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Low-velocity impact testing of foam core sandwich panels

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Abstract. Sandwich panels with aluminum facesheets and polyurethane or polystyrene foam core were tested in impact on an Instron Ceast 9340 impact tower with a total mass of 13.15 kg at initial velocities from 1.5 to 4.5 m/s. The faces were made from Al 6082-T6 sheet with a thickness of 1.5 mm and the thickness of the polyurethane panel (Necuron 100 core of density 100 kg/m^3) and of the polystyrene panel (commercial extruded polystyrene core of density 32 kg/m^3) were 15 mm, respectively 15 and 22 mm. The important events took place in less than 15 ms. Particularities of the impact response of the panels were observed and discussed. The influence of the speed of impact was analyzed for both types of panels. The contact force variation during impact has a different evolution as being modified by the core behavior.

Keywords: low-velocity impact, sandwich panels, damage, penetration.

1. Introduction

In the transport industry, energy absorption and crashworthiness are today critical issues in the design process of vehicles, aircrafts or vessels. Typically, low speed impacts may result from the collision with roadside safety elements, e.g., guard and bridge rails, median barriers or sign supports, debris thrown up from runaways and even from tool drops during maintenance.
In its raw form, pure aluminum is very soft and ductile. By adding alloying elements, the mechanical, physical and chemical properties, such as strength, toughness, corrosion resistance etc., can be improved, making aluminum suitable for structural applications. Furthermore, its low density, energy absorption

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capabilities and the ease with which complex shapes of cross-section can be extruded, make it very suitable for the aeronautic, offshore and automotive industries. In such industries the structural impact problems have become increasingly important and accordingly, the aluminum behavior to dynamic loads is of big interest for lightweight applications.

Over the last decades, a considerably number of scientific papers dealing with the mechanical behavior of aluminum to impact loading has been published [1-7]. 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 [8]. The model was validated with experimental results obtained for plates impacted by blunt, conical and hemispherical projectiles. Fagerholt et al. [9] experimentally and numerically investigated the continuous out-of-plane deformation of AA5083-H116 plates subjected to low velocity impact.

For sandwich structures the face sheets (skins) are made of light alloys such as aluminum or fiber-reinforced composites, while the core materials used in structural applications include honeycomb cores made of Nomex, fiberglass-reinforced thermoplastic, aluminum, and foam-type cores. Foam and honeycomb structures can be used in the manufacture of sandwich panels as a core because they exhibit a significant plateau stress and, in addition, a great failure strain. In this case, the area under the contact force-displacement curve, which represents the amount of absorbed energy will be larger. A quite recent review on low-velocity impact of sandwich structures [10] presented issues on the contact response and duration, deflection of the sandwich panel, classification of impact response, and suggested the solution methods which can be approached for various initial impact conditions (velocity, duration, boundary conditions, mass, angle). Attention to review the damage initiation and evolution mechanisms during impact was given.

Present paper studies the low-velocity impact response of sandwich panels with two types of core: polyurethane (PUR) and expanded polystyrene (PS). Facesheets made of aluminum Al 6082-T6 of 1.5 mm thickness were glued to the core. Variation of contact force in time and contact force as a function of the displacement of the impactor were monitored. The damage and the perforation of the sandwich panels was analyzed and conclusions were drawn.

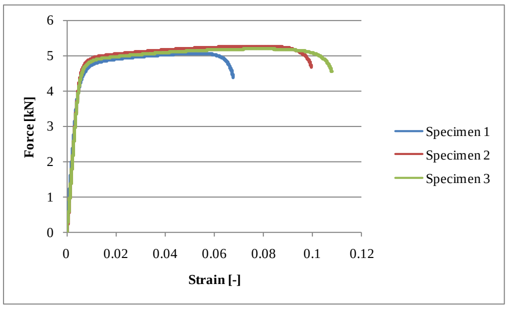
2. Experimental testing

The 6082-T6 alloy used for the facesheets can be considered as a structural alloy, since its proof strength at ambient temperatures is above 260 MPa, which is comparable to the yield strength of some grades of steel. Generally, this alloy has very good corrosion resistance and weldability. These properties can justify the application of this aluminum alloy in the automotive, aeronautical and off-shore industry, as well as in civil engineering.

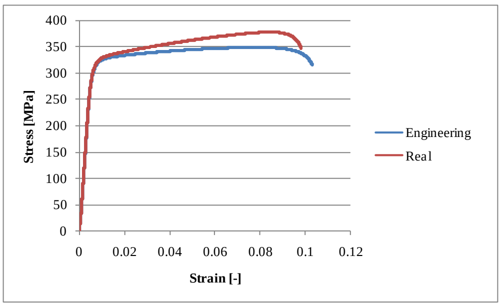
The material properties are obtained from tensile testing according to the *ISO 6892-1:2016 Ambient Tensile Testing of Metallic Materials*. The tests were carried out on a Zwick-Roell testing machine that can develop a maximum force of 10 kN with a loading speed of 1 mm/min. For measuring strains an extensometer with a gauge length of 50 mm was used. Conventional characteristic curves from three tests are shown in Fig. 1 a). The significant engineering and the corresponding real stress-strain curves are presented in Fig. 1 b).

The foams used for the core were PUR of 100 kg/m^3 and PS of 32 kg/m^3. They were acquired as plates having 12 mm thickness for PUR and 19 mm thickness for PS; this thickness was later reduced to 12 mm as to be comparable to the one of PUR.

The mechanical properties of a PUR foam in compression were established previously on cubic form specimens for various speeds of testing and temperatures, [11]. Fig. 2 a) shows the engineering curve obtained for a crosshead speed of 0.5 m/s for a similar foam of 93 kg/m^3 density; the same curve was also extended numerically for future use in the numerical simulations. For the PS foams (Fig. 2 b) we relied on the results given in literature [12] for a test done on a cylindrical specimen of 28 kg/m^3 density at same speed; the extended curve is shown in Fig. 2 b) together with the one for PUR as to make a comparison on the behavior of the two foams.

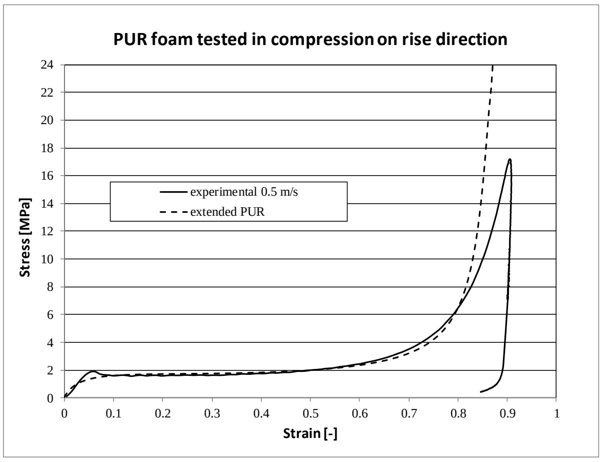


a)

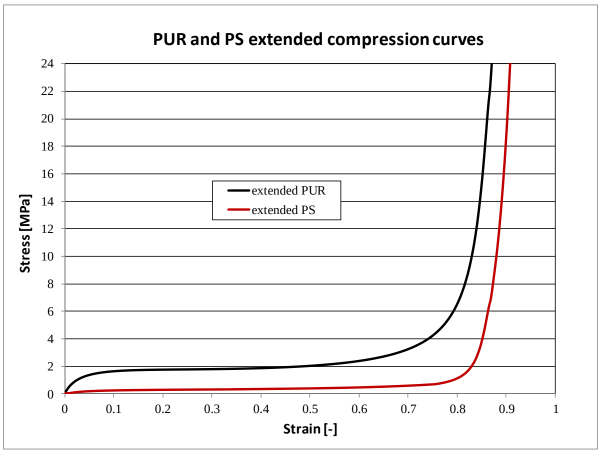


b)

Fig. 1. Traction stress - strain curves for Al6082-T6: a) experimental engineering curves; b) significant engineering curve and the calculated real curve.



a)



b)

Fig. 2. Compression engineering stress-strain curves: a) experimental and extended PUR foam of 93 kg/m^3 [11]; b) extended PUR and PS foam of 28 kg/m^3 [12].

The mechanical properties of the foams and of the facesheets are presented in Table 1. The values of Poisson's ratios for the two foams was considered zero as no length increase on transversal direction was noticed during compression tests.
The square sandwich panels prepared for testing had a size of 140x140 mm. Facesheets made of aluminum Al 6082-T6 of 1.5 mm thickness were glued with Araldite AW106 (Huntsman) to the two types of core: PUR Necuron 100 of density 100 kg/m^3 having thicknesses of 12 mm and PS of density 32 kg/m^3 having thicknesses of 19 mm, respectively 12 mm. Therefore, the thickness of the tested panels can vary from 15 mm up to 22 mm. The thickness of the adhesive layers of about 0.2 mm each was not considered in calculating the total thickness.

Table 1. Mechanical properties of the aluminum Al6082-T6 facesheets, polyurethane (PUR) and polystyrene (PS) foam core.

Material properties	Al 6082-T6	PUR	PS
Density, ρ [kg/m^3]	2700	100	32
Young's Modulus, E [MPa]	60,000	30	4.5
Poisson's ratio, ν	0.33	0	0
Yielding stress, σ_y [MPa]	315	1.8	0.35

An instrumented Instron Ceast 9340 Drop Tower Impact System used a cylindrical impactor (striker) 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. 3), 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 prove as being sufficient for most 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. 3 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.

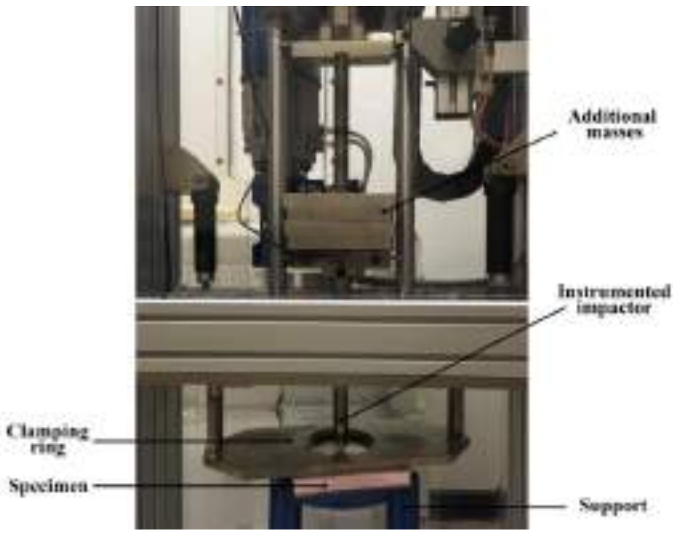


Fig. 3. Experimental setup with sandwich panel fixed for testing.

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. 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 133.14J, as done also in [13].

3. Response of sandwich panels to low-velocity impact testing

The impacted sandwich panels were abbreviated as following: type of foam (PUR or PS), core thickness (12 mm or 19 mm), and skin thickness of 1.5 mm. Therefore, as an example, PUR_12_1.5 means sandwich with PUR foam, 12 mm core thickness and 1.5 mm aluminum skin thickness. In average three tests (notated as 00, 01, 02) were done for each type of panel which were denoted as: PUR_12_1.5, PS_12_1.5, PS_19_1.5. For most type of panels initial impact speed was: 1.5 m/s, 2.5 m/s, 3 m/s, 3.5 m/s, 4 m/s, 4.5 m/s – in some cases some impact speeds were skipped as feeling that those tests would not provide important additional information. In the next figures, in general, only one test per impact speed is shown. In few situations plots are given for two tests as to confirm the correctness of the test.
Experimentally obtained plots from Fig. 4 are given for PUR_12_1.5 as the contact force variation in time during the impact event, for initial testing speeds from 1.5 m/s up to 4.5 m/s. For an event without damage the impact force curve variation in time should be symmetric for loading and unloading. 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 identical, and there is no severe damage of the top skin.
At a speed of 3.5 m/s two tests are shown. 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. They coincide entirely, and after these events the contact force increases back a little. 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. At all speeds the impacts last for less than 14 ms.

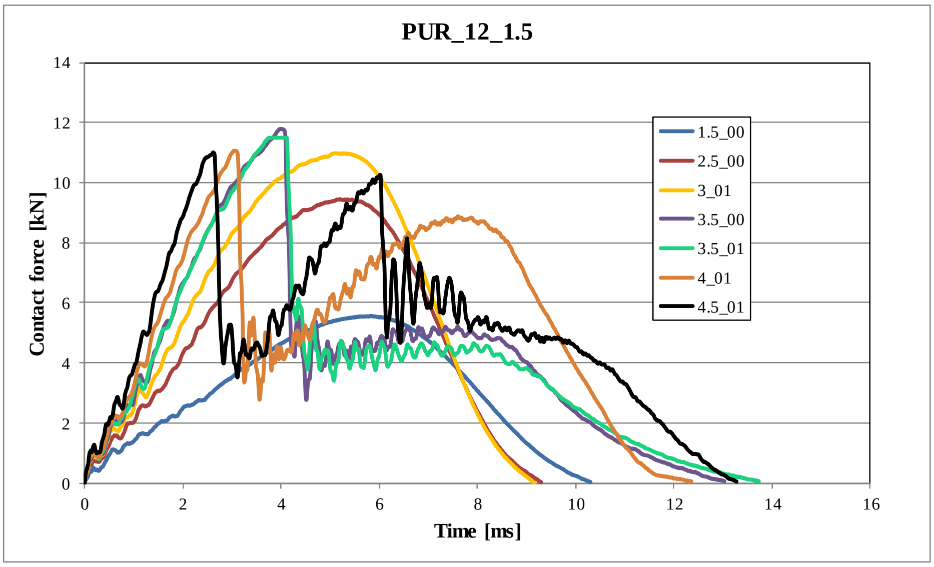


Fig. 4. Contact force evolution for panels with PUR foam of 12 mm thickness.

Comparison of the response of the panels with PUR core to the PS core with same thickness of 12 mm and same skins can be done in between Fig. 4 and Fig. 5.
For the PS 12 mm core thickness and 1.5 mm skin (Fig. 5) curves overlap nicely in loading for the two tests at 4 m/s and at 4.5 m/s are (surprisingly or not) almost identical and give almost the same type of response. There is no skin failure for this foam-skin combination.

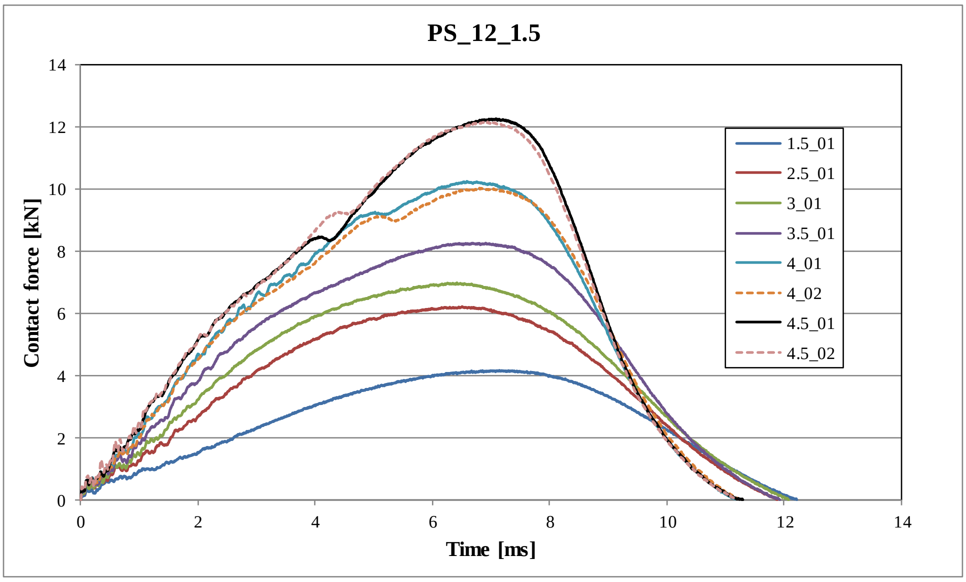


Fig. 5. Panels with PS foam of 12 mm thickness and skins of 1.5 mm.

As the PS core is more ductile the behavior of the sandwich panels is completely different. Regardless the speed of testing there is a severe indentation in the area 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.
A similar analysis of the response of the panels as done in Fig. 5 is now presented in Fig. 6 for panels with PS core having a thickness of 19 mm.

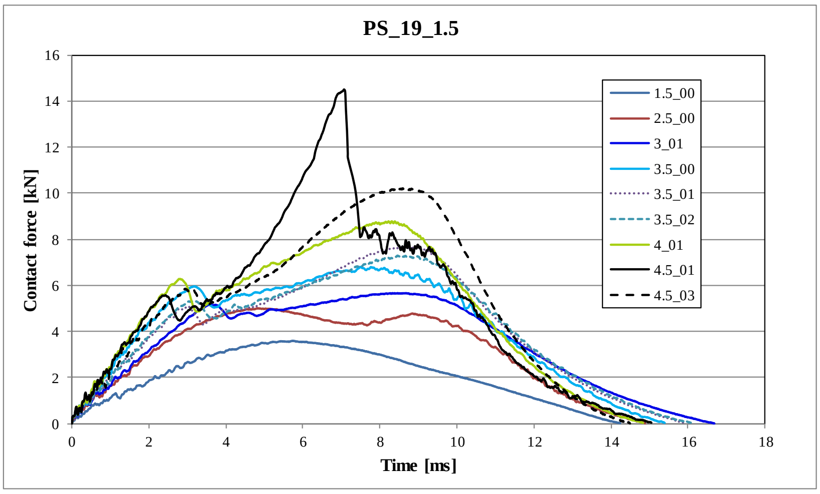


Fig. 6. Panels with PS foam of 19 mm thickness.

In Fig. 6 are shown three tests done at a velocity of 3.5 m/s with very few differences in between them. 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. At 4.5 m/s, in one test, most surely one which should be disregarded, the upper skin was perforated at an unexpected high force of above 14 kN. The other test gave 10.1 kN maximum force which is a plausible value as being in line with the other obtained results.
The force history of impact tests was plotted also to analyze how the contact force changed as a function of the impactor displacement. Fig. 7 analyses the PUR core sandwich response and Fig. 8 the one for the PS core. From the initiation of contact the force histories of all the sandwich panels, irrespective of the core material, show the same tendency, namely, the force history curve exhibiting an almost linear increase as the projectile contacts the panel and is followed by a prolonged contact with the core during loading. In unloading the type and the core and the aluminum sheet thickness influence significantly. The interpretation of these curves must be done in conjunction with the observations done on the failure of the panels.
Although loading is produced on the same path regardless the speed of testing, the failure of the top skin is produced starting from 3.5 m/s as to be seen from the abrupt drop of the force (Fig. 7). The two tests at 3.5 m/s give almost the same

response. As the crushing of the rigid foam starts the contact force signal has many variations, force starts to increase its value and eventually drops back to zero while the displacement of the impactor decreases. Only at 4.5 m/s the bottom skin is perforated, force drops suddenly to about 4.8 kN after 6 ms (see Fig. 4) and 20 mm displacement of the impactor, and the panel oscillates significantly without absorbing energy anymore. It is remarkable that when increasing speed above 3.5 m/s the increase of force is done again on the same path, although many irregularities are appearing.

For the PS 12 mm core thickness and 1.5 mm skin (Fig. 8 a) curves overlap nicely for loading, the two tests at 4 m/s give almost the same curves of response and the two at 4.5 m/s are identical. There is no skin failure for this foam-skin combination.

For the same PS core but with increased thickness of 19 mm (Fig. 8 b) contact force signals are oscillating a lot, especially during loading. Two tests at 3.5 m/s are shown as giving same panel response, but at 4.5 m/s (as commented before) one test (4.5_01) is giving somehow a very big maximum force and should be disregarded. The perforation of the top skin in this case is accidental. In conclusion, PS core panels response is ductile and improve a lot the sandwich panels' capacity of integrity.

In fact, as it will be seen by analyzing the impacted PS panels of core thickness 19 mm they deform significantly at 4.5 m/s and delaminations are produced.

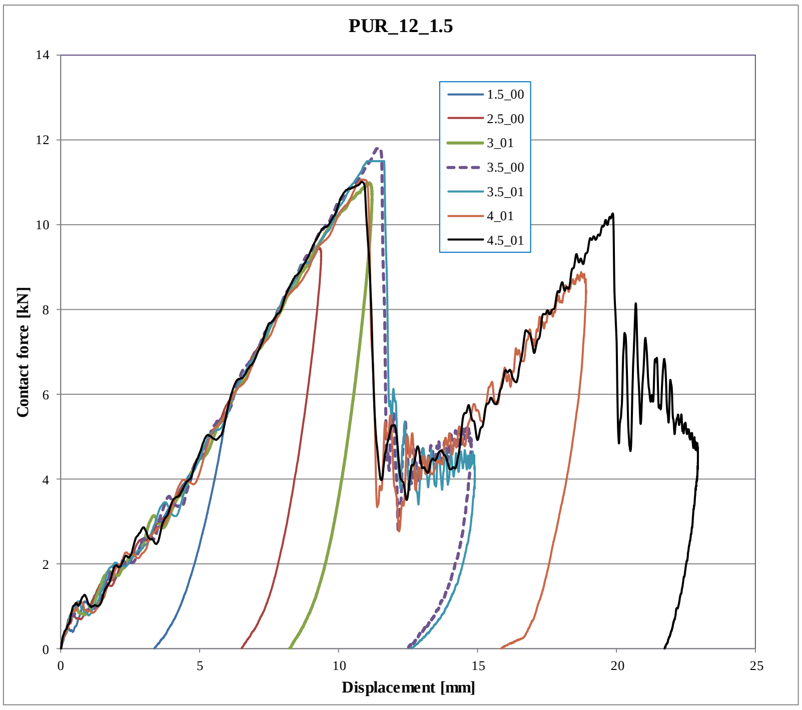
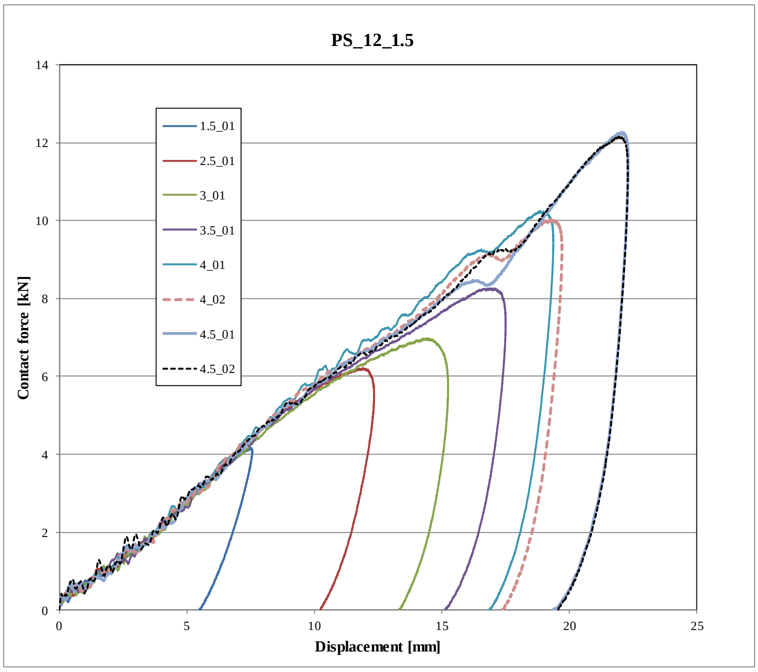
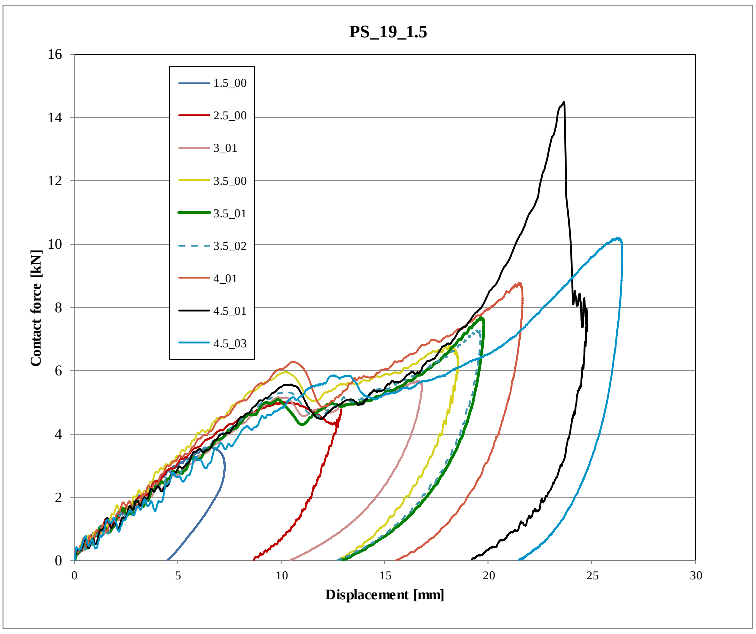


Fig. 7. Contact force-displacement variation for 12 mm PUR core.



a)

Fig. 8. Contact force-displacement for PS core: a) 12 mm.



b)

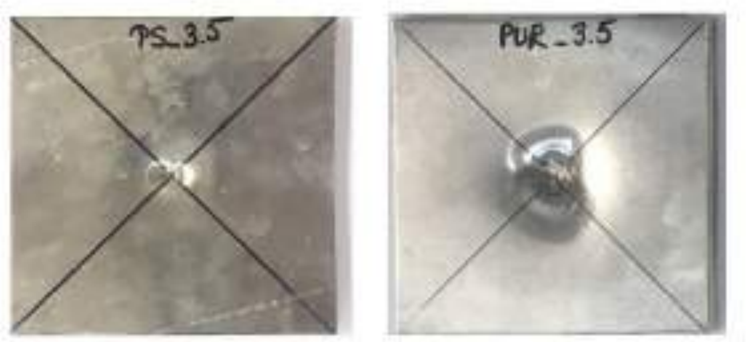
Fig. 8. Contact force-displacement for PS core: b) 19 mm.

4. Damage and perforation of impacted sandwich panels

A first comparison is done between PUR_12_1.5 and PS_19_1.5: although core thickness is different the mass of the panels is 182 grams, respectively 171 grams. Being about the same, from the point of view of an engineering application in looking for a lightweight solution, a decision on which variant to consider may be taken by assessing the integrity of the panels.

Clear observations of the response of the two types of impacted sandwich panels is presented in Fig. 9 a) for 2.5 m/s, respectively in Fig. 9 b) for 3.5 m/s. The previous comments can also be explained by the level of penetration produced in the top skin of the sandwich. The PUR panels are severely punctured as shown on the right side of both figures. However, the bottom skin remains totally undamaged at these speeds of impact. At 3.5 m/s the top skin of the panel is completely perforated for PUR and partially punctured for PS panel. The size of the indentation is also smaller. Thus, the PS panels behave better in impact, absorbing more energy.

a)

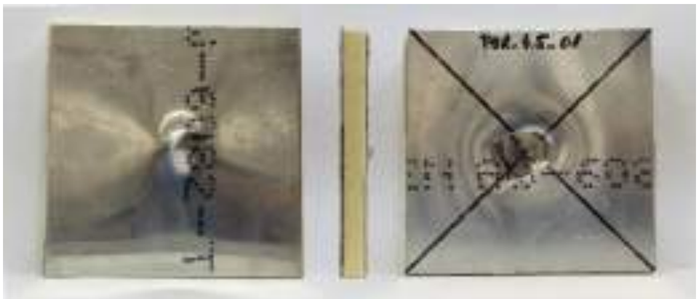


b)

Fig. 9. Impact response of sandwich panels: a) 2.5 m/s; b) 3.5 m/s. For each speed of testing on the left is the PS panel and on the right is the PUR panel.

Impact tests were repeated for two or three sandwich panels at each speed of testing and the reproducibility of the results was very good. The impact speed was afterwards increased to a maximum of 4.5 m/s (133.14 J) and, of course, all phenomena became very complicated. The response of the PS panel is presented in Fig. 10 a) for a velocity of 4 m/s. Top skin was damaged quite severely, and bottom skin was only slightly indented. The panel bended a lot along a median plane and the lateral view showed that delaminations were generated in the polystyrene core close to the top skin on opposite sides, as the core was weaker than the AW 106 adhesive. In all, the polystyrene core can absorb the impact energy with a good elastic recovery.
The PUR panel shown in Fig. 10 b) had a rigid behavior due to the higher density of the polyurethane core and didn't bend.
Top skin was severely perforated and, only for this panel, bottom skin failed also. The deformation concentrated towards the central part of the panel which was perforated and there were no delaminations at the interface of the core with the skins.

a)



b)

Fig. 10. Impact of sandwich panels at 4.5 m/s: a) PS panel; b) PUR panel. Bottom, lateral, and top views.

5. Conclusions

The low-velocity impact response of foam sandwich panels depends on the foam type, initial velocity, and core thickness. Variations of the contact force-time and contact force-displacement of impactor get more complicated as the initial velocity of testing is increased and the interpretation of the corresponding plots must be done carefully by analyzing both type of plots. From the force-displacement curves the absorbed energy of the sandwich panels can be calculated.
The polyurethane foam has a rigid behavior and failure is produced in a brittle manner. The polystyrene foam has a better recovery and absorbs more efficiently the impact energy.

Acknowledgements

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