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Edgewise and flatwise compressive behaviour of foam-filled sandwich panels with 3-D high density polyethylene skins

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A B S T R A C T

In this paper, the edgewise and flatwise compressive behaviour of an innovative sandwich panel, mainly developed for quick assembly of post-disaster housing as well as load bearing panels for pre-fabricated modular construction and semi-permanent buildings, is investigated experimentally and by finite element modelling. The panel is composed of two 3-D high-density polyethylene (HDPE) sheets as the skins, filled with high-density Polyurethane (PU) foam as the core. HDPE sheets manufactured with a studded surface considerably enhance the stress distribution and buckling performance of the sandwich panel. Material characterisation tests and flatwise compression and edgewise compression experiments were performed in accordance with ASTM standards to evaluate the compressive strength and the load-carrying behaviour of the sandwich panels. A finite element analysis and validation were also conducted to model the compressive behaviour of sandwich structures. Results demonstrate that the developed sandwich panel exhibits very good compressive performance.

1. Introduction

Sandwich composite structures have attracted the attention of construction professionals because of many advantages such as lightweight, high strength, corrosion resistance, durability and speedy construction. Various forms of sandwich construction are being produced by combining different skin and core materials, with various geometries. Foam-filled sandwich panels, as efficient building elements, are becoming a major player in modular construction with a variety of applications in residential and commercial buildings worldwide (Sharafi et al. 2017, 2018a). These products are popular because they are light, easy to install and have good thermal and acoustic properties. In addition to their applications as non-structural building elements, sandwich panels with polyurethane foam-core and exterior and interior facing materials such as gypsum (Sharafi et al. 2014, 2015), engineered wood or some composite materials can be parts of the structure of a building (Thomsen et al. 2006).

Alongside the foam-filled composite panels, in recent years, considerable research efforts have been continuously looking for new construction materials and efficient designs for sandwich structures. Fang et al. (2015) developed innovative GFRP-bamboo-wood sandwich beams and investigated their mechanical performance experimentally and by finite element modelling. Hou et al. (2014) described

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the manufacturing and testing of graded conventional/auxetic honeycomb cores, manufactured using Kevlar woven fabric epoxy employing Kirigami techniques, consisting of a combination of Origami and ply-cut processes. Reis and Rizkalla (2008) presented an innovative 3-D glass fibre reinforced polymer (GFRP) panels with foam-core designed to overcome delamination problems, typically encountered in traditional sandwich panels. Lameiras et al. (2013) developed an innovative and thermally efficient sandwich panel for the structural walls of a pre-fabricated modular housing system, comprising GFRP connectors and two thin layers of Steel Fibre Reinforced Self-Compacting Concrete.

Compared to the other innovative structural composite panels, different designs of foam-filled sandwich panels are among the most widely investigated types of composite structures (Tuwair et al., 2015), and a large number of research studies regarding the behaviour of foam-filled sandwich composites have been published in the literature (Ferreira & Esculapio, 2016). A wide range of studies on the foam-filled composite panels are on those made of GFRP skins and rigid polyurethane (PU) foam-core (Allen & Neal, 2013; Ferreira & Esculapio, 2016). Recently, Codyre and Fam (2016) studied the effect of density of a Polyisocyanurate foam-core on the behaviour of axially loaded sandwich panels with GFRP skins, for different panel heights. Mohamed et al. (2015) proposed new designs of foam-filled glass reinforced composite sandwich structures, using two-part thermoset polyurethane resin systems as matrix materials, with vacuum assisted resin transfer moulding process. Fam and Sharaf (2010) explored the feasibility of fabrication and flexural performance of panels composed of low-density polyurethane foam-core sandwiched between two GFRP skins. The shear response of the composite sandwich panels with Polyvinylchloride foam-core between GFRP skins using epoxy resin was investigated by Mostafa et al. (2013).

Despite their very competitive costs, the stiffness and strength of a majority of these conventional foam-filled sandwich panels hardly meet the structural requirements for use in building floors or walls, at least for standard spans and loads. Conventional sandwich panels are susceptible to some different failure modes. Delamination of the skins from the core, buckling or wrinkling of the compression skin, flatwise crushing of the core and rupture of the tension skin are some of the very common types of failure. The main weaknesses of these panels stem from the low stiffness and strength of the core, and the skin's susceptibility to delamination and buckling, owing to the local mismatch in stiffness and the lack of reinforcements bridging the core and the skins (Correia et al., 2012). The use of stitches for connecting the two side skins (Potluri et al., 2003), or use of reinforcing ribs (Dawood et al., 2010) are two popular strengthening techniques being employed for improving the mechanical performance of standard sandwich panels. Sharafi and co-workers (2018b), investigated the flexural and shear performance of foam filled sandwich panels. Some researchers have explored the fracture toughness and crack growth mechanism of foam materials under different tensile and shear loads (Marsavina et. al. 2013, 2014; Aliha et al. 2018), because the crack growth is one of the major failure modes in foam made structures.

In this study, in order to enhance the properties of the foam-filled sandwich panels with regard to such failure modes, a new sandwich panel is proposed, in which 3-D high density Polyethylene (HDPE) sheets with 2 mm thickness are used as the skins, and high-density PU foam is used as the core, as illustrated in Fig. 1 with a total thickness as 100 mm. Using the HDPE sheets, manufactured with approximately 1200 studs per square meter, higher pull-out and delamination strength, as well as better stress distribution, and buckling performance can be achieved. The studs also improve the resistance of the face sheets and foam-core from de-bonding and increasing the interface strength between the foam-core and the face sheets.

The fabrication of these sandwich panels takes place in a single step. Therefore, the face sheets and foam-core are integrated into one construction. This innovative sandwich panel was developed to be used as modular walls and floors in rapid assembly buildings, in a recent research project on the semi-permanent post disaster housing at the Centre for Infrastructure Engineering at Western Sydney University. Rapid assembly, lightweight and easy transportation, durability, and wide range of applications are some merits of this new design. Given that the introduction of a new design typically brings new challenges to designers to utilize the new properties of the materials and geometry, the main goal of this research work is to investigate some structural properties of the newly developed sandwich panel.

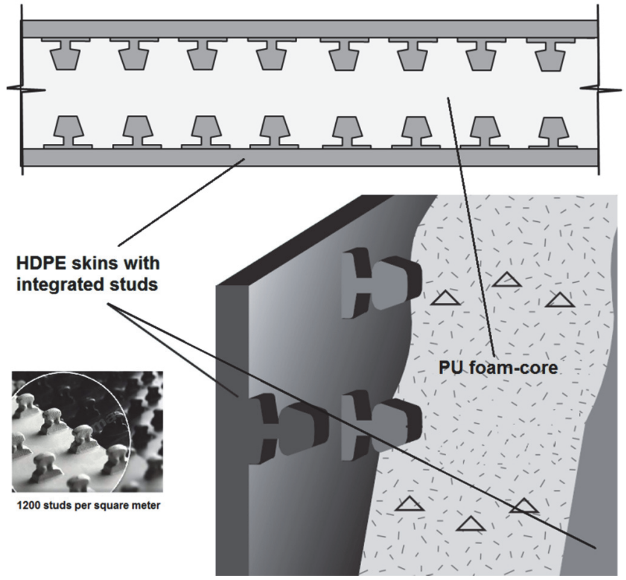

Fig. 1. Schematic illustration of the sandwich panel with 3-D HDPE skins and PU foam-core

2. Characteristics of the materials

The detailed descriptions of the tests carried out on material characterization of the constituent materials i.e. PU rigid foam and 3-D HDPE skin sheets are presented here. In addition to use the manufacturers' data, some experimental tests were performed, in order to evaluate the basic material properties. High density PU high-density rigid foam was chosen for the core material, according to some preliminary finite element investigations. Table 1 shows the basic mechanical properties of the PU, provided by the manufacturer, and validated in the laboratory. The detailed mechanical behaviour and stress-strain curves are presented in Sharafi et al. (2018b). Using uniaxial load machine, three cubic specimens (dimensions: 50mm×50mm×50mm) were tested based on the ASTM E1730 and ASTM D1621 at a loading rate of 5 mm/min in order to identify the structural properties (ASTM-E1730, 2015; ASTM, 2010). This type of PU foam, which is made of a 100:110 weight ratio mixture of AUSTHANE POLYOL AUW763 and AUSTHANE MDI, can undertake considerable deformation before the failure. The results showed that the foam has an average yield stress of 3.51 MPa, and the elastic modulus of 135.5 MPa.

Table 1. Mechanical properties of the selected PU rigid foam

Density (kg/m^3)	Compressive yield strength (MPa)	Tensile yield strength (MPa)	Shear yield strength (MPa)
192	3.51	1.896	1.034

The face skins of the sandwich panels are made of 3-D HDPE sheets primarily produced as a concrete embedment liner to provide protection from mechanical damage and a corrosive and erosive environment. In addition to resistance to chemical and environmental threats, its relatively high strength, and in particular its 3-D studded face can effectively contribute to the sandwich composites' structural performance by providing high pull out strength, minimum lateral movement of the skin, and stronger bonding through the shear keys on their surface (Fig. 2).

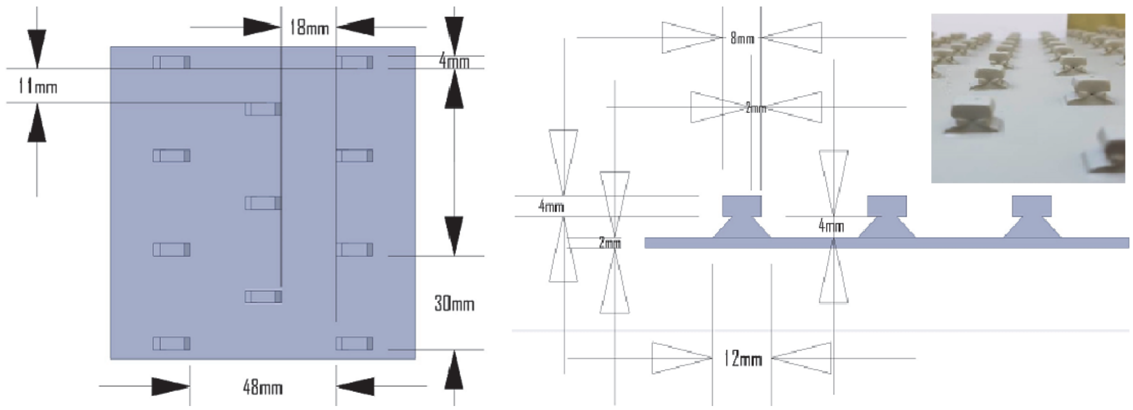

Fig. 2. 3-D studded facing sheet.

Table 2 shows some mechanical properties of the 3-D HDPE sheet, provided by the manufacturer and validated by experimental tests in the laboratory, in accordance with the ASTM D5199 (ASTM-D5199, 2012), ASTM D1505 (ASTM-D1505, 2010) and ASTM D6693 (ASTM-D6693, 2015) at a loading rate of 5 mm/min. In order to identify the structural behaviour of the skin, in-plane tensile tests were conducted on two principal perpendicular directions (lengthwise and crosswise) of the HDPE sheets, using a universal hydraulic testing machine. Five identical specimens were tested for each direction of the HDPE face sheet.

Table 2. Mechanical properties of the HDPE sheets

Density (g/cm^3)	Tensile strength at yield (MPa)	Shear strength at yield (MPa)	Elongation at break (%)	Stud pull-out strength (kN/m^2)	Average module of elasticity (MPa)
0.94	20.2	5.2	500	670	159

3. Experimental investigation of composite specimens

For sample preparation, the specimens were prepared by pouring the PU foam liquid into the temporary moulds containing two layers of HDPE sheets, attached to the sides, as shown in Fig. 3. The dimensions of each sample were set based on the corresponding standard test. No glue bond was used to allow the entire composite action to be burdened with the mechanical attachment between the studded surface and the foam.

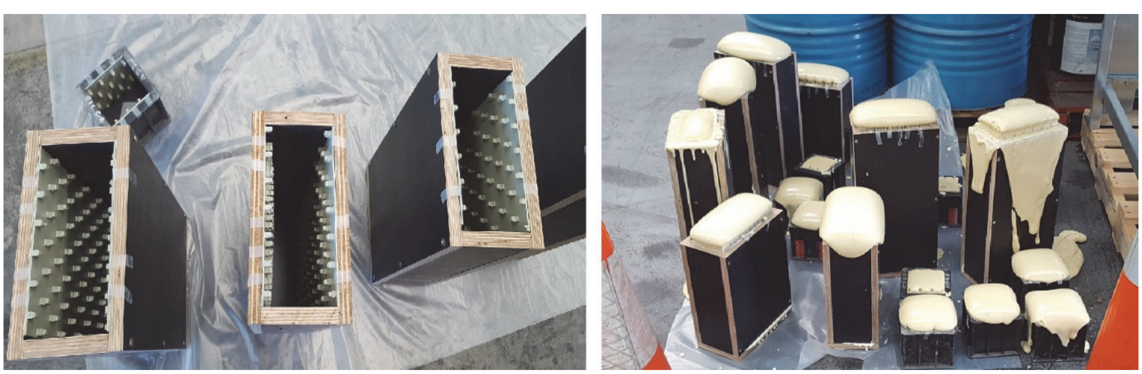

Fig. 3. Test specimen preparation.

3.1. Edgewise compressive strength

The edgewise compressive strength of sandwich construction is important as it provides the basis for the assessment of the load-carrying capacity (Mohamed et al., 2015). The compressive properties of the sandwich composite along the direction parallel to the plane of the sandwich face skin were evaluated through edgewise compression tests on 100mm×200mm×300mm samples using a test rig (universal testing machine) in accordance with the ASTM C364 standard (ASTM-C364, 2016). The specific machine configuration setup is shown in Figure 8, with the bottom plate fixed and the top plate moving downwards at a constant velocity of 0.5 mm/min using an edgewise compression test fixture. The use of such quasi-static tests implies that the loading force has sufficient time to be transmitted throughout the entire graded sandwich structure before the specimen fails. Attention was paid to make sure the ends of the specimen are flat to prevent localized end failures. Fig. 4 shows the test setup and the stress-strain curve.

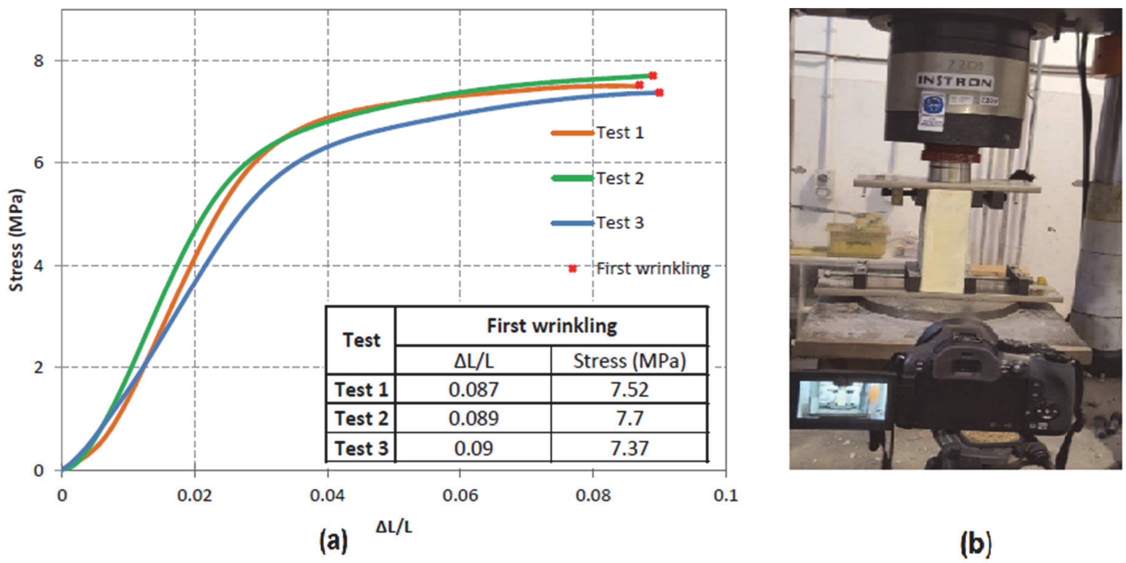

Fig. 4. Edgewise compression experiments (a) results and (b) test set up

Fig. 4 shows a good agreement between edgewise compressive behaviour of composite panel and foam compressive behaviour at linear phase. Composite panel can bear 3.51 MPa of compressive stress at a strain of 0.016. Then, at 4 MPa (strain 0.02) the slop of diagram changes approximately to a strain of 0.04 in composite panel. After this point, the behaviour is nonlinear until a stress of 7.53 MPa (strain of 0.09). At this point, the first wrinkling happened at HDPE sheets. Therefore, the failure mode of the specimens under edgewise compression, as shown in Fig. 5, was local buckling (wrinkling) of the HDPE sheets between two edge studs, resulting in a local delamination and de-bonding between the face and core. Despite the specimens' rather considerable bulge under pressure, no global delamination was observed. Although the post-buckling strength of the HDPE sheets could resist more compression, the load associated with such wrinkling failure mode was considered as the edgewise strength of the specimens. By applying more pressure to the specimens and after about 118 sec, an edge crush and large deformation will occur on the edges of HDPE sheets (at a stress of 16.71 MPa), shown in Fig. 6.

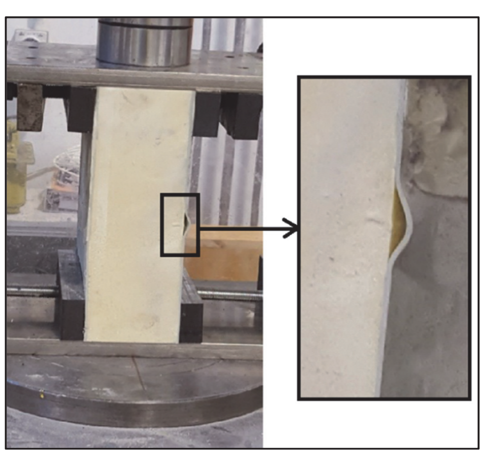

Fig. 5. Local buckling (wrinkling) in the compression edgewise test

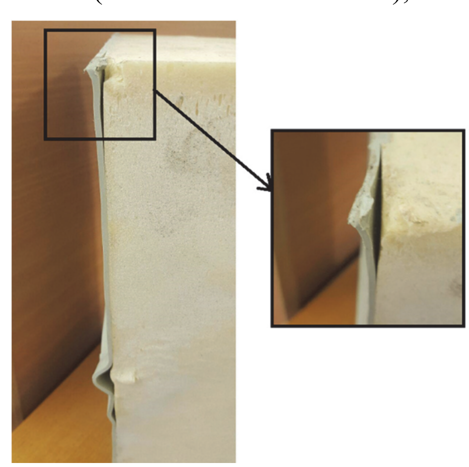

Fig. 6. HDPE edge crush in the compression edgewise test

For design purposes, the non-linear behaviour of the stress–strain relationship can be approximated by two linear behaviours with different stiffness. The initial portion can be used to determine the initial elastic modulus using regression analysis of the data up to 2% strain. Due to the significant non-linear behaviour observed beyond the strain level of 2%, the second slope, conservatively representing the reduced elastic modulus can be determined approximately based on the data measured between strains of 4% up to failure strain. These two calculated slopes are extended between 2% and 4% strain until they intersect each other in order to obtain the full approximation of the compressive edgewise behaviour (Fig. 7).

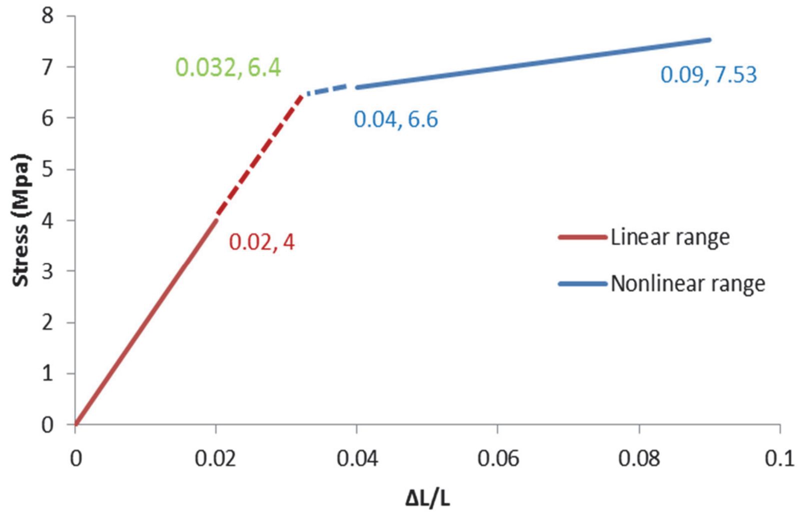

Fig. 7. Design Elasto-Plastic diagram of composite panel under edgewise compression

3.2 Flatwise compressive strength

The compressive strength of the composite was also assessed through the flatwise compressive tests (Abdi et al., 2014; Norouzi & Rostamiyan, 2015) of small sandwich cubes. Four specimens were tested to determine the flatwise compressive strength and elastic modulus for the sandwich core's structural design properties, using a universal testing machine and following the ASTM C365. The test rig was setup accordingly. Specimens had 100 mm thickness and a constant square cross-section of 100 mm × 100 mm corresponding to a cross-sectional area of 10,000 mm^2, which was smaller than the 10,323 mm^2 area recommended by the ASTM C365. Each specimen was cantered under the loading plate to ensure a uniform load distribution. All specimens were tested under displacement control with the bottom plate being fixed and the top plate moving downwards at a constant velocity of 0.5 mm/min. Flatwise compressive tests were performed until the load–displacement curve indicated a collapsed structure, i.e. with significantly high deformation of specimens. Fig. 8 and Table 3 show the results. In addition, Fig. 9 illustrates the results of Table 4 for one of the specimens.

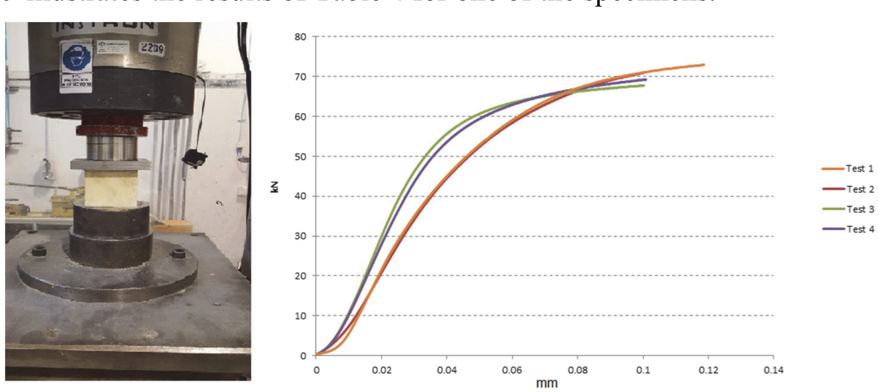

Fig. 8. Flatwise compressive experiments results

Table 3. Results of the flatwise compressive experiments on the specimens

Test No.	$\sigma_{0.001}$ (mm)	$\sigma_{0.003}$ (mm)	$P_{0.001}$ (kN)	$P_{0.003}$ (kN)	Compressive Chord Modulus, E (MPa)
1	1.51	3.51	13.47	40.47	135
2	1.46	3.46	13.16	39.31	130.8
3	1.33	3.33	16.67	49.94	166.4
4	1.34	3.34	16.04	47.65	158
Average					147.55
Standard Deviation					17.35
CV%					11.8

$\sigma_{fc0.02}=P_{0.02}$ / A = flatwise compressive stress at 2% deflection, MPa
$P_{0.02}$ = applied force corresponding to $\sigma_{0.02}$, N
$\sigma_{0.02}$ = recorded deflection value such that σ/t is closed to 0.02
t = measured thickness of core specimen prior to loading , mm

$E_{fc} = ((P_{0.003} - P_{0.001}).t)/((\sigma_{0.003} - \sigma_{0.001}).A)$= core flatwise compressive chord modulus, MPa
$P_{0.003}$ = applied force corresponding to $\sigma_{0.003}$, N
$P_{0.001}$ = applied force corresponding to $\sigma_{0.001}$, N
$\sigma_{0.003}$ =recorded deflection value such that σ/t is closed to 0.003
$\sigma_{0.001}$ = recorded deflection value such that σ/t is closed to 0.001

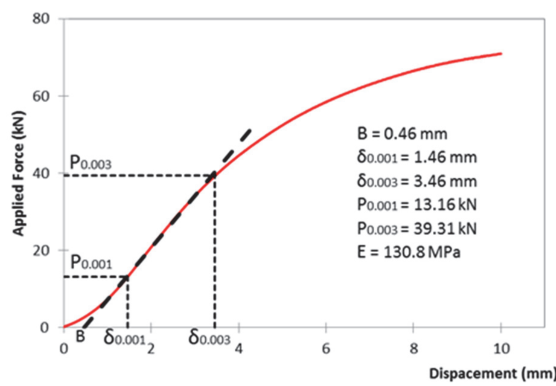

Fig. 9. Description of flatwise compressive experiments calculation for test no. 2 (for example)

The first part of the curve was relatively linear in the elastic region, followed by the plateau region where the stress was almost constant under increasing deformation, and was produced by the development of localized buckling within the foam cell walls. Then, there was a sharply increasing loading region at a large strain corresponding to solidification. Some minor variations were observed among the specimens, and the average compressive elastic modulus of the sandwich panels was 147.55 MPa. The yield region occurred at an average stress of 4.3 MPa, attributed to buckling of the foam's internal cell walls, with over 22% improvement compared to bare foam. As the deformation increased, the cell walls stacked on top of each other resulting in the closure of most of the voids. Therefore, the foam-core became densified and displayed higher strength. The results indicate that the flatwise compressive behaviour of the specimens is governed by the rigid foam behaviour, and the composite specimens show a similar behaviour to the foam specimens. That is, experiment results confirmed that although a separation between the core and the skin is observed at the failure load, the possible local ruptures in the foam, due to the increased stress on the studs' tips, do not influence the flatwise compressive behaviour of the sandwich composite.

4. Finite element modelling

The FE modelling was performed using ANSYS 16.2 where a quasi-static three-dimensional model has been developed to simulate and predict the mechanical performance of the composite sandwich panel under compression. For FE modelling, the same dimensions, and the same loading rate were considered as for the experimental program. The PU foam was meshed using Hexahedral dominant, Quadrilateral and Triangular meshing. The HDPE sheets were meshed using Multizone Hexahedral/prism with Quadrilateral and Triangular elements while the studs meshed using hexahedral elements (Figs. 10 and 11). The mechanical properties of the PU foam and the HDPE sheets, obtained from experiments, were used for calibrating the inputs.

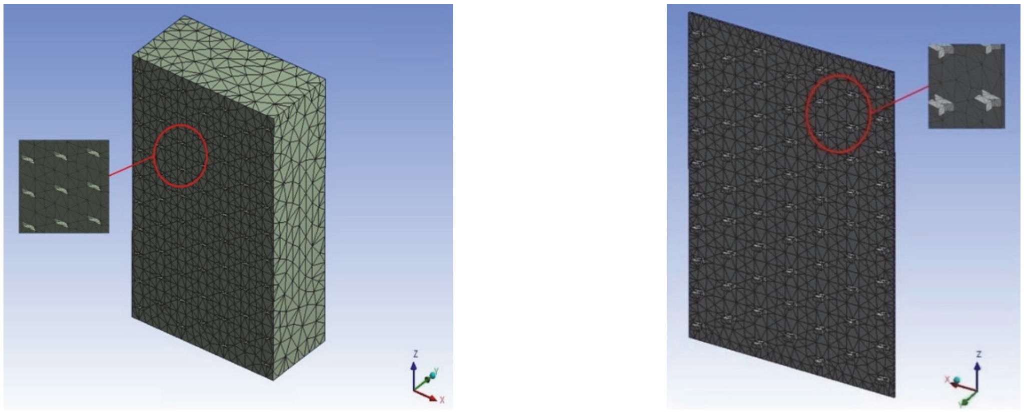

Fig. 10. Finite element meshes at foam core (left) and HDPE sheets (right)

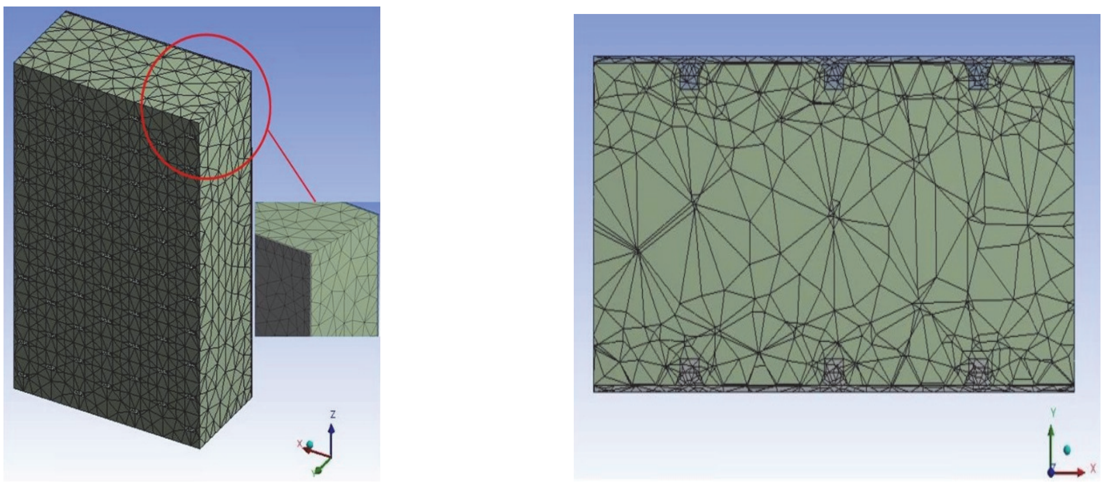

Fig. 11. Composite panel Finite element meshes (left) and section at studs position (right)

4.1 FEM results for edgewise compression

As presented in Table 2, the modulus of elasticity of the PU foam in this study is E_{PU} = 135.5 MPa, which is not so much different from the HDPE material (159 MPa). On the other hand, the HDPE is relatively a thin sheet of material with not considerable resistance against compression. Therefore, it could be expected to observe relatively similar stress and strain in both PU foam and HDPE, especially in linear range. Hence, the HDPE will not significantly changes in the edgewise load-bearing capacity of specimens (Fig. 12).

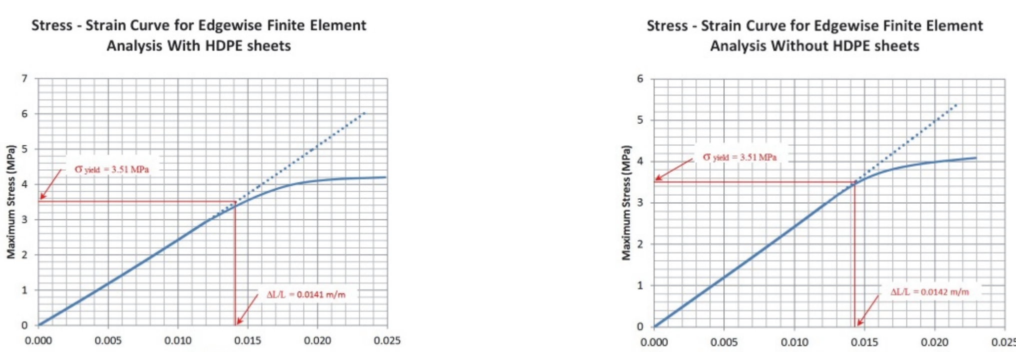

Fig. 12. FE analysis results for edgewise model with (left) and without (right) HDPE sheets

The results shows a very good agreement between numerical analysis and experimentals. As can be seen in Figure 12, PU foam reaches to its yield point (3.51 MPa) at bottom edge with a maximum strain of 0.014 mm/mm which is very close to experimental result as 0.016 mm/mm. In this situation, the HDPE sheets remain in elastic range yet. In addition, there is not any notable compressive or shear stress concentration at studs at the end of foam yielding range (Fig. 13). However, these researchers in another article have showed the critical role of studs in bending behaviour.

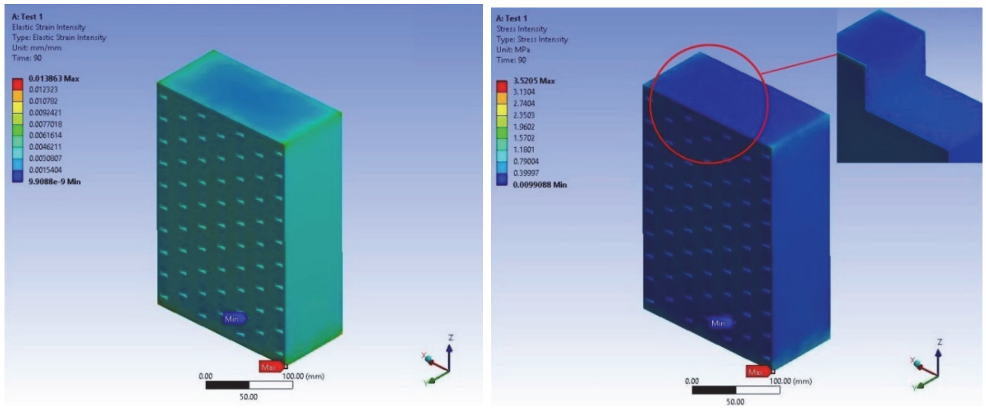

Fig. 13. Stress and strain of PU core at foam yielding point.

By applying more pressure, the HDPE reaches to its compressive yielding point (15.956 MPa) at top edge (Fig. 14) as similar as the experimental test as 16.71 MPa (Fig. 10).

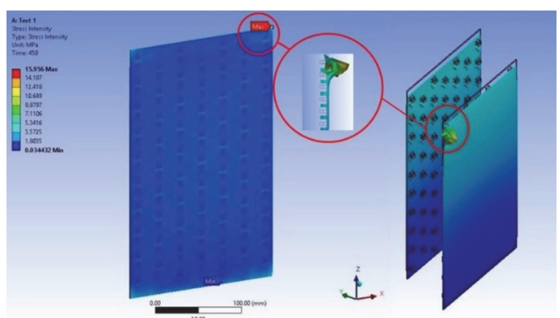

Fig. 14. Ultimate deformation diagrams under edgewise compression.

The FE model shows the stress is evenly distributed along the sample. This confirms the fact that the load is evenly applied at the top using the distributing plate. The evenly distributed load will eliminate the possibility of stress concentration. This amount of stress (15.956 MPa) is very close to experimental result (16.71 MPa) and shows a good agreement between experimental tests and numerical analysis at the collapse point. In addition, the FEM model confirmed that relative deformation for HDPE sheets and the PU foam is negligible; meaning that they work well as a composite section (Fig. 15).

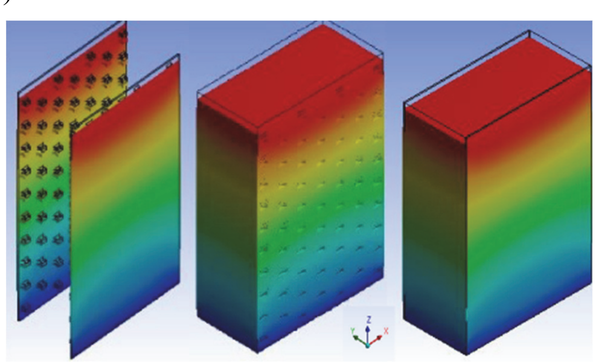

Fig. 15. The typical relative deformation of PU and HDPE under edgewise compression.

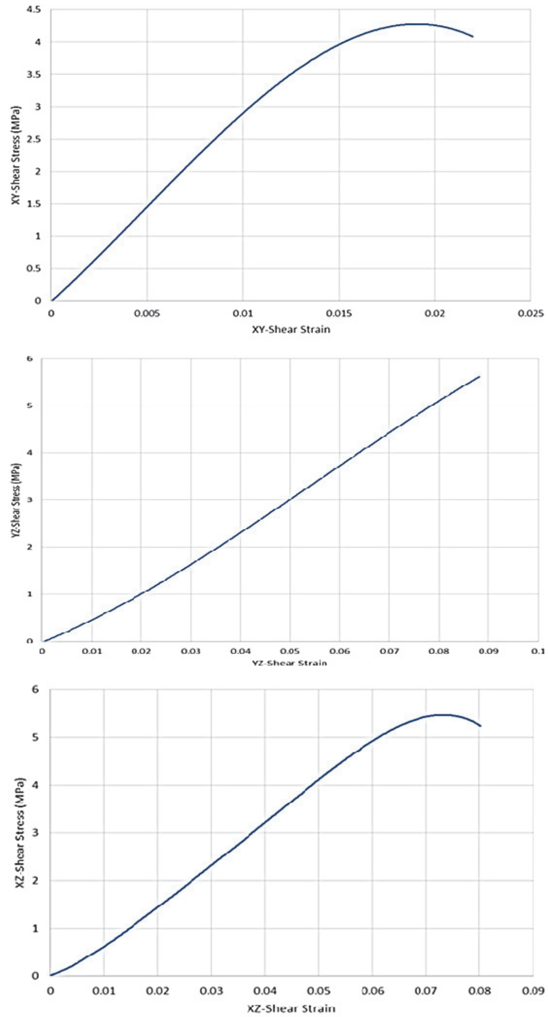

Fig. 16. Maximum shear stress under edgewise compression in the principal directions

Fig. 16 and Fig. 17 illustrate the maximum shear stress diagrams for xy, zx, and yz-planes. The composite exhibits fairly linear shear behaviour in the xy-plane for strains below 0.01, while linear behaviour in yz-plane and zx-plane can be seen in higher ranges of strain. It is worth mentioning that at experimental tests, the first shear yielding occurs at the corners of foam, approximately at the same time with the first wrinkling (Figure 17). This fact can be a reason for the local wrinkling accrued by the lateral pressure on the Studliner at yielding point (Fig. 18).

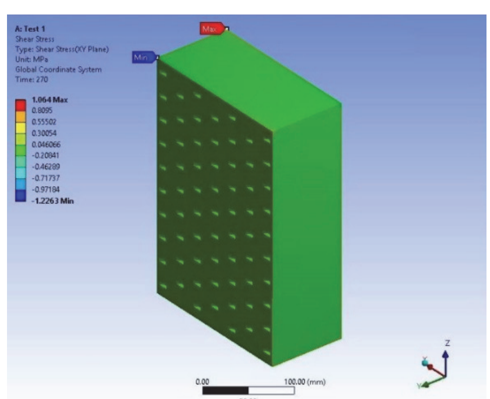

Fig. 17. Stress distribution counter of X-Y shear stress of PU at shear yielding point.

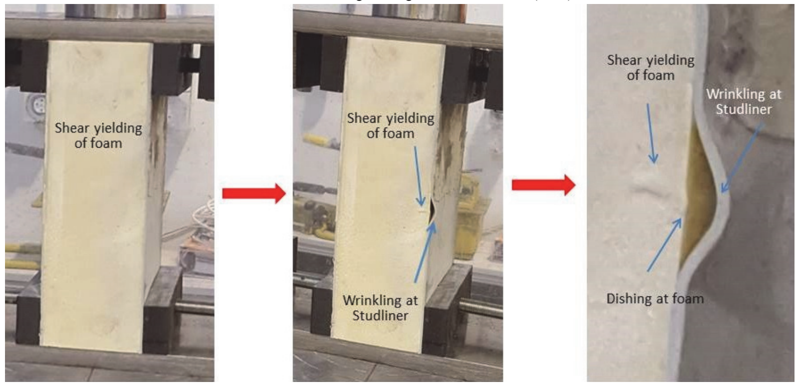

Fig. 18. Wrinkling at studliner due to shear yielding of foam

Fig. 19 shows a comparison between the FEM model and experimental results for von Mises stress of the composite sample under the edgewise compression. Although FE model predicts the composite strength for lower strains accurately, for higher strains (over 0.04) it underestimates the edgewise strength.

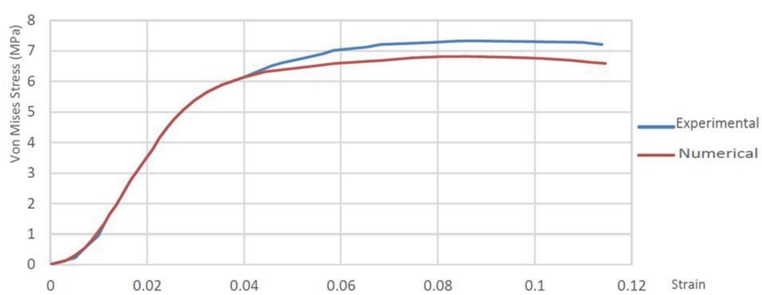

Fig. 19. Comparing FEM and experimental results for von Mises edgewise compressive stress.

4.2 FEM results for flatwise compression

The FE modelling results of flatwise compression model are shown in Figs. 20 to 22. High deformation values are localised in the foam-cores. Although the flatwise compression behaviour of the composite is mostly governed by the behaviour of the foam-core, the failure is due to the local separations between the skin and core at the ultimate stage. Confirming the experimental results, the deformation of the skin was negligible compared with that of the core. With regard to the shear behaviour, there was a uniform distribution of shear stress in the xy and yz-planes with the exception of areas around the edges. As shown in Fig. 21, in lower ranges of strain (up to 0.02), the composite shows a relatively linear shear behaviour in both the xy and yz-planes. In the zx-plane however, the composite exhibits non-linear shear behaviour with considerably lower shear resistance compared to those of xy and yz planes; meaning that the composite undertakes lower shear stress before it fails in zx-plane.

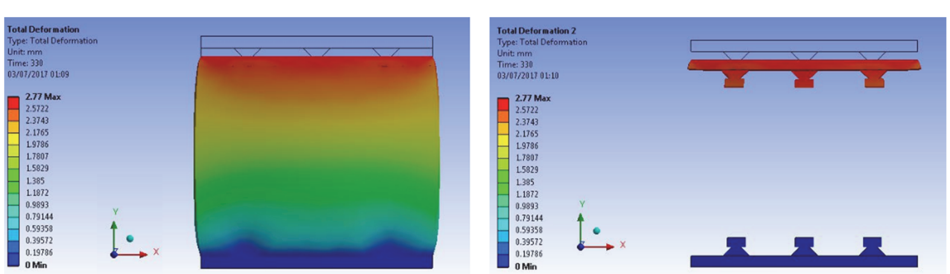

Fig. 20. The relative deformation diagrams under edgewise compression

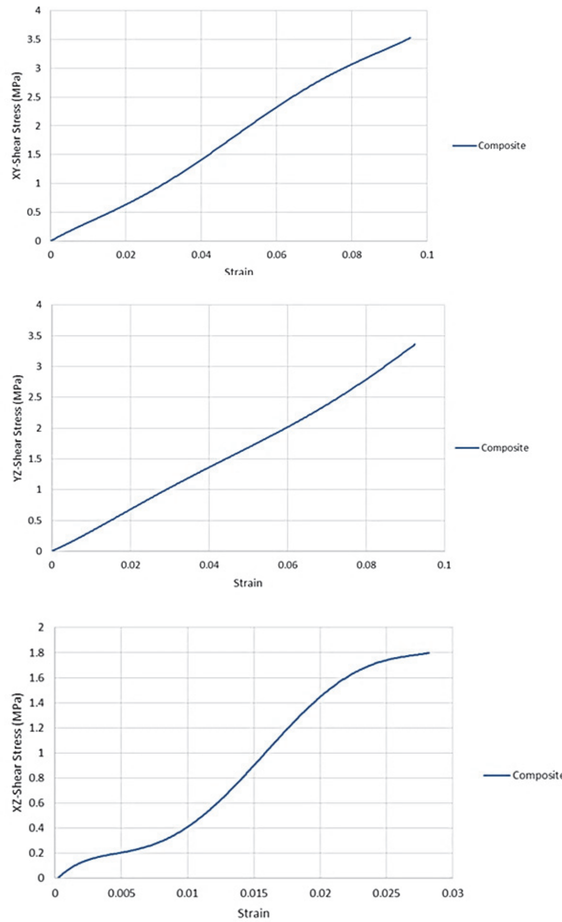

Fig. 21. Maximum shear stress under flatwise compression in the principal directions.

Fig. 22 shows a comparison between the FEM model and experimental results for von Mises stress of the composite sample under the flatwise compression, which shows a good agreement between the results.

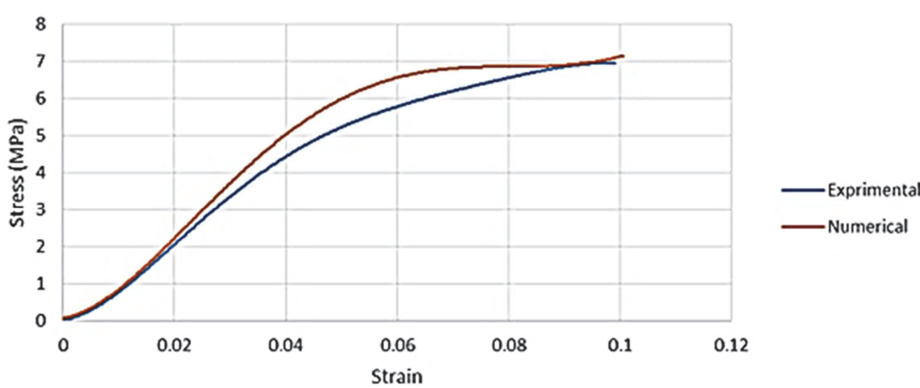

Fig. 22. Comparing FEM and experimental results for von Mises flatwise compressive stress.

5. Conclusion

The compressive behaviour of a newly developed sandwich panel proposed for post-disaster rapid assembly buildings is studied. The panel is fabricated by filling high-density polyurethane foam-core between two 3-D high density polyethylene skins. The compressive performance of the panel was investigated through material characterisation tests and flatwise compression and edgewise compression experiments, and validated and modelled by the finite element method. The failure behaviour, the test values and the FE modelling results suggest very good bond strength between PU foam-core and the 3-D HDPE skins in compression that offers interesting capabilities in terms of flatwise compression and edgewise loading.

The failure mode of specimens under the edgewise compression was local buckling (wrinkling) of the HDPE sheets between two edge studs, resulting in a local delamination and de-bonding between the face and core. The results of the flatwise compression test, on the other hand indicated that the flatwise compressive behaviour of the specimens is governed by the rigid foam behaviour. Despite some minor discrepancy between the FE model and experimental tests, the results suggest that the FE model well agrees with the experimental test results, and could be used as a design tool to evaluate the compression performance of the sandwich panels.

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