b) expanded polystyrene foam sandwich structures.

As regards the specimen with two layers of aluminium, the maximum deformation could not be determined as the impactor penetrated the specimen, through the two aluminium layers. In order to simulate the material failure, in the program it has been defined a maximum plastic strain where the materials starts to fail until breaking. This phenomenon could be observed in Fig. 10, b [7]. After program processing, it was found that the maximum deflection recorded for the specimen with two layers of steel was 5.596 mm (Fig. 11).

a) b)

Fig. 10. Deformed shapes of two expanded polystyrene foam sandwich specimens
a) with steel layers; b) with aluminium layers.

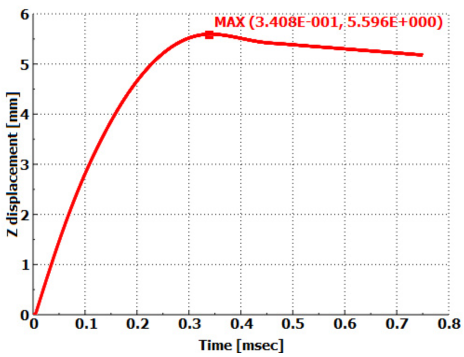


Fig. 11. Displacement – time variation for steel expanded polystyrene foam sandwich configuration.

4.4 Analysis of contact force magnitude and absorbed energy for the steel/ aluminium sandwich configurations

In Fig. 12 and 13 is plotted the contact force magnitude versus time for the steel and aluminium specimens, whereas in Fig. 14 and 15 the absorbed energy of the four sandwich configurations.

As one can see, in case of samples with steel and PU foam there is a maximum contact force of 815,4 [N] , whereas in those with aluminium and PU foam the level of this force is lower (642,6 [N]). This force decrease is due to the fact that the aluminium layers absorb a higher energy through their plastic deformation than the steel ones. Consequently the wave shock is lower in case of aluminium sandwich sample in comparison to the steel layered specimen.

The maximum impact occurs at $0{,}154\cdot10^{-3}$ [sec] in the first case, respectively at $0{,}170\cdot10^{-3}$ [sec] in the second case. In Fig. 13 the contact force in the aluminium layered - EPS specimen do not reflect the real maximum contact force because the specimen is penetrated by the impactor.

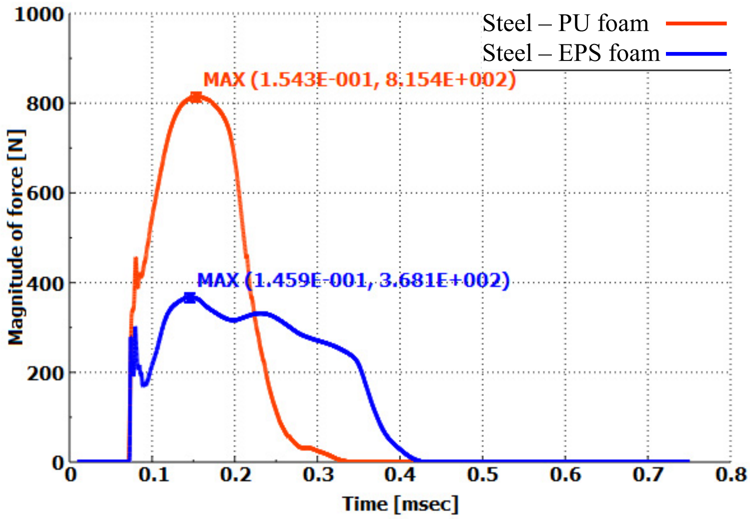


Fig. 12. Time dependence of the contact force intensity between the steel layered polyurethane/ expanded polystyrene sandwich structure and the support.

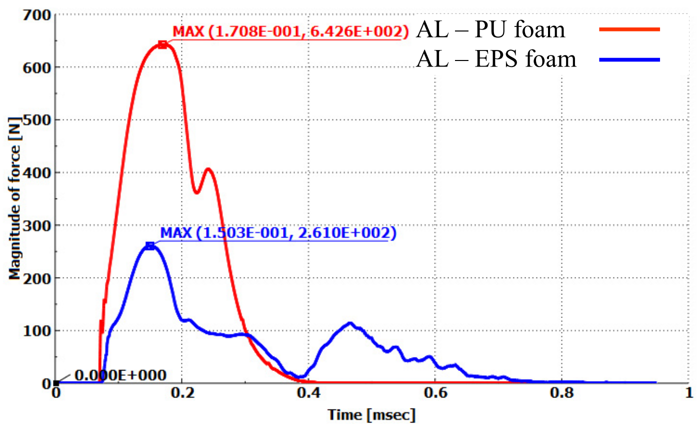


Fig. 13. Time dependence of the contact force intensity between the aluminium layered polyurethane/ expanded polystyrene sandwich structure and the support.

As one can see in Fig. 12 the contact force registered for the PU foam and steel layers is almost two times greater that the contact force measured for the EPS foam and steel layers. This is due to the fact that the EPS foam has a better plastic deformation than PU foam. Consequently the EPS foam core dissipates more energy than the PU core does.

In case of the polyurethane foam specimen, regardless of cover layers (steel or aluminium) the energy absorbed has approximately the same value of about 1 [kJ].

For the specimen with expanded polystyrene core, only in the case where the skins are made of steel there is no any impactor penetration, the energy input being at a value substantially equal to that of the corresponding foam specimen. In case of the aluminium layers and polystyrene foam specimen, as the impactor penetrates the sample, the absorbed energy level decreases due to the fact that the core is damaged.

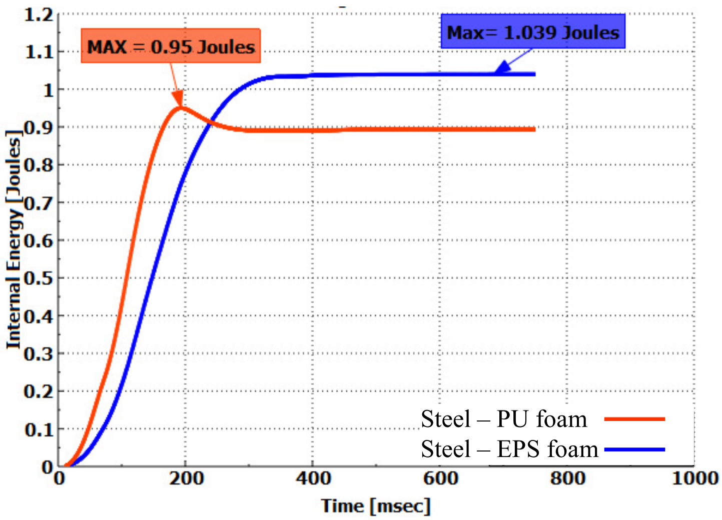


Fig. 14. Time dependence of the absorbed energy for the steel layered polyurethane/ expanded polystyrene sandwich structure.

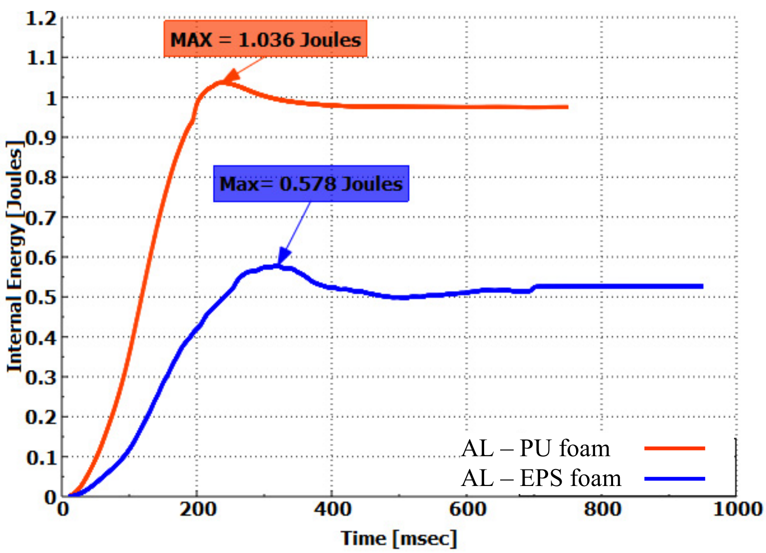


Fig. 15. Time dependence of the absorbed energy for the aluminium layered polyurethane/ expanded polystyrene sandwich structure.

Conclusions

This purpose of this work was to evaluate the impact behaviour of sandwich composites made in several configurations:

- Polyurethane (PU) foam core with two coatings of steel / aluminium;
- Expanded polystyrene (EPS) core with two coatings of steel / aluminium;

The idea of this paper started from two studies conducted by Burbank in [8] and by Shah and Topa [9] on the impact behaviour of polyurethane foam polystyrene respectively.

Polyurethane foam (PU) core has been considered for sandwich design due to its high stiffness and toughness. Polyurethane foam is used for multiple applications that normally focus on its shock absorption properties. Examples are: packaging, footwear, furnishings etc. In order to absorb energy, it is important that the foam is in its rubbery state. Concerning the EPS foam, this material is effectively used by manufacturers to save weight and provide energy absorbing protection. For most applications, the two foams will require a low modulus to operate effectively (as a shock absorbing or cushioning material).

The selection of two core materials was justified by the fact that they had a completely different behaviour on the impact energy absorption and deformation mode: unlike polystyrene foam which has a predominantly plastic behaviour (with high residual deformations 5.59 mm), the polyurethane foam core specimen had a predominantly elastic behaviour, with a tendency to return to its original shape.

Another parameter considered in the study analysis was related to the contact force measured at the fixed support during the collision: if case of PU foam specimen it was registered a higher value of the contact force between the support and the sample (815 N) compared to the force experienced by the fixed support for EPS foam (368 N).

The decision to consider sandwich structures with two metallic layers was justified to verify how these layers influence the absorbed energy or the contact force between specimen and support. Following these simulations it has been observed that the absorbed energy has no major variations (ranging between 0.95 [J] and 1.089 [J]) for specimens with one or two layers of steel. In the use of aluminium layers and EPS core sandwich structure it was observed that both layers and core are penetrated by the impactor.

Simulations confirmed the considerable influence of the core, specially its stiffness and strength, on the performance of the collided panels. The models, validated with the experimental results existing in scientific literature, allowed simulating the behaviour of the different sandwich structures with a good accuracy.

Due to the central hole of the support, the measured contact force varied from one case to another, meaning that in case of the PU and EPS specimens with two steel layers was higher than the ones with two aluminium skins. This is due to the shock wave which produced the material deformation through the central hole of the support.

The present study confirmed that composite sandwich panels made of aluminium/ steel skins and PU/ EPS foam cores have significant potential for a wide range of structural applications, presenting significant stiffness and strength. Starting from these studies, the authors intend to continue their investigation on the influence of different adhesive layers applied at the interface between the core and the skins, in order to determine the interlaminar stresses which occur at the moment of impact.

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