EXPERIMENTAL AND NUMERICAL STUDY OF LOW VELOCITY IMPACT ON SANDWICH PANELS WITH ALUMINUM FACESHEETS AND FOAM CORE

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Abstract. This study investigates the effect of foam core type in sandwich structures under low velocity impact. The structures consist of aluminum facesheets and polystyrene and polyurethane foam core with density of 32 kg/m^3, respectively 100 kg/m^3. Low velocity impact tests are performed using an instrumented drop weight tower (Instron CEAST 9340). The sandwich panels are subjected to impact velocities in the range of 1.5 – 4.5 m/s. Force-time histories are plotted to determine the impact damage response of the structure. A dynamic finite element model (FEM) of the phenomena observed experimentally is proposed. A low-density foam material model is used in order to explore the core behavior, while the plastic kinematic material model is used to predict the failure of the facesheets. To overcome the problems related to large deformations of the finite elements, a mesh free model is developed using the smoothed particle hydrodynamics (SPH) method. The numerical variation of the contact force in time is validated by comparison with experimental test results.

Key words: foam sandwich panels, experimental impact tests, Finite Element Method, low-density foam, smoothed particle hydrodynamics method.

1. INTRODUCTION

Nowadays, sandwich structures have proved to be an important part of several applications around the globe. They are extensively being used in transport, marine, civil, military and aerospace industries. The multitude of facesheets, core materials and core facings interfaces represent the actual source of their superior advantages like high specific bending stiffness, good energy absorption, excellent thermal insulation, acoustic damping etc. However, sandwich structures are susceptible to impact loading and may be subjected to different impacts such as tool drops, bird strikes, hail stones and runaway debris through life. This results in damage to the structure, such as local core crushing, facesheet indentation, debonding of the

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facesheet from the core and even penetration, which severely compromises the structural integrity of the sandwich panels [1–2].

The mechanical behavior of aluminum plates subjected to an impact loading has been the focus of many studies [3–6]. The principal aim of these researches was to find a solution to the need of replacing traditional steel alloys by metallic materials with improved strength to weight ratio. Reviews presented in the literature on the analytical and experimental investigation of aluminum alloys subjected to impact loading, have focused on the penetration and perforation processes and on the parameters that influence them. An analytical model that predicts the maximum plastic deformation of rectangular plates with simply supported and fully clamped boundary conditions, was developed by Jones and Paik [5]. The model was validated with experimental results obtained for plates impacted by blunt, conical and hemispherical projectiles. Fagerholt et al. [6] have investigated experimentally and numerically the continuous out-of-plane deformation of AA5083-H116 plates subjected to low velocity impact.

The study on the behavior of sandwich structures subjected to impact loading is usually accomplished through experimental and numerical analyses [7–11]. The major concerns regard the effects of impact velocity and energy, impactor shape and diameter, core material and thickness and facesheet type on the impact behavior and resulting damage. Some of the experimental analyses on sandwich panels [12–14] reveal the great interest in using low-density polymeric foams as they have better energy absorption capabilities showing little evidence of debonding at the skin-core interface and as the strain rate sensitivity increases with the density of the core material. Damage localization in cellular foams after impact was presented by several researchers [14–17].

Experimental determination of the impact behavior of sandwich panels is neither resourceful nor cost effective, and in many cases finite element modeling (FEM) and analysis are used for these types of studies to predict the behavior and failure of these panels [18–21]. 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 low-velocity impact.

The present paper presents an experimental and numerical investigation on the low-velocity behavior of sandwich panels with facesheets made from Al 6082-T6 and two commercially available foam cores made from polyurethane (PUR) and expanded polystyrene (PS). Both foams have relatively low densities, of 100 kg/m^3, respectively 32 kg/m^3. Such sandwich panels are lightweight, absorb well the impact energy and are quite cheap. The description of the impact drop tower, the used materials and testing procedure are presented. Next, the contact force variation during impact is analyzed through representative plots as to reveal the influence of the initial velocity and the core response. A simulation of the sandwich panels response in impact is also described by presenting details on the particularities of the materials models, choice of contact types, foam erosion considerations and comparison of the experimentally and numerically obtained damage events. It is underlined that a correct calibration of the numerical model is to be done based on experimental results. To overcome the problems related to large deformations of the finite elements, a mesh free model is also developed by using the smoothed particle hydrodynamics method (SPH) available in ANSYS LS-Dyna.

2. EXPERIMENTAL METHODOLOGY

2.1. Used materials

The sandwich panels tested in this study are made from identical facesheets combined with two different core materials. The material of the facesheet is aluminum Al 6082-T6 which is one of the strongest alloys from the 6xxx series, due to the heat-treated and artificially aged processes. The thickness of the facesheets is 1.5 mm. The core materials are polyurethane foam of 100 kg/m^3 density and expanded polystyrene foam of 32 kg/m^3 density. They have a thickness of 12 mm for the PUR and 19 mm for the PS. As the core height has a significant influence on the impact response of sandwich structures [22], the thickness of the PS was subsequently reduced to 12 mm, as to eliminate the geometry effect on the bending stiffness of the panels. Table 1 summarizes the properties of all used materials: the thickness was measured directly, the density was obtained from the manufacturer's data, while the Young's modulus, tensile strength of the aluminum, compressive strength of the foams were obtained from mechanical tests and published literature [23,24].

Table 1

Mechanical properties of the aluminum Al 6082-T6 facesheets, polyurethane (PUR) and polystyrene (PS) foam core

Mechanical properties	Al 6082-T6	PUR	PS
Density, ρ [kg/m^3]	2700	100	32
Young's Modulus, *E* [MPa]	68000	30	4.5
Poisson's ratio, ν [–]	0.33	0	0
Yielding stress, σ_y [MPa]	315	1.8	0.35

The square sandwich panels prepared for testing had a size of 140 × 140 mm. The faces were bonded on each side of the core using and epoxidic adhesive, type Araldite AW106. The bonding surface of the aluminum facesheets was cleaned of oxide material and contaminants using sand paper and acetone. The thickness of the tested panels was therefore 15 mm or 22 mm. The thickness of the adhesive layers of about 0.2 mm each was not considered in calculating the total thickness.

2.2. Impact testing procedure

An instrumented Instron Ceast 9340 Drop Tower Impact System was equipped with an instrumented impactor with a hemispherical head of 20 mm diameter and the impact force was measured during the impact. The initial impact velocity of the striker was measured with an optical cell. The sandwich plates were placed on an adjustable in height test specimen support with a circular hole of 100 mm diameter (Fig. 1), which eventually allowed the striker to fall if the plate was perforated. A clamping ring was pressed over the sandwich plate by a pneumatic system with a maximum force of 3 kN. The system INSTRON CEAST DAS 64K can acquire data with a frequency up to 4 MHz. In our tests data acquisition was done with a frequency of 200 kHz for an initial estimated time of 40 ms, but 20 ms proved as being enough for used impact speeds.

A special attention was given to the positioning and the 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 specimen support and the clamping ring. The energy carrier of gravitationally accelerated type had a mass of 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. Only the first impact was considered for monitoring the phenomena and comparisons of the responses of the tested sandwich panels. The load cell mounted close to the tip of the impactor is capable to record a maximum force of 47 kN. The drop tower system provides information on the contact force variation in time, contact force variation versus striker displacement, or variation of the absorbed energy in time.

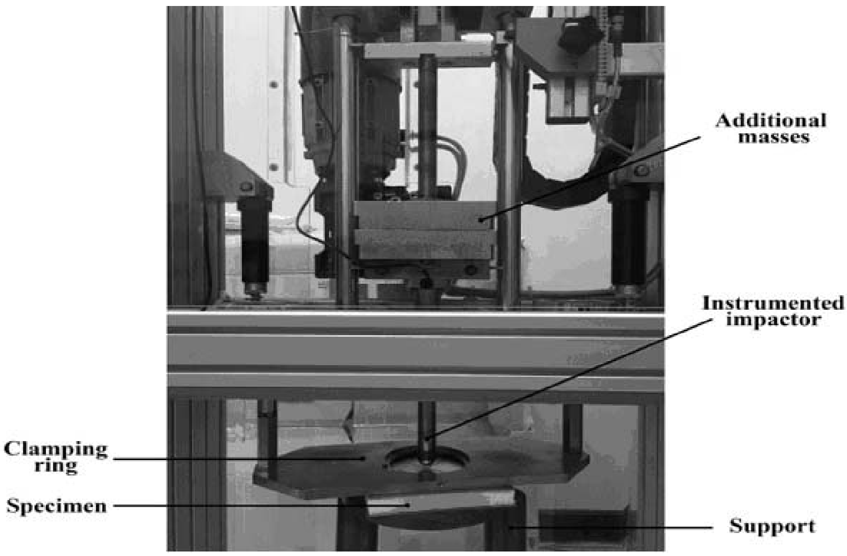

Fig. 1 – Experimental setup with sandwich panel fixed for testing.

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.

The initial speed of impact was increased from 1.5 m/s up to 4.5 m/s, therefore the kinetic energy of impact increased from 14.79 J up to a maximum value of 133.14 J.

3. SETUP OF NUMERICAL MODELING

The numerical modeling of the response of the sandwich panels with aluminum facesheets and foam core subjected to low velocity impact was carried out using the dynamic explicit finite element analysis program LS-Dyna. Only two sandwich panels, with PUR foam core of 12 mm thickness and PS core of 19 mm thickness were chosen for this numerical study.

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).

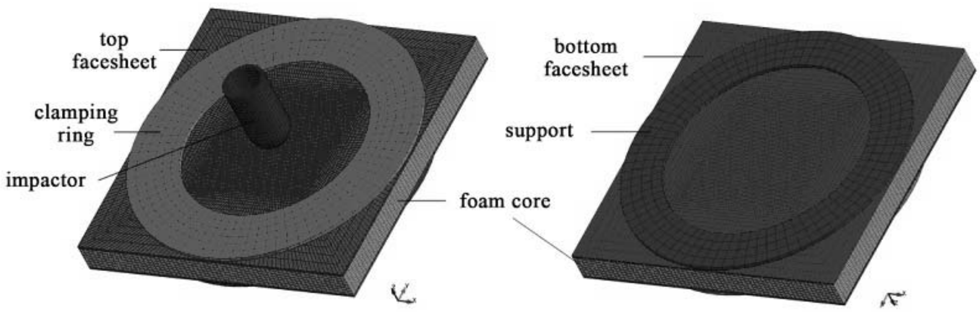

Fig. 2 – Finite element model: top and bottom view.

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 foam core 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. The nominal compression curves obtained from testing are represented for PUR and PS in Fig. 3a. The extended compression stress-strain curves resulting from extrapolation up to 315 MPa (the yielding stress of aluminum) and seen in Fig. 3b are needed for the numerical simulations. For the failure of the foam core, the volumetric strain and maximum principal stress criteria were implemented using card ADD_EROSION.

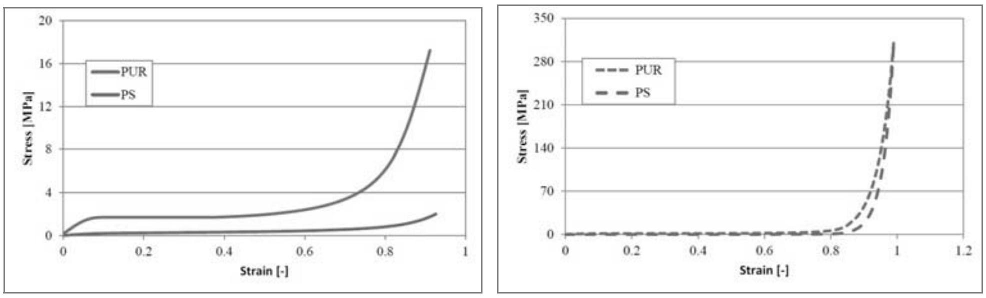

Fig. 3 – Nominal and extended PUR and PS compression stress-strain curves: a) nominal; b) extended.

The material properties of the aluminum facesheets and polystyrene core are listed in Table 2. The aluminum specimens were tested statically and aluminum facesheets were tested at impact up to 4.5 m/s; the listed material properties resulted after the calibration of the tangent modulus, effective plastic strain and the strain parameters from the kinematic model to the experimental curves. For the low-density material model of PUR the cut-off stress was determined previously in [23] after performing tests up to 6 m/s and for PS from [24]; the hysteresis and shape factors as well as the viscous coefficient were derived from our experiments after performing impact tests on the sandwich panels. For the impactor, support and clamping ring conventional steel properties (density ρ = 7,850 kg/m^3, Young's modulus E = 210 GPa and Poisson's ratio ν = 0.3) were assigned for the simulation.

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.

Table 2

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

Al 6082-T6 facesheets		PUR/PS core	
Property	**Value**	**Property**	**Value**
Tangent modulus, E_t [GPa]	0.85	Hysteresis factor, *HU*	0.4/0.1
Strain rate parameter, C [s^{-1}]	5e7	Shape factor, *SHAPE*	1.2/2
Strain rate parameter, p	3.5	Viscous coefficient, *DAMP*	0.5/0.5
Effective plastic strain, f_s	0.33	Cut-off stress, *TC* [MPa]	2.5/0.35

The smoothed particle hydrodynamics (SPH) method was also used in order to eliminate the drawback of the deletion of the elements that undergo large deformations in the FE method. Because these methods are both using a Lagrangian formulation, it is possible to couple them, in order to manage to exploit each one's potentials and avoid their deficiencies.

The DEFINE_ADAPTIVE_SOLID_TO_SPH option in LS-Dyna allows the user to choose that the finite elements transform to SPH particles after the erosion criteria is reached. This coupling method helps a lot to improve the total computational time. Therefore, the same finite element model was used with the additional add of the DEFINE_ADAPTIVE_SOLID_TO_SPH option to the elements of the foam core.

4. RESULTS AND DISCUSSIONS

4.1. Experimental contact force-time impact curves

The adopted testing velocities were: 1.5 m/s, 2.5 m/s, 3 m/s, 3.5 m/s, 4 m/s and 4.5 m/s. The impacted sandwich panels were abbreviated as following: type of foam (PUR or PS) followed by core thickness (12 mm or 19 mm) and impact velocity mentioned in legend. Therefore, as an example, PUR_12_1.5 means sandwich with 12 mm thickness PUR foam, tested at 1.5 m/s. The results are presented in Figs. 4–6.

For a linear elastic impact event the impact force curve variation in time should be symmetric for loading and unloading. From Fig. 4 it can be noticed that, for the PUR_12 panels, this does not happen even for the lower speed of impact of 1.5 m/s, showing that unloading takes less time than loading, as it is accompanied by additional damping phenomena. At 2.5 m/s and at 3 m/s the unloading curves are almost identical, and there is no severe damage of the top skin. At 3.5 m/s the force drops suddenly from about 11790 N to 4450 N due to the severe damage of the aluminum top facesheet of the sandwich, which is penetrated by the striker. The brittle behavior of the polyurethane foam influences this drop of force and the puncture of the skin is followed by some vibrations of the striker. At 4 and 4.5 m/s the maximum force is a little bit smaller than before and again decreases rapidly indicating perforation of the top skin, force increases back as core is damaged, but only for 4.5 m/s there is a second abrupt drop of the force as the bottom skin fails; for 4 m/s force decreases again after about 8 ms without any significant variation.

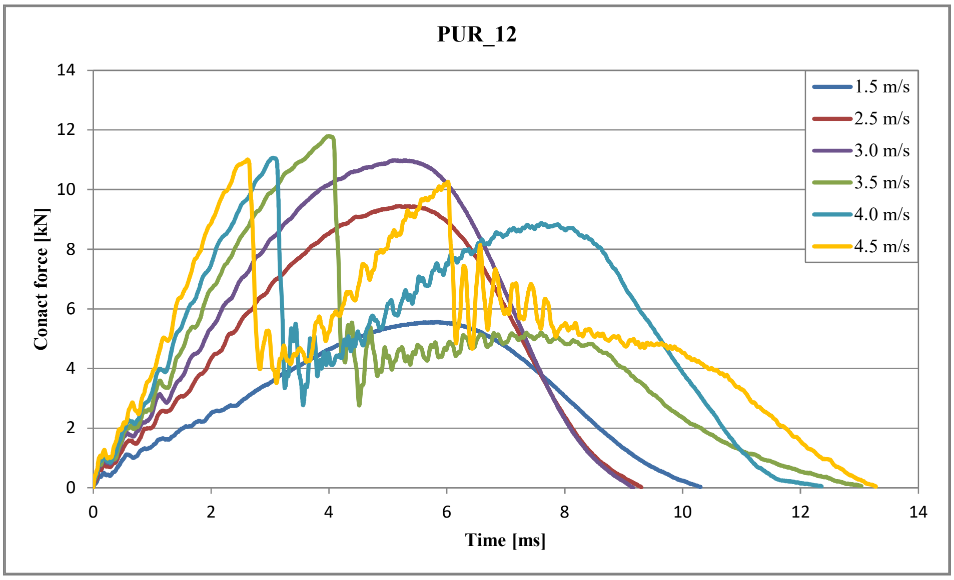

Fig. 4 – Contact force variation in time for panels with PUR foam of 12 mm thickness.

Comparison of the response of the panels with PUR core to the PS core with same thickness of 12 mm can be done in between Fig. 4 and Fig. 5. As the PS core is more elastic the behavior of the sandwich panels is completely different. At 4 m/s and 4.5 m/s there is severe indentation where impact is produced and, more than that, there is no skin perforation, not even of the top one. The maximum force at impact is even a little bit greater for PS than for the PUR sandwich.

At speeds from 3 to 4.5 m/s the maximum force for the PUR panels is in between 11–11.7 kN. For the PS panels the maximum force increases as speed of impact increases from close to 7 kN at 3 m/s to about 12.1 kN at 4.5 m/s.

A similar analysis of the response of the panels is now presented for panels with PS core having a thickness of 19 mm (Fig. 6). As expected, maximum impact force decreases, the panels absorb better the impact energy, and besides some oscillations registered at the beginning showing probably some rearrangements of the specimens in between the support and clamping ring the force varies uniformly during the impact event. It should be noticed that, at 4 m/s the maximum force of about 8.3 kN is obtained after less than 9 ms. For the same thinner core of 12 mm, at the same speed, the maximum force of about 10 kN was obtained after 7 ms.

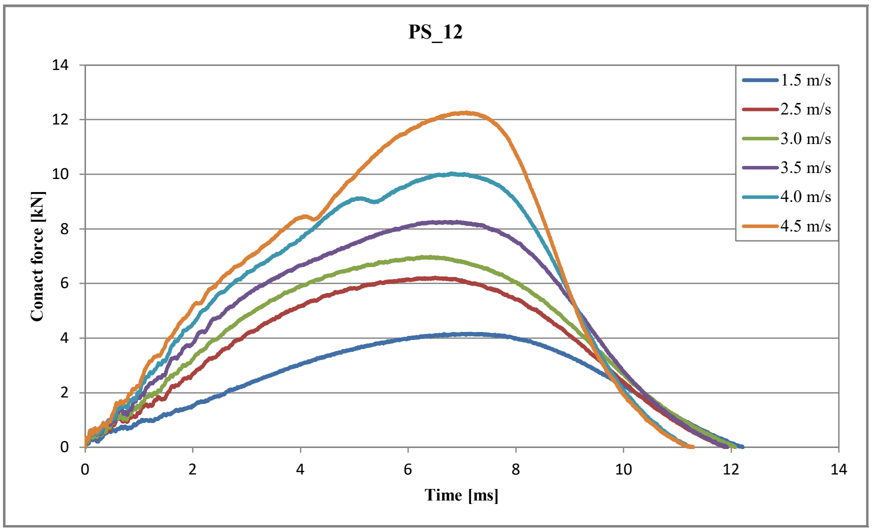

Fig. 5 – Contact force variation in time for panels with PS foam of 12 mm thickness.

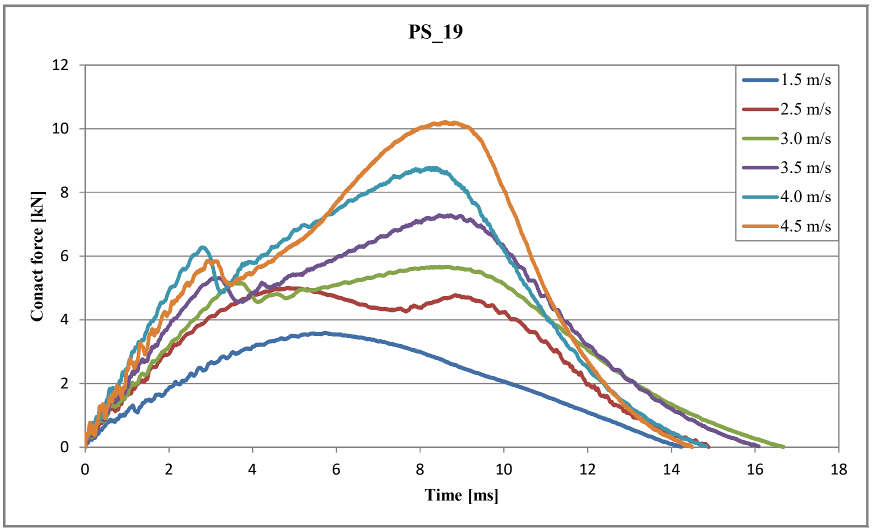

Fig. 6 – Contact force variation in time for panels with PS foam of 19 mm thickness.

Comparing the two PS panels with different core thicknesses, at lower speeds of impact, a reasonable symmetry for loading and unloading during impact is noticed for the thinner core. For the thicker core the damage of the panel is more localized around the area of impact – top skin and core – especially for the higher speed of 3 m/s. Maximum force is smaller for the 19 mm core for all speeds of testing. When impact speed is increased, it is more evident that the panels with 19 mm core suffer an important indentation and a drop of force after about 3 ms and reach a maximum value after 8-9 ms. When core is 12 mm values of maximum forces increase at higher speeds being produced in the range of 6.4–7.3 ms.

4.2. Numerical results

The contact force variation in time obtained from the LS-Dyna simulation for the PUR panel with 12 mm thickness and for the PS panel with 19 mm thickness is compared with the results of the impact tests.

Fig. 7 shows the comparison of the numerical (Num) force-time curves obtained at 1.5 m/s, 3 m/s and 4.5 m/s for the PUR panel with the experimental (Exp) ones. It can be noticed that the slopes of the initial and last part of the force-impact curves which denote the stiffness of the sandwich panels are similar for the experiment and the simulation. Also, the impact duration is quite the same.

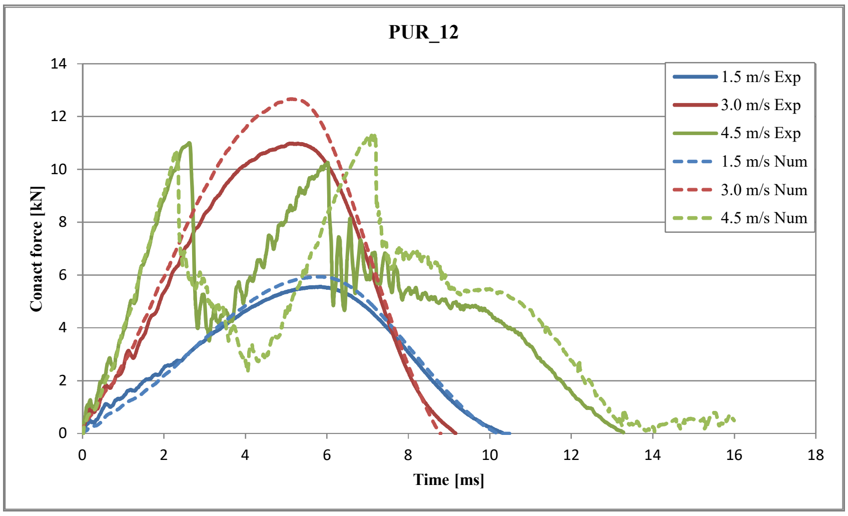

Fig. 7 – Comparison of the numerical and experimental contact force - time curves for the PUR panel with 12 mm core thickness.

Differences appear regarding the maximum impact force as the initial impact velocity increases. The numerical value is always greater than the experimental one, the biggest difference being recorded at 3 m/s. Furthermore, at 4.5 m/s, the shape of the two curves is similar, but undergoes an offset after reaching the first force peak. This is due to the deletion of the finite elements of the foam core after reaching the imposed erosion criteria.

The numerical and experimental contact force-time response for the PS sandwich panel with 19 mm core thickness are compared in Fig. 8. There is a reasonable agreement in the overall simulation results regarding the stiffness, peak force and impact duration. However, the maximum impact force and impact duration are over estimated to a small degree in the numerical simulation.

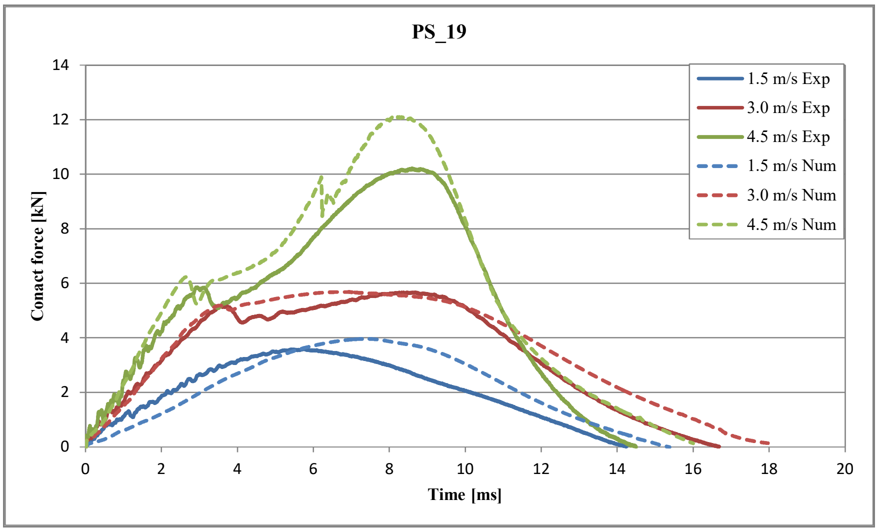

Fig. 8 – Comparison of the numerical and experimental force - time curves for the PS panel with 19 mm core thickness.

The comparative numerical results obtained using the FEM and the FEM + SPH methods for a PUR sandwich panel impacted at 4.5 m/s are presented in Fig. 9. As it can be noticed, the model that replaces the deleted finite elements with SPH particles manages to describe better the influence of the foam core upon the overall response of the panel as compared to the experiment.

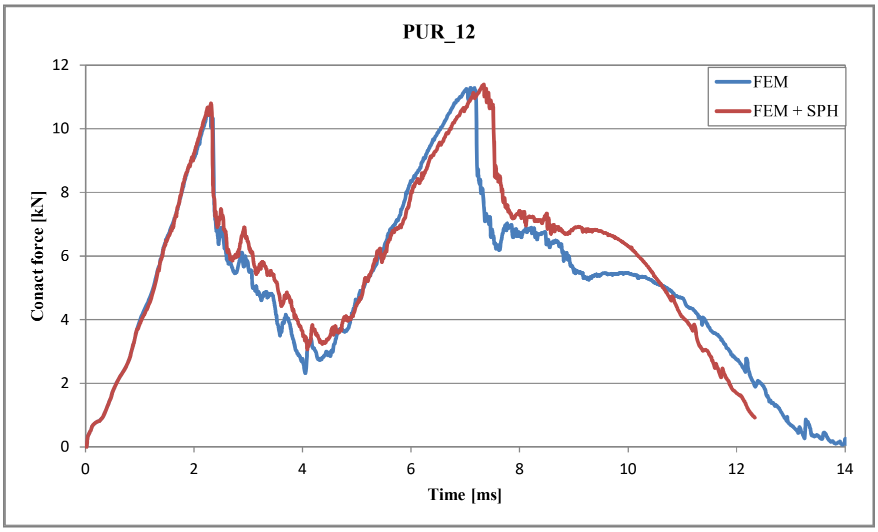

Fig. 9 – Comparison of the numerical FEM and FEM + SPH contact force-time curve for the PUR panel with 12 mm foam core.

The two curves are identical until the first finite elements are eroded and start to be replaced by SPH particles. From this point until the first peak force is reached, the differences between the two curves are very small, since the core's influence is considerably small compared to the upper facesheet. When perforation occurs, and the impactor gets in contact with the core's SPH particles, the differences between the two curves start to be visible. It must be though noticed that they have the same shape. While the impactor moves forward in the panel the particles rearrange and, when the impactor reaches the bottom facesheet, they are all distributed on the sides of the impactor.

5. CONCLUSIONS

An experimental testing program to study the influence of the foam core of sandwich panels with aluminum facesheets on the damage and penetration of the panels was conducted. The PUR core panel had a more rigid response, deformed less, and failure of the facesheets was noticed. The variations in time of the contact force of the impactor can quantify most of the important events. The PS sandwich panel is less damaged during impact as it is more flexible and has very good absorption properties. For the thicker core of 19 mm the top facesheet is severely bended. The thinner core of 12 mm has even greater energy absorption ratios and no facesheet perforation occurred but, of course, the panel deformed more due to a lower bending stiffness. Therefore, when a primary design parameter is penetration resistance and energy absorption, the PS core is a very good candidate.

The 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 can correctly reproduce the failure features of the panels. An alternative to element deletion due to large deformations was proposed by coupling the finite element and the smoothed particle hydrodynamics methods. Such an analysis manages to describe better the core influence, but in order to get a better overall response for the panel the coupling method should be extended also to the facesheets.

The reliability of using low-velocity impact simulations is promising in general, but specific local damage events can be quantified correctly only through experiments.

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