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LOW VELOCITY IMPACT RESPONSE AND DAMAGE CHARACTERISTICS OF FOAM CORE SANDWICH PANELS WITH THIN GFRP FACESHEETS

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Abstract. The impact response and damage characteristics of foam core sandwich panels with composite facesheets subjected to low velocity impact were experimentally investigated in this paper. Drop weight tests were carried out involving different impact velocities, foam and facesheet type. Two commercial foams were used as core for the sandwich panels: polyurethane Necuron 100 of density 100 kg/m^3 and extruded polystyrene of density 32 kg/m^3. The experimental results were compared in terms of force-displacement response and damage status. It was found that the addition of short glass fibres to the composite facesheets increased the maximum impact force and reduced the debonding of the bottom facesheets for both foam grades. The use of lower density polystyrene foam increased the flexibility of the panels and improved the ultimate failure response of the composite sandwich panels.

Key words: foam core, glass fibres, sandwich panel, impact response, damage assessment.

1. INTRODUCTION

Sandwich structures usually consist of two strong and stiff facesheets separated by a low-density core. Faces are generally made of metal alloys [1], fibre reinforced composites [2] or fibre metal laminates [3] and are responsible for carrying the transverse loads or bending moments. The core comprises of honeycombs [4], corrugated materials [5], polymeric/metallic foams [6–7], lattices [8] or balsa wood [9] and is responsible for absorbing the impact energy by local plastic deformations whilst still offering enough overall support to prevent high local bending strains in the facesheets.

Composite sandwich structures are susceptible to low velocity impact damage caused by minor and major in size objects, such as hail stones or runaway debris or dropped tools. They can undergo significant damage in terms of matrix cracking, fibre failure, facesheet indentation, local core crushing, debonding of the facesheet from the core and even penetration, which drastically reduces the integrity of the structure.

Extensive studies on the behaviour of composite sandwich structures subjected to dynamic loads were carried out by many authors over the last years in order to understand their impact response and damage characteristics. Researches deal with both quasi static [10–13] and dynamic behaviour [14–20], in trying also to develop analytical models, [21–22]. Mostafa et al. [11] studied theoretically, experimentally, and numerically the flexural behaviour of a polyurethane (PUR) foam and glass fibre reinforced polymer (GFRP) composite facesheet sandwich panel and found that the panel failed due to shear failure of the core accompanied with skin-core delamination in the constant shear region. Styles et al. [12] found different failure mechanisms between specimens with different core thickness using the 3D image correlation method to get the strain distribution in sandwich beams with aluminium foam core. Mathieson et al. [13] studied the in-plane behaviour of GFRP/PUR sandwich beams and established that skin wrinkling in compression is responsible for structure failure under in-plane bending. The static and fatigue behaviour of PVC foam sandwich composites loaded in three-point flexure has been examined by Kulkarni et al. [14]. Failure of the core has been monitored as a function of number of cycles and it was found that the crack propagation takes place in three stages: core-skin debonding, core shear, followed by another core-skin debonding. Schubel et al. [16–17], Yang et al. [18] and Liu et al. [19] used historical curves and cross section appearance to characterize the damage and failure of sandwich structures and concluded that peak loads in impact load history curves stand for the failure of different components. Yang et al. [20] used scanning electron microscopy (SEM) to obtain the fracture characteristics of foam core and GFRP faces. It was found that cracking in the matrix, debonding between different layers and some fibre breaking in the facesheet are the main damage modes after impact. Zhang et al. [21] proposed an analytical solution of plastic behaviour of fully clamped geometrical asymmetric sandwich beams in low velocity impact using the quasi-static method. Feli et al. [22] proposed a spring-mass model to obtain the residual and ballistic limit velocity of a projectile shot into sandwich panels. Both models were proved to be accurate and efficient.

Drop weight tests on sandwich panels with unidirectional carbon facesheets and PUR foams of different grades were performed by Long et al. [23] as to investigate the failure details; penetration and delamination of the facesheets and crushing of the foam were observed experimentally after testing and finite element simulations based on a user-defined material subroutine were proposed. It was shown that sandwich panels with a hard core proved to be more vulnerable to delamination than the ones with a soft core. Another research, [24], characterized also the type and extent of the damage observed in a variety of sandwich configurations with graphite/epoxy facesheets and foam or honeycomb cores. Several configurations, involving two different core heights and two or three skins were investigated in order to evaluate the damage of the core after impact and to find the best configuration in terms of impact energy absorption [25].

This paper studies the influence of core grade and thin composite facesheet type on the impact response of sandwich panels by experimental testing as it was also done before with aluminium and thicker composite facesheets, [26]. The variation of the force-displacement curves gives consistent indications on the local characteristic damage events. Observations on the types of failures are done and damage assessment conclusions are presented.

2. SANDWICH PANELS MATERIALS AND TESTING METODOLOGY

Sandwich panels were made of two facesheets and a foam core. Each composite facesheet had 8 layers of fibre glass roving of 500 g/m^2 and the general-purpose epoxy system used as matrix was EPOLAM 2017. Three different types of facesheets were obtained by adding different amounts of short glass fibres in the resin matrix: type A – 0 g of short glass fibres/100 g resin, type B – 6.4 g of short glass fibres/100 g resin and type C – 9.3 g of short glass fibres/100 g resin. Thickness of the facesheets slightly varied in between 2–2.5 mm due to the manual manufacturing process. The foams used as core for the sandwich panels were polyurethane (PUR) Necuron 100 of density 100 kg/m^3 and commercial extruded polystyrene (PS) of density 32 kg/m^3, both having thicknesses of 12 mm. Facesheets were bonded to the core using an epoxy adhesive, type Araldite AW106 (Huntsman). The panels were cut into square specimens of 140x140 mm. The mass of the panels with PUR foam core was 167.13±5.24 grams and for the PS foam core of 158.14±4.79 grams.

Low velocity impact tests with a range of impact velocities between 3 m/s and 4 m/s were performed according to ASTM D7136, [27], using a drop weight tower, as presented in Fig. 1.

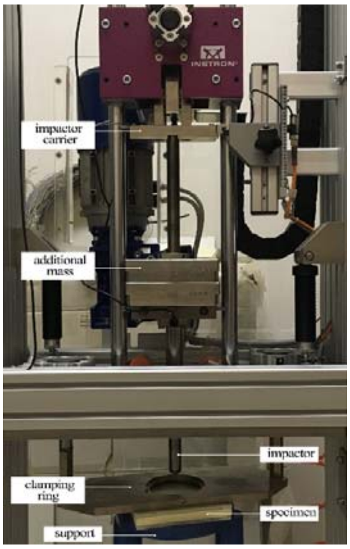


Fig. 1 – INSTRON Ceast 9340 drop tower impact system.

The INSTRON Ceast 9340 is a gravitationally accelerated impact drop tower that can reach impact velocities up to 4.6 m/s and impact energies of almost 430 J. It is equipped with an instrumented impactor, having a hemispherical head of 20 mm diameter, which can directly measure the impact force using a strain gauge transducer which is mounted inside an elastic element. The sandwich plates are placed on an adjustable in height test specimen support with a circular hole of 100 mm diameter (Fig. 1), which eventually allows the striker to fall if the plate is perforated. A clamping ring is pressed over the sandwich plate by a pneumatic system with a maximum force of 3 kN. This force cannot be adjusted during testing. Data is acquired using an INSTRON Ceast DAS 64K system, with a frequency up to 4 MHz. The machine's software allows the user to obtain other impact characteristics such as: absorbed energy, displacement of the impactor, and of course the measured contact force during impact. Therefore force-time and force-displacement plots can be easily obtained.

The tests were done at three impact velocities: 3 m/s, 3.5 m/s and 4 m/s. The desired impact velocities were reached by adjusting the falling height of the impactor. The impact mass was kept constant for all tests, and it was obtained by adding two additional masses of 5 kg each to the total weight of the impactor assembly (3.15 kg), in total 13.15 kg. Therefore, the corresponding impact energies were 59.17 J, 80.54 J and 105.20 J. The specimens were impacted in the centre, thus special attention was given to the positioning and the alignment of the panels. Data acquisition was done with a frequency of 200 kHz for a maximum estimated time of 40 ms which proved as being sufficient to follow all the significant events. Only the first impact was considered for monitoring the impact phenomena and comparisons of the responses of the sandwich panels which were tested.

3. RESPONSE OF IMPACTED SANDWICH PANELS

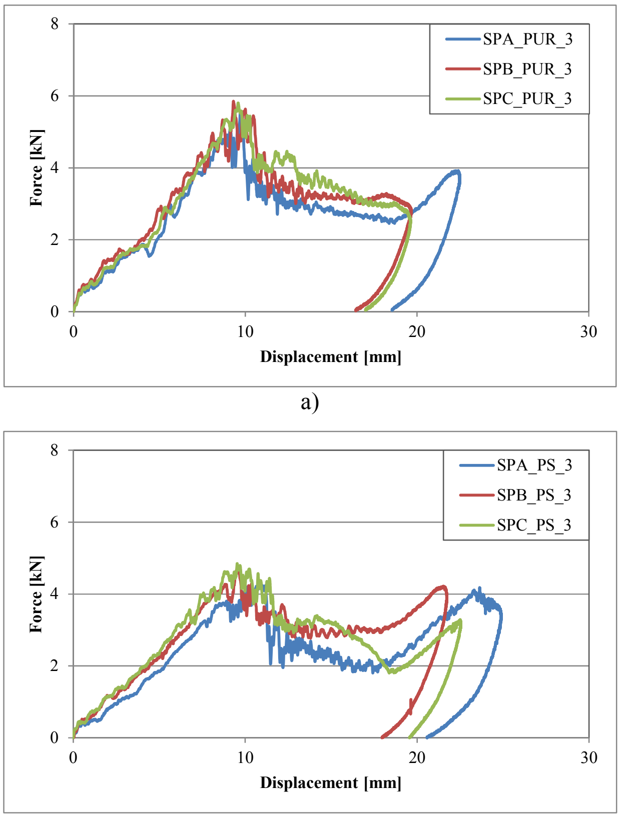
The impacted sandwich panels were abbreviated as following: sandwich panel (SP) with composite facesheets type (A, B or C), foam core type (PUR or PS) and impact velocity. Therefore, as an example, SPA_PUR_3 means sandwich panel with composite facesheets type A and polyurethane (PUR) foam core impacted at 3 m/s.

3.1. Force-displacement response

The results of the experimental investigations are presented in the form of force-displacement curves in Figs. 2 to 4. As no filters were used, the curves have many oscillations which may be introduced by two primary sources: the natural frequencies of the impactor and the flexural vibrations of the impacted panels, [26].

Force-displacement curves show an initial linear variation as the impactor contacts the panel. The slope of the curves represents the stiffness of the sandwich structure and, as it can be seen, this is always greater for panels with facesheets that have an addition of short glass fibres (type B and C). The linear increase of force is followed by severe oscillations until reaching the first force peak value because of the brittle failure of the glass fibre composite facesheets including matrix cracking, fibre breaking and delaminations, [28]. The sudden drop of force after reaching the first peak value with further increase in displacement indicates the perforation of the upper facesheet. The plateau that follows corresponds to the penetration process of the impactor into the foam core and contributes significantly to the energy absorption capacity of the sandwich panel. A second peak of the impact force appears as the impactor reaches the bottom facesheet of the panel. The last part of the curve, after reaching the second peak value, usually indicates the rebounding, penetration or perforation situations.

For the lowest impact velocity of 3 m/s (see Fig. 2a and Fig. 2b) the first peak force is always greater than the second, irrespective of facesheet and core type. The addition of short fibres in the facesheets determines the increase of the first peak value and the decrease of the second. The maximum displacement of the impactor is also smaller. Thus, the addition of short fibres in the facesheets determines an increase of rigidity for the sandwich structure. Panels with PUR foam core have a higher first peak of force than those with PS foam core and this is due to the increased rigidity of the polyurethane foam. On the contrary, the second peak is smaller and, for panels with facesheets type B and C, it's almost negligible. As it can be seen from Fig. 2a and Fig. 2b all force-displacement curves show a force drop with many oscillations during fibre failure and matrix cracking, meaning that the upper facesheet is perforated. The decrease of force with further decrease of displacement after reaching the second peak force for SPA_PUR_3 and all PS panels indicates that the bottom facesheet doesn't undergo perforation and thus the impactor is rebounded. For the SPB_PUR_3 and SPC_PUR_3 panels the second peak of the force is not produced as the bottom facesheet is barely damaged as to be seen also from Fig. 6. An exception can be noticed in the case of SPA_PS_3 curve (Fig. 2b) where the second peak force is followed by some oscillations and a small increase of displacement before its decrease, which indicates that some damage in the bottom facesheet occurred. Still, the impactor was rebounded. The force-displacement curve remains *closed* when there is no perforation of the bottom facesheet.



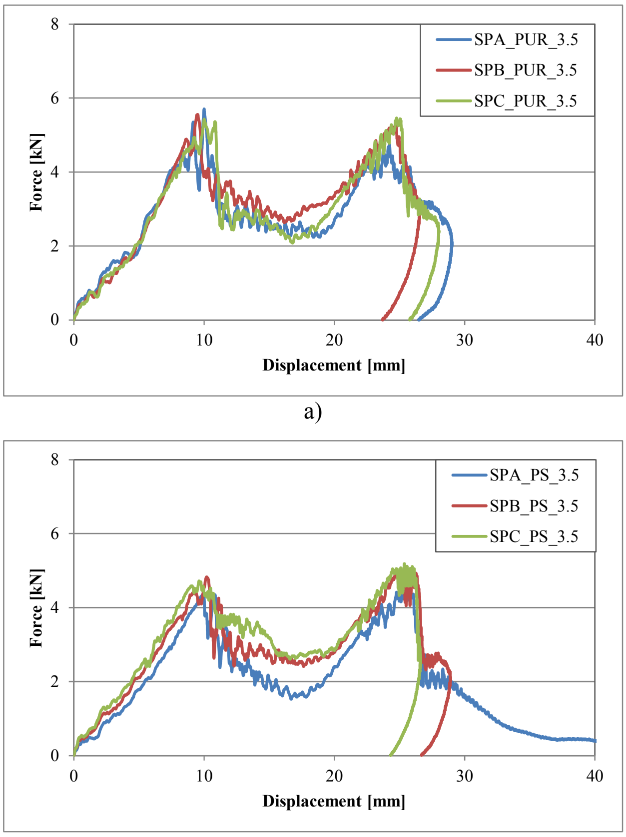
a)

b)

Fig. 2 – Force-displacement curves for sandwich panels impacted at 3 m/s: a) PUR foam core; b) PS foam core.

Figures 3a and 3b present the force-displacement curves for sandwich panels impacted at 3.5 m/s. The increase of velocity determines the penetration of the upper facesheet and the crushing of the foam core underneath the impactor, which results in an increase of value for the second peak force. For PUR foam core panels both force peaks have about the same value. The force drop that occurs after reaching the second peak force indicates the degradation of the bottom facesheet in the form of fibre rupture, debonding in between the composite layers and even perforation of the bottom facesheet as for curve SPA_PS_3.5. When the bottom facesheet fails the force-displacement curve becomes *opened*, meaning that displacement increases as the impactor is not rebounded. The more elastic behaviour of the PS foam core determines smaller force oscillations after reaching the first peak value and thus diminishes the degradation of the upper facesheet. It is to be noticed that adding short fibres for SPB_PS_3.5 and SPC_PS_3.5 make the top facesheet to be more rigid (type C curve being above type B as expected) and lead to the increase of the force in the plateau region in between the force peaks.

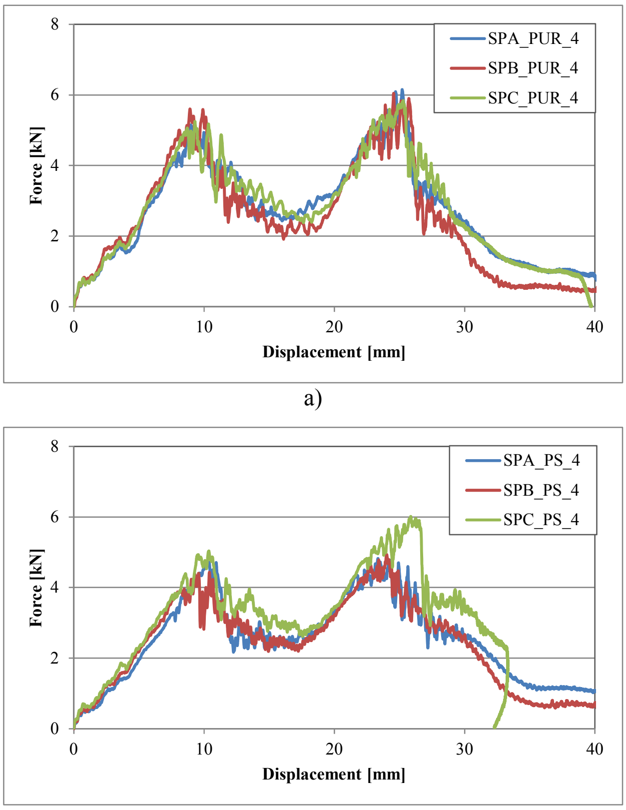
Further increasing of the impact velocity to 4 m/s determines in most cases the complete penetration of the sandwich panels and the complete loss of their loading capacity (see Figs. 4a and 4b). Except the SPC_PS_4 curve, which is a *closed* curve thus indicating that there was no perforation of the bottom facesheet, all curves are *opened*, meaning that the sandwich panel has both facesheets penetrated. The second peak force reaches a value of 6 kN (Fig. 4b) as for the PUR foam panels, but the drop of force is more evident as this panel barely withstands the impact. In fact, the bottom facesheet is severely damaged as to be seen also from Fig. 6.



a)

b)

Fig. 3 – Force-displacement curves for sandwich panels impacted at 3.5 m/s: a) PUR foam core; b) PS foam core.



a)

b)

Fig. 4 – Force-displacement curves for sandwich panels impacted at 4 m/s: a) PUR foam core; b) PS foam core.

3.2. Damage assessment

Damage assessment through visual inspection of the sandwich panels revealed that the impact loading induced damage as matrix cracking, debonding, fibre rupture, core crushing and facesheet perforation. Close up images of the central part of the impacted sandwich panels are presented in Fig. 5 and Fig. 6.

For the lowest impact velocity of 3 m/s (see Fig. 5), the upper facesheet is perforated, with matrix cracking and severe fibre ruptures, due to both through thickness shear mode and tension mode. Though, sandwich panels with PUR core fail mostly under shear mode, due to the brittle behaviour of the polyurethane foam, while sandwich panels with PS core fail mostly in tension mode. Moreover, the elastic behaviour of the PS foam core allows the impactor to push apart the ruptured fibres and hence create a bigger perforation cavity. The bottom facesheet fails only through matrix cracking and debonding between fibres and matrix due to tension failure, with no fibre rupture.

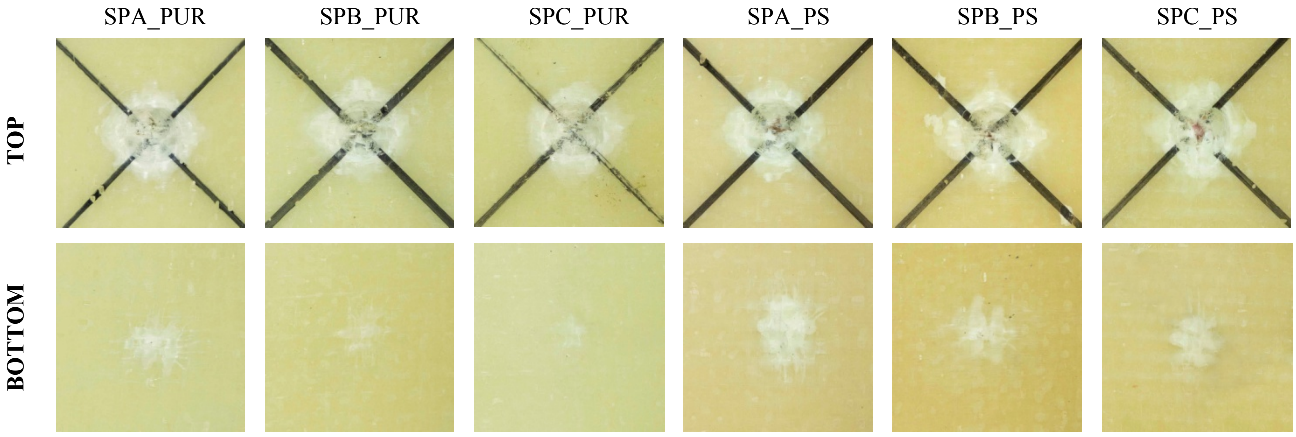


Fig. 5 – Failure of sandwich panels impacted at 3 m/s.

For the highest impact velocity of 4 m/s (Fig. 6) all the sandwich panels were perforated, except the sandwich panel with PS foam core and facesheets type C (SPC_PS). This panel had the most rigid facesheets, due to the highest amount of added short fibres, and absorbed better the impact energy due to the elastic behaviour of the PS foam core.

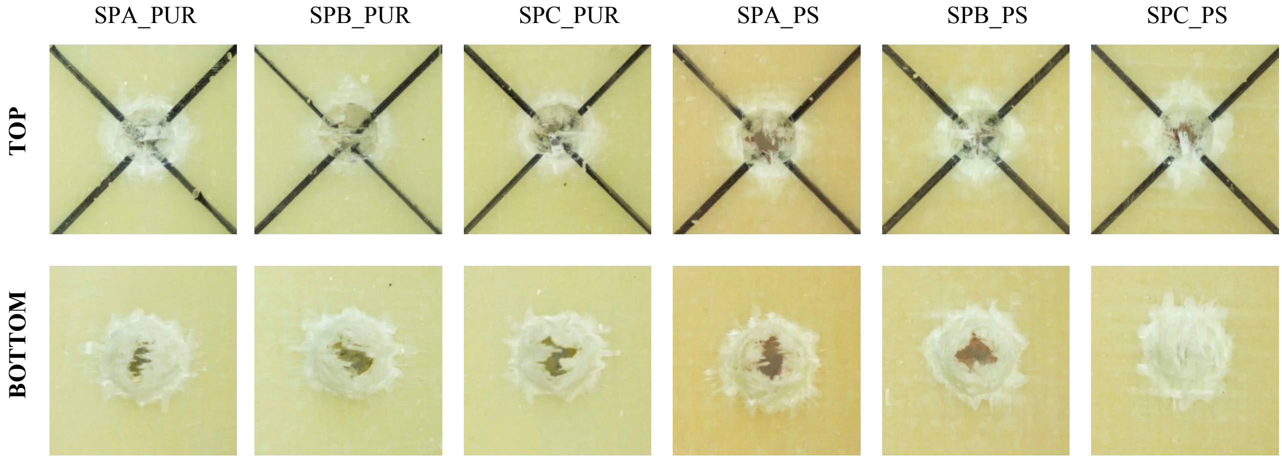


Fig. 6 – Failure of sandwich panels impacted at 4 m/s.

In order to quantify the damage produced in the facesheets we measured the debonding area which is visible on the surface of the facesheets as being whiter that the initial colour of the panel. The measured dimensions in millimetres are denoted as width x height and given in Table 1 for all the tested panels on both facesheets, top and bottom. Top facesheet perforation is produced for all sandwich panels and marked as an existent event, while bottom facesheet perforation is produced in most cases regardless the type of foam core at an initial impact speed of 4 m/s (exception being SPC_PS), and only for SPA_PS panel at 3.5 m/s.

Several observations can be done:

- top facesheet perforation and debonding size is about the same for all types of facesheets and both core grades; at the chosen initial speeds the impactor penetrates rapidly the composite skins in the same manner;
- the more rigid composite facesheet makes a difference for the bottom facesheet, especially if PS core is used in reducing a little bit the size of the debonding;
- PUR core, being more rigid, reduces the visible debonding size for bottom facesheet type C, with the highest content of added short fibres, at speeds of 3 and 3.5 m/s; that is 10×12 mm for PUR instead of 15×31 mm for PS, respectively 33×32 mm for PUR instead of 43×23 mm for PS;
- at 4 m/s the more rigid PUR core and facesheets type B and C reduce slightly the debonding size on the top skin; however, on the bottom facesheet the PS foam core more elastic response succeeds to keep about the same debonding surface as the PUR foam core, even without perforation for type C facesheet.

Table 1

Summary of damage events induced by impact loading

Impact speed and type of panel		Facesheet perforation				Debonding			
		Top		Bottom		Top		Bottom	
		PUR	PS	PUR	PS	PUR	PS	PUR	PS
3 m/s	A	✓	✓	x	x	38 × 36	34 × 34	35 × 25	23 × 35
	B	✓	✓	x	x	33 × 34	38 × 37	19 × 20	25 × 23
	C	✓	✓	x	x	37 × 34	39 × 34	10 × 12	15 × 31
3.5 m/s	A	✓	✓	x	✓	32 × 31	31 × 30	40 × 34	44 × 31
	B	✓	✓	x	x	32 × 30	32 × 34	43 × 30	29 × 47
	C	✓	✓	x	x	33 × 32	36 × 34	33 × 32	43 × 23
4 m/s	A	✓	✓	✓	✓	33 × 34	31 × 34	46 × 36	42 × 36
	B	✓	✓	✓	✓	32 × 29	34 × 35	44 × 31	39 × 37
	C	✓	✓	✓	x	34 × 28	33 × 36	42 × 32	34 × 43

✓ existent event
x non-existent event

4. CONCLUSIONS

The paper investigates the low velocity impact behaviour of sandwich panels with composite facesheets and polyurethane and polystyrene foam core by performing drop weight impact tests. The force-displacement response and failure characteristics are analysed in detail.

The force-displacement response is characterized by the existence of two peaks of the impact force related to the loading of the two facesheets. The first force peak value is produced at about the same displacement of the impactor, despite the impact velocity, while the second peak value starts to be more evident when increasing the impact velocity, due to the faster densification of the core beneath the impactor. Sandwich panels with facesheets that have an addition of short fibres are stiffer and exhibit higher values of peak force. The response of the sandwich panels is also influenced by the foam core grade. Panels with PUR foam core gave an overall more rigid response, a higher first peak impact force and a slightly smaller debonding surface on the top facesheet as compared to panels with PS foam core. However, on the bottom facesheet the debonding surface is about the same for both foam cores, but the PS foam core helps in avoiding at the limit the perforation of the skin with an evident drop of the impact force.

In the range of initial impact velocities at which tests were done, the failure behaviour of the composite sandwich panels is influenced by apparently small differences of the facesheet stiffness and core grade. More rigid panels increase the impact force but are more vulnerable to complete perforation. Lower density PS foam decreases the mass of the panels and the more elastic response increases their integrity being in favour of an efficient lightweight design.

REFERENCES

1. A. GILIOLI, C. SBARUFATTI, A. MANES, *Compression after impact test (CAI) on NOMEX™ honeycomb sandwich panels with thin aluminum skins*, Compos. Part B-Eng., **67**, pp. 313-325, 2014.
2. Y. ZHANG, Z. ZONG, Q. LIU, J. MA, Y. WU, Q. LI, *Static and dynamic crushing response of CFRP sandwich panels filled with different reinforced materials*, Mater. Design, **117**, pp. 396-408, 2017.
3. C.Y. TAN, H.M. AKIL, *Impact response of fiber metal laminate sandwich composite structure with polypropylene honeycomb core*, Compos. Part B-Eng., **43**, pp. 1433-1438, 2012.
4. H. WANG, K.R. RAMAKRISHNAN, K. SHANKAR, *Experimental study of the medium velocity impact response of sandwich panels with different cores*, Mater. Design, **99**, pp. 68-82, 2016.
5. K. WEI, Y. PENG, Z. QU, R. HE, X. CHENG, *High temperature mechanical behaviors of lightweight ceramic corrugated core sandwich panels*, Compos. Struct., **176**, pp. 379-387, 2017.
6. L. JING, C. XI, Z. WANG, L. ZHAO, *Energy absorption and failure mechanism of metallic cylindrical sandwich shells under impact loading*, Mater. Design, **52**, pp. 470-480, 2013.
7. S. ZHANG, J.M. DULIEU-BARTON, O.T. THOMSEN, *The effect of temperature on the failure modes of polymer foam cored sandwich structures*, Compos. Struct., **121**, pp. 104-113, 2015.
8. G.J. MCSHANE, D.D. RADFORD, V.S. DESHPANDE, N.A. FLECK, *The response of clamped sandwich plates with lattice cores subjected to shock loading*, Eur. J. Mech. A-Solids, **25**, pp. 215-229, 2006.
9. N. JOVER, B. SHAFIQ, U. VAIDYA, *Ballistic impact analysis of balsa core sandwich composites*, Compos. Part B-Eng., **67**, pp. 160-169, 2014.
10. C. STEEVES, N. FLECK, *Collapse mechanisms of sandwich beams with composite faces and a foam core, loaded in three-point bending. Part II: experimental investigation and numerical modeling*, Int. J. Mech. Sci., **46**, pp. 585-608, 2004.
11. A. MOSTAFA, K. SHANKAR, E. MOROZOV, *Behavior of PU-foam/glass-fiber composite sandwich panels under flexural static load*, Mater. Struct., **48**, pp. 1545-1559, 2015.
12. M. STYLES, P. COMPSTON, S. KALYANASUNDARAM, *The effect of core thickness on the flexural behavior of aluminum foam sandwich structures*, Compos. Struct., **80**, *4*, pp. 532-538, 2007.
13. H. MATHIESON, A. FAM, *In-plane bending and failure mechanism of sandwich beams with GFRP skins and soft polyurethane foam core*, J. Compos. Constr., **20**, *1*, p. 04015020, 2016.
14. N. KULKARNI, H. MAHFUZ, S. JEELANI, L. CARLSSON, *Fatigue crack growth and life prediction of foam core sandwich composites under flexural loading*, Compos. Struct., **59**, *4*, pp. 499-505, 2003.
15. R. OLSSON, T. BLOCK, *Criteria for skin rupture and core shear cracking induced by impact on sandwich panels*, Compos. Struct., **125**, pp. 81-87, 2015.
16. P. SCHUBEL, J. LUO, I. DANIEL, *Low velocity impact behavior of composite sandwich panels,* Compos. Part A-Appl. S., **36**, *10*, pp. 1389-1396, 2005.
17. P. SCHUBEL, J. LUO, I. DANIEL, *Impact and post impact behavior of composite sandwich panels,* Compos. Part A-Appl. S., **38**, *3*, pp. 1051-1057, 2007.
18. P. YANG, S. SHAMS, A. SLAY, B. BROKATE, R. ELHAJJAR, *Evaluation of temperature effects on low velocity impact damage in composite sandwich panels with polymeric foam cores*, Compos. Struct., **129**, pp. 213-223, 2015.
19. C. LIU, Y. ZHANG, L. YE, *High velocity impact responses of sandwich panels with metal fiber laminate skins and aluminum foam core*, Int. J. Impact Eng., **100**, pp. 139-153, 2017.
20. B. YANG, Z. WANG, L. ZHOU, J. ZHANG, L. TONG, W. LIANG, *Study on the low-velocity impact response and CAI behavior of foam-filled sandwich panels with hybrid facesheet*, Compos. Struct., **132**, pp. 1129-1140, 2015.
21. J. ZHANG, Q. QIN, C. XIANG, Z. WANG, T. WANG, *A theoretical study of low-velocity impact of geometrically asymmetric sandwich beams*, Int. J. Impact Eng., **96**, pp. 35-49, 2016.
22. S. FELI, S. JAFARI, *Analytical modeling for perforation of foam-composite sandwich panels under high-velocity impact*, J. Braz. Soc. Mech. Sci, **39**, 2, pp. 401-412, 2017.
23. S. LONG, X. YAO, H. WANG, X. ZHANG, *Failure analysis and modeling of foam sandwich laminates under impact loading*, Compos. Struct., **197**, pp. 10-20, 2018.
24. T. ANDERSON, E. MADENCI, *Experimental investigation of low velocity impact characteristics of sandwich composites*, Compos. Struct., **50**, *3*, pp. 239-247, 2000.
25. H.A. PETRESCU, A. HADĂR, Şt.D. PASTRAMĂ, *Experimental program for impact tests on a honeycomb core composite material*, P. Romanian Acad. A, **18**, *2*, pp. 150-157, 2017.
26. O.A. MOCIAN, D.M. CONSTANTINESCU, M. SANDU, Şt. SOROHAN, *Experimental evaluation of the response of sandwich panels in low-velocity impact*, P. I. Mech. Eng. L-J. Mat., **233**, pp. 315-327, 2019.
27. ASTM D7136/D7136M-12, *Standard test method for measuring the damage resistance of fiber-reinforced polymer matrix composite to a drop-weight impact event*, West Conshohocken, PA, USA: ASTM International, 2012.
28. A. GLISZCZYNSKI, T. KUBIAK, P. ROZYLO, P. JAKUBCZAK, J. BIENIAS, *The response of laminated composite plates and profiles under low-velocity impact load*, Compos. Struct., **207**, pp. 1-12, 2019.

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