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INFLUENCE OF CORE THICKNESS ON THE IMPACT BEHAVIOR OF SANDWICH PANELS WITH POLYSTYRENE FOAM CORE: EXPERIMENTAL AND NUMERICAL INVESTIGATION

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The paper investigates the low velocity impact behavior of composite sandwich panels with aluminum Al 6082-T6 facesheets and commercial polystyrene (PS) foam core. Drop weight tests are carried out involving different impact velocities. Force - time history curves show that the core thickness has a significant influence on the impact damage behavior and energy absorption capability of the panels. Sandwich panel with thicker core proves to be less damaged during impact and has very good absorption properties. Also a numerical model of the complete experimental setup is developed using the dynamic explicit finite element analysis program LS-DYNA. The model has the advantage of reproducing the failure features correctly and can be used for further researches.

Keywords: sandwich panel, polystyrene foam, low velocity impact, core thickness, energy absorption, damage

1. Introduction

Sandwich panels consist of two thin facesheets adhered to a lightweight core and possess great capabilities for energy absorption, weight reduction and structure protection due to their high flexural stiffness and low structural weight. They are being increasingly used in important industries such as aerospace, automotive, marine or civil engineering [1-2] and thus the interest in understanding their behavior to different structural loadings is important for further developments. Despite their numerous advantages, sandwich structures are easily being damaged under bending or impact loading along the out-of-plane direction. More than that, low velocity impact cases, such as debris thrown up

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from railways, hailstone or even tools dropped during maintenance, can significantly reduce the residual strength of the structure through complex failure modes such as shearing and crushing of the core, local indentation and deformation of the facesheets, delamination etc.

The high energy absorption, relative low cost, good sound damping, non-combustibility, moisture resistance, durability and easy fabrication has led to the development and employment of cellular foams as core for sandwich structures to the detriment of other lightweight core materials such as balsa woods, honeycombs or corrugated sheets. Although honeycomb structures offer the highest strength to weight ratio they suffer from corrosion damage from water ingress. Expanded polystyrene is a rigid and tough, recyclable, closed-cell cellular plastic material and one of the most common polymeric foam, used in a variety of applications including impact mitigation packaging, protective elements, structural crashworthiness and construction material filling [3].

Over the last two decades, the dynamic behavior and energy absorption characteristics of sandwich panels with foam core have attracted extensive attention. Among the literature, most studies focus on the behavior of core material and are usually accomplished by experimental testing and numerical simulations [4-6]. In the work of Steeves et al. [7], Jiang et al. [8] and Vitale et al. [9], collapse of sandwich beam under three point bending was divided into core shear, face micro buckling, face sheet indentation and core crushing depending on the geometry and density of the foam core. According to Ozdemir et al. [10], the core material and thickness is one of the main factors determining the impact behavior of sandwich structures and it was shown that the energy absorption capacity of sandwich structures increased with increasing core thickness. The response of bare aluminum foam blocks and their sandwich panels with various tailored facesheets under a drop weight impact loading was investigated by Mohan et al. [11]. The results revealed that increase in foam thickness and the use of facesheets enhanced the impact energy absorption capacity. Olsson and Block [12] proposed a criterion for core shear cracking and skin rupture of carbon fiber reinforced polymer (CFRP) foam core sandwich panels during low velocity impact. Peak loads predicted by their criteria were found similar to the experimental results. Damage localization in cellular foams after impact was presented by several researchers [13-15]. Combined experimental and numerical studies in looking to evaluate the response of the sandwich panels constituted a strong option as it was done, only as an example by several researchers [16-17], and only FEM simulations have attracted more studies [18-20] as being less expensive and time consuming; many of them consider a foam core for the sandwich. However, the calibration of the FEM impact model should be carefully done. Only experimental results can provide a good understanding of the impact events and response of the sandwich panel in conjunction to the localized damage produced during the impact.

The present paper presents an experimental and numerical investigation on the behavior in low velocity impact of sandwich panels with aluminum Al 6082-T6 facesheets and a commercially available foam core made from expanded polystyrene (PS). Two types of sandwich panels with facesheets of 1.5 mm thickness and core of 12 mm, respectively 19 mm thickness are considered in the study. The entire experimental procedure, as well as the used materials and specimen configuration are presented. The contact force variation during impact is analyzed through representative plots as to reveal the influence of core thickness upon the overall response of the panels. A simulation of the sandwich panels' response in impact is also described by presenting details on the particularities of the material models, choice of contact types, foam erosion considerations and comparison of the experimentally obtained damage events. Conclusions regarding the impact behavior of sandwich panels underline the core thickness influences, the energy absorption capabilities, and the damage characteristics of the panels.

2. Experimental methodology

2.1 Materials

The sandwich specimens used in the tests were manufactured of identical facesheets combined with a foam core with two different thicknesses. The facesheets material was aluminum Al 6082-T6 of 2700 kg/m^{3}density, while the core was manufactured by expanded polystyrene of 32 kg/m^{3}density. The core was bonded to the facesheets using an epoxy adhesive, type Araldite AW 106. Table 1 summarizes the properties of the used materials: the mechanical properties of the aluminum (yielding stress, Young's modulus) were obtained from tensile testing while the compressive strength of the expanded polystyrene was taken by similarity from published literature [3]. The sandwich panels were cut into squares of 140x140 mm for the impact tests.

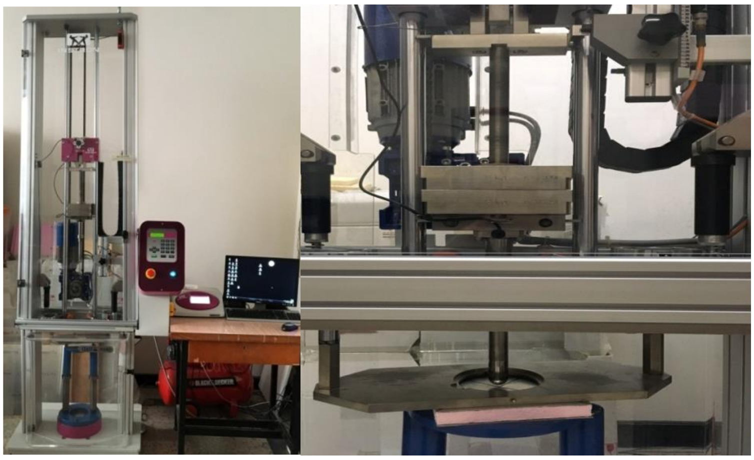
Table 1

Material properties of aluminum Al 6082-T6 facesheets and PS foam core

Mechanical properties	Al 6082-T6	PS
Thickness, t [mm]	1.5	12/19
Density, ρ [kg/m^3]	2700	32
Young's Modulus, E[MPa]	60000	4.5
Poisson's ratio, ν[-]	0.33	0
Yielding stress, σ_y [MPa]	315	0.35

2.2 Impact testing

The impact testing was performed on an instrumented INSTRON 9340 drop tower (Fig. 1 a) equipped with a hemispherical impactor of 20 mm diameter that can directly measure the impact force during the test, as being a force transducer with strain gauges. In our experiments the total weight of the impactor assembly was 3.15 kg and two additional masses of 5 kg each were added. Therefore, the total mass of the energy carrier was 13.15 kg. The specimens are placed on an adjustable in height support and fixed with a pneumatic clamping system. The fixing plate of the clamping system and the support have a circular opening of 90 mm, respectively 100 mm, allowing the impactor to hit the specimen and eventually fall if perforation occurs (see Fig. 1 b). Special attention was given to the positioning and alignment of the specimen as to obtain the impact in the middle of the plate. Fig.1 shows the sandwich panel fixed in between the support and clamping ring. The real time impact force was recorded with the INSTRON CEAST DAS 64k system at 200 kHz and used to determine the displacement of the impactor. The absorbed energy was calculated as the area contained under the force curve in the force-displacement plot.



a) b)

Fig. 1 Experimental setup: a) Instron Ceast 9340; b) sandwich panel fixed for testing

The sandwich panels were impacted with the same mass and different impact velocities ranging between 1.5 and 4.5 m/s. The velocity of the impactor was modified by increasing or decreasing the release height of the impactor's assembly. The corresponding impact energy is between 14.79 J and 133.14 J. The European Standard *ISO 6603-2:2000 Plastics - Determination of puncture impact behavior of rigid plastics -- Part 2: Instrumented impact testing* was used as guidance. This standard was last reviewed and confirmed in 2015.

3. Numerical model

The low velocity impact of the experimentally tested sandwich panels was also analyzed using the dynamic explicit finite element analysis program LS-DYNA. As to assure the reliability of the results, the numerical model was built in accordance with the experimental setup, as shown in Fig. 2; the model considers the actual geometry of the sandwich panels and comprises the square sandwich plate, the 20 mm diameter steel impactor, the support and the clamping ring. The entire model is meshed using SOLID 164 8-node solid structural elements with reduced formulation and size ranging between 0.75 mm and 7.5 mm. The mesh near the impact zone was refined adequately enough as to provide detailed information in this region (see Fig. 2).

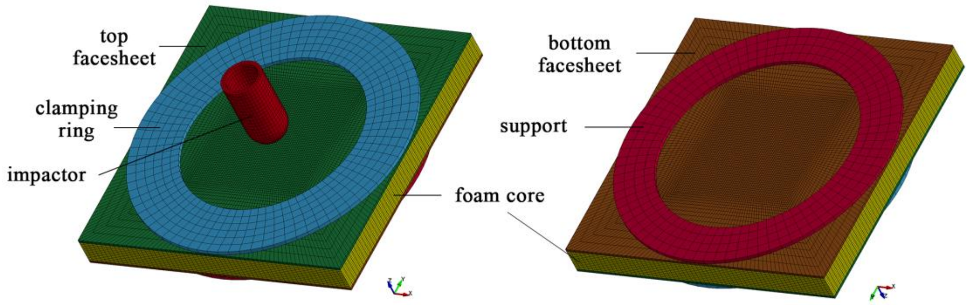


Fig. 2 Finite element model: top and bottom view

The impactor, support and clamping ring were modeled as rigid bodies, using the RIGID material model. Aluminum facesheets were modeled using the PLASTIC_KINEMATIC material model, recommended in analyzing problems of impact and penetration; it is a bilinear material model which considers the effects of strain rate and hardening of the material upon the yielding function. It also includes a failure criterion based on the fracture strain. For the polystyrene foam core, which is a reversible foam with rate sensitivity, material model LOW_DENSITY_FOAM was considered as an acceptable compromise. This material model, even if it describes a completely recoverable behavior, allows control of the shape and hysteresis of the unloading curve of the foam through two different parameters. An extended compression stress-strain curve resulting from extrapolation and seen in Fig. 3 is needed for the numerical simulations. The nominal compression curve obtained from testing is represented using the scale at the right of Fig. 3 and the red curve. The left scale and the blue curve are used for the representation of the extended curve. For the failure of the foam core, the volumetric strain and maximum principal stress criteria were implemented using the card ADD_EROSION.

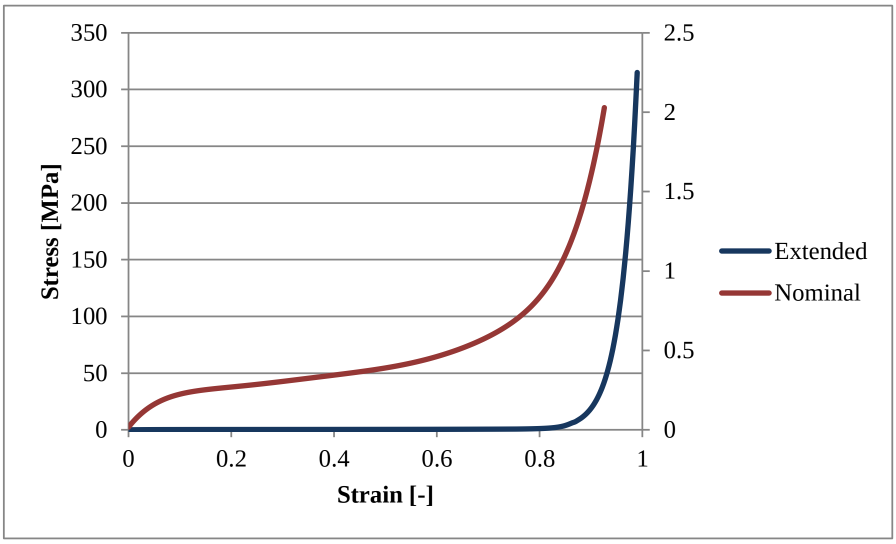


Fig. 3 Nominal and extended compression stress-strain curve for the polystyrene foam

The material properties of the aluminum facesheets and polystyrene core are listed in Table 2. For the impactor, support and clamping ring steel properties (density = 7850kg/m^3, Young's modulus = 210 GPa and Poisson's ratio = 0.3) were assigned for the simulation.

Table 2

Material properties of aluminum facesheets and polystyrene core used in the plastic kinematic and low-density material models

Al 6082-T6 facesheets		PS core	
Property	Value	Property	Value
Tangent modulus, E_t	0.85 GPa	Hysteresis factor, *HU*	0.1
Strain rate parameter, *C*	5e7 [s^{-1}]	Shape factor, *SHAPE*	2
Strain rate parameter, *p*	3.5	Viscous coefficient, *DAMP*	0.5
Effective plastic strain*, f_s	0.33	Cut-off stress, *TC*	0.35 MPa

Contact between the impactor and sandwich panel was established using an ERODING_SINGLE_SURFACE option. Even if this type of contact usually determines an increase in computational time, it manages to update contact for interfaces were elements are eroded due to failure, as between the foam core and the upper aluminum facesheet. The adhesive bonding between the facesheet and the core was modeled using a TIEBREAK_SURFACE_TO_SURFACE contact. For the epoxy adhesive AW106 the normal failure stress was established as 24 MPa, and the one in shearing as 17 MPa. The contact between the sandwich panel and the support and clamping ring was described using an AUTOMATIC_SURFACE_TO_SURFACE contact.

4. Results and discussions

4.1 Results of the experimental tests

The impacted sandwich panels were abbreviated as following: foam type, core thickness and impact velocity. Six impact velocities were selected: 1.5 m/s, 2.5 m/s, 3 m/s, 3.5 m/s, 4 m/s and 4.5 m/s. Therefore, as an example, PS_12_3.5 means test on a sandwich panel with 12 mm PS core thickness and an impact velocity of 3.5 m/s.

In Fig. 4 and Fig. 5, experimentally obtained force versus time curves for both types of panels are plotted comparatively to analyze how the impact force changes with time. It can be seen that, irrespective of the core thickness, the force histories of all sandwich panels show the same tendency: they exhibit an almost linear increase as the impactor hits the panel, followed by a prolonged contact with the core. At higher impact velocities (Fig. 5), there is a sudden drop of the force after it reaches the first peak value, indicating a loss of stiffness caused by core crushing. More than that, the densification of the polystyrene foam core causes the force to rise again after the initial drop reaching, in some cases, a higher peak value.

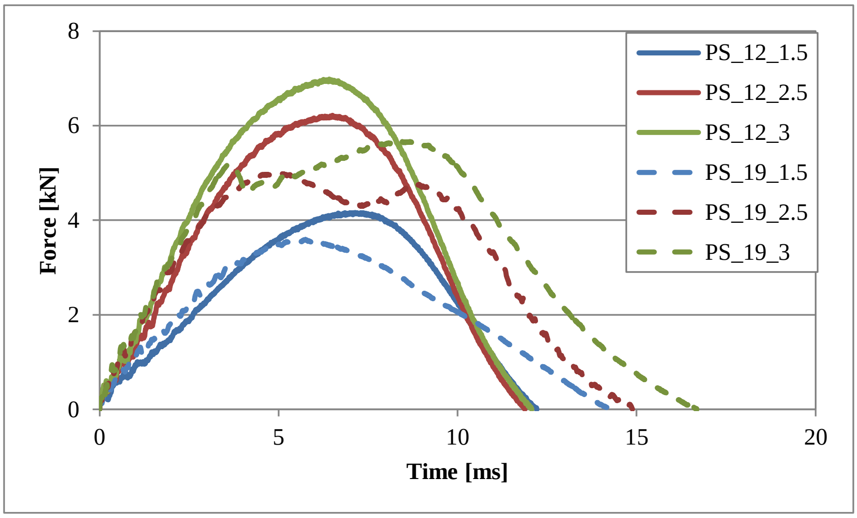


Fig. 4 Comparison of the impact force for the PS_12 and PS_19: 1.5 m/s to 3 m/s

For all six testing velocities the maximum peak force of the sandwich panel with 12 mm core thickness is bigger than for the one with 19 mm core thickness and increases with increasing impact velocity. On the contrary, the impact duration is smaller and decreases at higher velocities. From Fig. 4 it results that at lower impact velocities for the thinner core a reasonable symmetry for loading and unloading during impact is noticed while for the thicker core the damage of the panel is more localized around the area of impact.

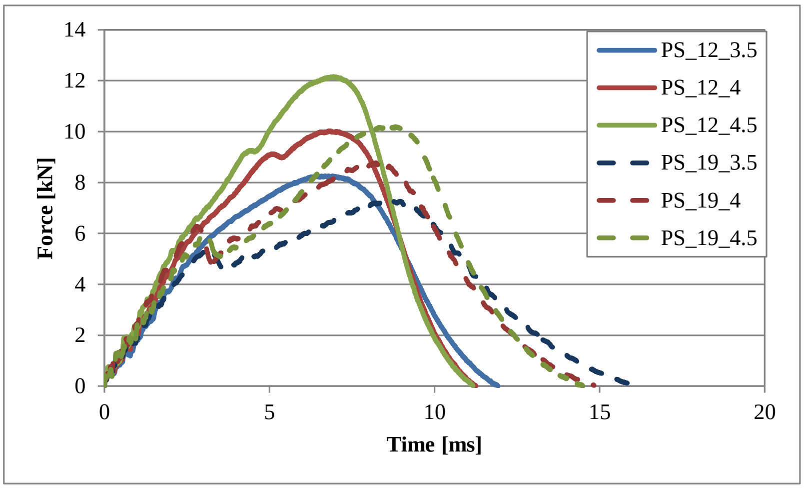


Fig. 5 Comparison of the impact force for the PS_12 and PS_19: 3.5 m/s to 4.5 m/s

The influence of the polystyrene foam thickness on the response of the impacted sandwich panels can also be observed by visual inspection and is presented in Fig. 6. Top and lateral views put into evidence that for the sandwich panel with 19 mm core thickness top facesheet is severely damaged through local indentation and bending.

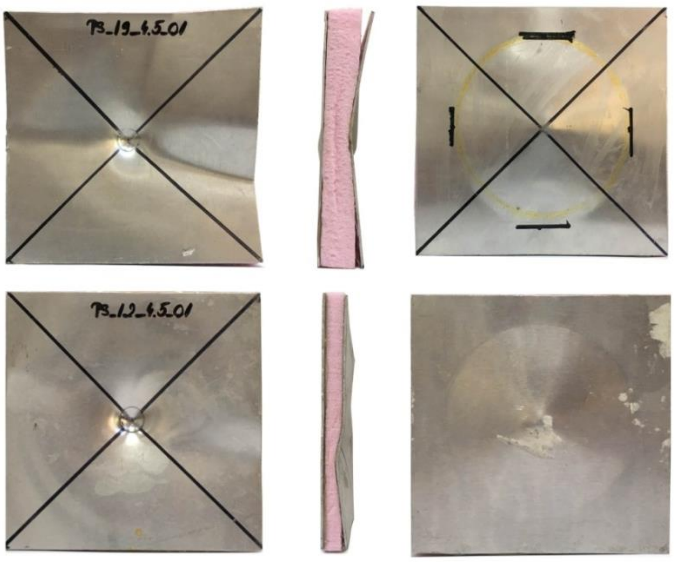


Fig. 6 Impacted sandwich panels at 4.5 m/s: top, lateral and bottom view

Also, the lateral view shows that delaminations were generated in the polystyrene core close to the top facesheet. For the sandwich panel with 12 mm core thickness the upper facesheet deforms less and no delaminations occur. Instead, the indentation of the bottom facesheet is bigger and the mark of the circular support is more evident. When impact velocity is increased (Fig. 5) the panels with 19 mm core thickness suffer an indentation and a drop of force after about 3 ms and reach the maximum value after 8-9 ms. For the panels with 12 mm core values of maximum forces increase at higher speeds being produced in the range of 6.4-7.3 ms.

4.2 Results of the numerical simulations

The contact force history obtained from the LS-Dyna simulation was compared with the results of the impact tests for three impact velocities: 1.5 m/s, 3 m/s and 4.5 m/s. A comparison between the force - time curves obtained from the LS-Dyna simulation (Num) and experiment (Exp) for the sandwich panel with 19 mm core thickness is presented in Fig. 7. It can be noticed that the numerical and experimental force responses are quite similar. The loading part of the curves, which indicates the stiffness of the panels, is almost identical. It is followed then by a region of core dominated plateau in the force response. At higher impact velocities, the second peak force indicates the densification of the foam core and the loading of the bottom facesheet. After reaching the maximum value the force decreases and the panel starts to unload. The unloading paths are well represented.

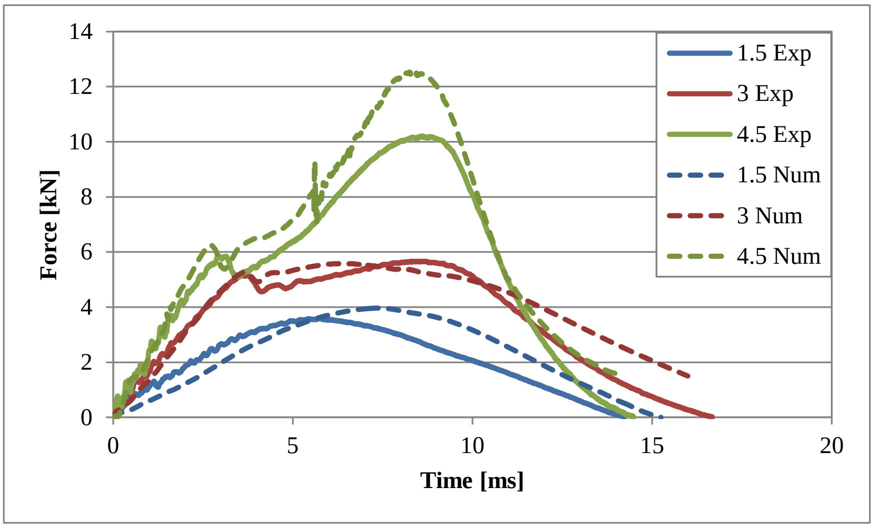
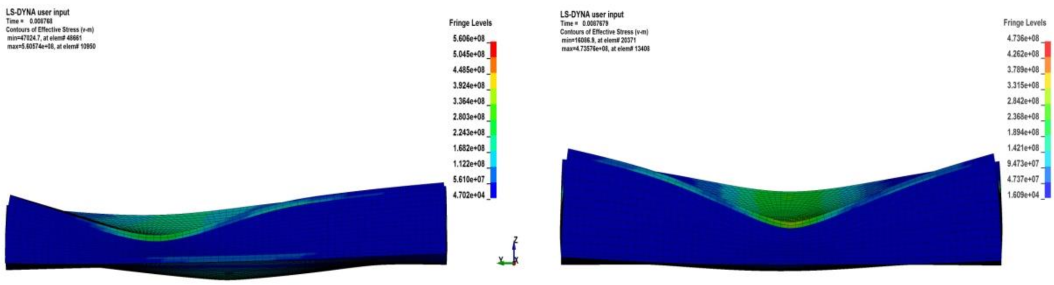


Fig. 7 Comparison of the experimental and numerical force - time curves for the sandwich panel with 19 mm core thickness

The simulation over-estimates the peak force and impact duration for the 1.5 m/s and 4.5 m/s impact velocities, the differences being though under 16 %. For the 3 m/s impact velocity the maximum force is slightly smaller. However, the model accurately captures the failure modes, such as delaminations or bending of the upper facesheet with no penetration even at the highest impact velocity (see Fig. 8).

Fig. 8 Delamination between the foam core and the upper facesheet

The damage process of the two panels subjected to 3 m/s impact velocity after t = 8.768 ms is presented in Fig. 9. The numerical simulation of the process helps to understand the effect of core thickness on the damage of the panels and further confirm the experimental results.



a) b)

Fig. 9 Deformation process of the sandwich panels subjected to 3 m/s velocity at t=8.768 ms; a) 12 mm core thickness; b) 19 mm core thickness

As shown in Fig. 9 a), the sandwich panel with 12 mm core thickness has a larger deformation of the bottom facesheet and the value of the maximum equivalent von Mises stress is 560 MPa. For the panel with 19 mm core thickness (Fig. 9 b)) the out of plane deformation of the upper facesheet is larger and limited to the vicinity of the impact location. Even though, due to the higher absorption capability of the thicker core, the equivalent von Mises stress is only 473 MPa, less than for the sandwich panel with 12 mm core thickness.

5. Conclusions

The paper investigates the influence of core thickness on the response of sandwich structures with aluminum facesheets and polystyrene foam core subjected to low velocity impact through experimental testing using an instrumented drop tower. The sandwich panels were compared in terms of their force - time history curves and damage mechanisms. The thickness of the foam core is found to be very important in the penetration resistance and damage mechanism of the panels. For the thicker core of 19 mm the top facesheet is severely bended and cohesive delaminations result between the core and the facesheet. The thinner panel with 12 mm core deforms more due to a lower bending stiffness, but in neither of the two cases penetration is produced.

A numerical modeling carried out using the finite element software LS-Dyna was proposed to simulate the failure behavior of sandwich panels under impact loading. Low density foam material model used by LS-Dyna has the capability to control the shape and hysteresis of the foam core during unloading and hence the model could correctly reproduce the failure features of the panels.

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