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Behavior of integrated connections between adjacent foam-filled modular sandwich panels

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ABSTRACT

Connections represent major challenges in the design of composite structures, mainly because they entail discontinuities in the geometry of the structure and material properties, and introduce high local stress concentrations. Despite some constructability complications, integrated connection could be a reliable solution. In this paper, the structural behaviour of an integrated connection for implementation between adjacent composite sandwich panels in rapid assembly buildings is studied. The integrated connection system consists of 3-D high density polyethylene (HDPE) skin faces, and cores of high-density polyurethane (PUR) foam integrated into the sandwich panels at the moment of their production. The study included experimental investigations regarding the mechanical and structural response of the connection under actual applied loads, and its torsional rigidity, rotational stiffness and behaviour under lateral loading is investigated. Using Finite Element modelling, the stress distribution and the mechanisms of failure are studied. The results show a good agreement between the numerical and experimental results.

1. Introduction

Composite lightweight sandwich panels are an effective solution for building construction due to their high strength to weight ratio and adequate levels of acoustic and thermal insulation. Building systems made of composite sandwich panels can be quickly assembled on site, allowing for considerable time savings in fabrication and assembly. Sandwich panels are being increasingly used in civil engineering structural applications, and have already been successfully applied in the construction of walls, roofs and building envelope (Garrido et al., 2016). There are several types of sandwich panels with different facing or core materials, as well as various geometric designs. Polyurethane (PU) foam filled sandwich panels are one of the most popular kind of them. In addition to non-structural applications of polyurethane foam filled sandwich panels, they can be parts of the structure of buildings (Thomsen et al., 2006). Low self-weight and relatively high stiffness and durability have increased the demand for this type of composite structures. In fact, foam-filled sandwich construction, characterised by two relatively thin and stiff faces and a relatively thick and lightweight foam core, is becoming an interesting solution for building wall and floor systems. Many studies in the literature indicate that the

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stiffness and strength of a majority of conventional foam-filled sandwich panels and connections hardly meet the structural requirements for use in building floors or walls, at least for standard spans and loads, mainly due to some different failure modes such as delamination of the skins from the core, buckling or wrinkling of the compression skin, flatwise crushing of the core or rupture of the tension skin. The main deficiencies of this type of composite panels are their low load carrying capacity and susceptibility to the occurrence of local and global failure modes like crack growth in the foam material (Aliha et al., 2018), compared those made by traditional materials, like concrete and steel (Mastali et al., 2017). In addition, when designing structures by sandwich panels, they must be efficiently interconnected upon assembly, in order to provide an integrated system (Sharafi et al., 205, 2017, 2018a) appropriate connection systems between composite sandwich panels must be provided. The design of such connection is not an easy task. That is why, although different solutions for the connections between adjacent sandwich panels have been considered in the construction industry, a large majority of them have been developed for non-structural or secondary structural sandwich panels.

The rigidity and flexibility of innovative composite connections in buildings design have been widely investigated in the literature. Kempf and Feldhusen (2004) focused exclusively on finding about 850 solutions to mechanically connect sandwich panels. In another study, Garrido et al. (2015) studied the connections between adjacent composite sandwich panels for use in building floor rehabilitation, and proposed an adhesively bounded connection system. Mohan et al. (2015) studied the moment–rotation behaviour and the joint stiffness of a series of beam–column connections using a single cantilever test set-up. Kujawa and Szymczak (2014) investigated rotational resistant stiffness of the zed-purlins connection with sandwich panels. A new foam-filled sandwich panel was developed by Sharafi and coworkers (Sharafi et al., 2018b,c ; Nemati et al., 2018), which is composed of 3-D high density Polyethylene (HDPE) sheets, as the skins with a thickness as 2 mm, and high-density PU foam core with a total thickness as 100 mm. This paper investigates the performance of the integrated connections for the newly developed composite panel, and experimentally and numerically assesses their structural performance under monotonic loading. The integrated connection system between adjacent sandwich panels for use in rapid assembly construction for post-disaster housing is studied. Experimental and numerical investigations are conducted to study the connections' behaviour under actual loading conditions, the overall mechanical response, and the stress distributions. To that end, the panel-to-panel joints are tested to evaluate failure modes, moment resistance, initial rotational stiffness and rotational capacity of the connections. These connections are experimentally tested under vertical loads in a cantilever configuration. Then, using finite element (FE) analysis and the obtained moment–rotation relationships, the stress distributions in the connection components are investigated.

2. Description of the panels and integrated connections

In order to enhance the properties of the foam-filled sandwich panels, a new sandwich panel was proposed, with 3-D HDPE skins HD-PU foam core, as shown in Fig. 1. The HDPE sheets manufactured with approximately 1200 studs per square meter, provide higher pull-out and delamination strength, as well as better stress distribution, and buckling performance (Sharafi et al., 2018b,c; Nemati et al., 2018). The studs also improve the resistance of the face sheets and foam-core from debonding and increasing the interface strength between the foam-core and the face sheets. Table 1 presents some physical and mechanical properties of HDPE sheets and PU high-density rigid foam.

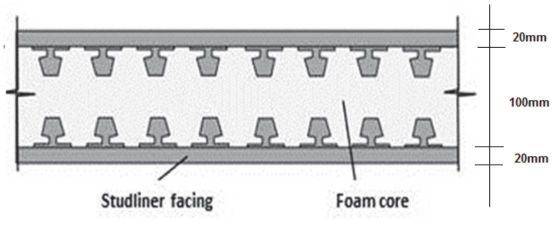

Fig. 1. Sandwich sections with 3D-HDPE skins and HD-PU foam core.

Table 1. Physical and mechanical properties of the HDPE skins and PU core

		HDPE sheets		
Density (kg/m^3)	Thickness (mm)	Tensile Yield trength (MPa)	Shear yield strength (MPa)	Modulus of elasticity (Mpa)
940	2	20.2	5.2	159
		PU foam		
Density (kg/m^3)	Compressive yield strength (MPa)	Tensile yield strength (MPa)	Shear yield Strength (MPa)	Modules of elasticity (Mpa)
192	3.51	1.9	1.03	134.5

The fabrication of these sandwich panels takes place in one step. Therefore, the face sheets and foam core are integrated into one element (see Fig. 2). 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 in Sydney. The connections between the panels are constructed by continues foam casting to achieve better integrity.

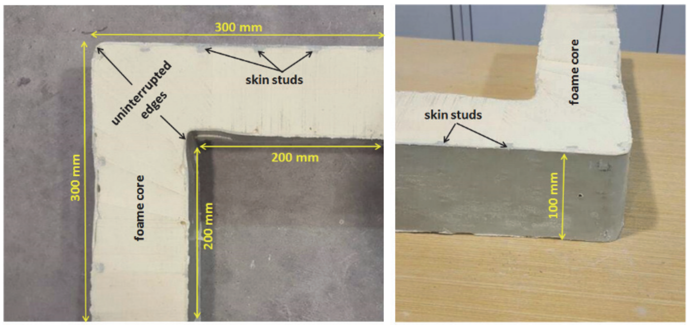

Fig. 2. Integrated connection with HDPE skins and PU foam core

The primary function of these connections is to guarantee the transfer of lateral (seismic and wind) loads between the composite panels, as well as between panels and roof in rapid assembly post disaster buildings. In addition, this connection accounts for restricting the rotation (i.e. the maximum deflections along the span). This is a significant factor because in practice, the maximum allowable deformation is usually the governing factor in the design of lightweight composite sandwich panels (Sharafi et al., 2018c).

3. Experimental investigation

The structural behaviour of a connection depends, for a given type of load, on the stress distribution within the connection, which in turn depends on the joint geometry and the mechanical properties.

3.1. Test setup

Six L shape specimens, representing the connections between adjacent sandwich panels, were tested. In order to better study the composite performance and compare the results with non-composite behaviour, three of the specimens were made of composite sections, while here of them were foam-only sections; all of them were manufactured by one shot casting method in wooden formworks and were cut out of actual adjacent sandwich panels. The composite connections comprised of 2 mm thick 3-D HDPE face sheets enclosing a 96 mm thick core of rigid PU foam. A summary of the most relevant properties of the constituent materials used in the connection, obtained from material characterisation tests ASTM E1730, ASTM D1621 (ASTM), ASTM D5199 , ASTM D1505 and ASTM D6693 (ASTM-D6693, 2015)), are shown in Table 1.

The test specimens were supported in a cantilever configuration test rig, and a point load was applied at 40 mm of the free edge, as illustrated in Fig. 3. The vertical angle that supported the cantilever angle was connected to a steel frame comprised of fixed profiles by a bolted steel strip with a width of 50 mm. The vertical displacement was measured at the top face of the cantilever angle at the load application point by a displacement transducer automatically and with a stroke of 700 mm and precision of 10e-5 mm. Load was applied by a 300 ton hydraulic jack with a displacement rate of 5 mm/min according to literature. A load distribution steel plate (15 mm thick, 100 mm long and 80 mm wide) and a roller were positioned between the test specimen and the hydraulic jack. Additionally, as shown in Fig. 3 the local rotations of specimens were measured at four points of cross-section by electrical inclinometers with a precision of 10e-6 degree. Using these inclinometers the relative rotation of any two points can be calculated as difference of related inclinometers rotations (Shek et al., 2012). To study the behaviour, the specimens were monotonically loaded up to failure.

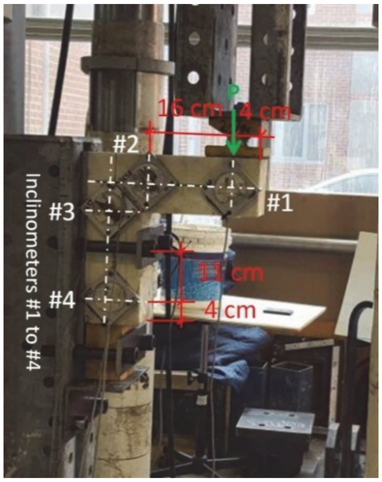

Fig. 3. Cantilever configuration of experimental tests

3.2. Test Results

The results obtained from the experimental tests are illustrated in Figs. (4-7). Fig. 4. and Fig. 5 illustrate the load-displacement curves obtained for foam-only and composite connection systems respectively; and Fig. 6 and Fig. 7 illustrate the load vs. connection angle (Δ) obtained for simple and composite connection systems respectively. Table 2 presents a summary of the ultimate (or failure) loads, ultimate connection angle and ultimate displacement for both simple and composite systems. Detailed discussion is provided in the following sections for each type of connection.

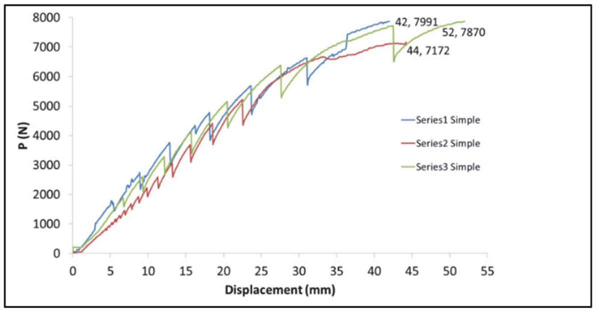

Fig. 4. Load vs. displacement for foam-only specimens at loading point

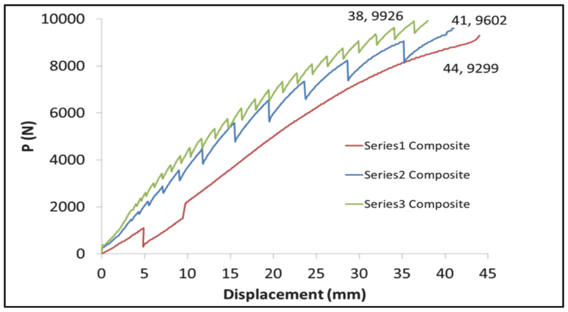

Fig. 5. Load vs. displacement for composite specimens at loading point

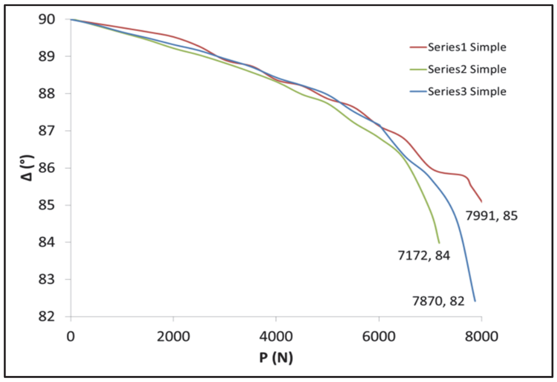

Fig. 6. Load vs. connection angle (Δ) curves for foam-only specimens

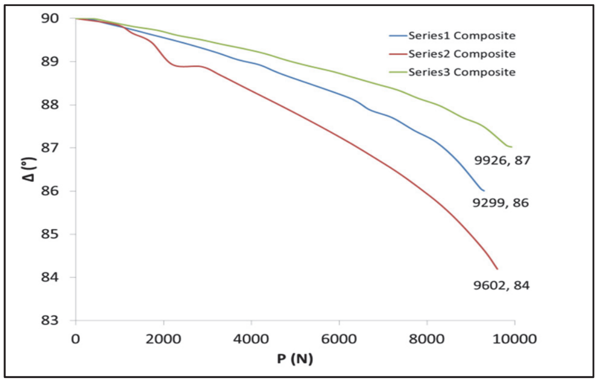

Fig. 7. Load vs. connection angle (Δ) for composite specimens

Table 2. Summary of the experimental carried tests for both simple and composite systems

Test Details		Ultimate Load (N)	Ultimate Displacement (mm)	Ultimate Rotation (Degree)
Foam-only Tests	Specimen 1	7991	42.0	5.0
	Specimen 2	7172	44.0	6.0
	Specimen 3	7870	52.0	8.0
	Average	7678	46.0	6.3
	CV (%)	5.8	11.5	1.8
Composite Tests	Specimen 1	9299	44.0	4.0
	Specimen 2	9602	41.0	6.0
	Specimen 3	9926	38.0	3.0
	Average	9609	41.0	4.3
	CV (%)	3.3	7.3	1.8

4. Discussion

4.1. Behaviour of foam-only connections

As the diagram indicates, all the foam-only connection specimens presented similar behaviours with regard to both rotation and displacement. They also show relatively full elasto-plastic behaviour up to failure with regard to both displacement and rotation. Accordingly, Table 3 shows the bending ultimate strength, connection rigidity, connection rotational stiffness, as well as relative ultimate cantilever deflection of simple connections.

Table. 3. The connections' structural properties

Bending ultimate strength (kN.m)	Rigidity (%)	Rotational stiffness (kN.m/Rad)	Relative ultimate cantilever deflection (%)
1.612	93	14.532	18.4

The failure modes observed in these series of tests are shown in Fig. 8. The first failure mode was a shear crack occurred at the vertical side of internal edge. By applying more pressure to the specimens, connections collapsed in a brittle manner at vertical arm and approximately at the level of bottom surface of horizontal arm. Development of shear stress and consequently the tensile stresses at the edges were the reason of brittle fracture which caused by a sudden reduction of foam tensile area.

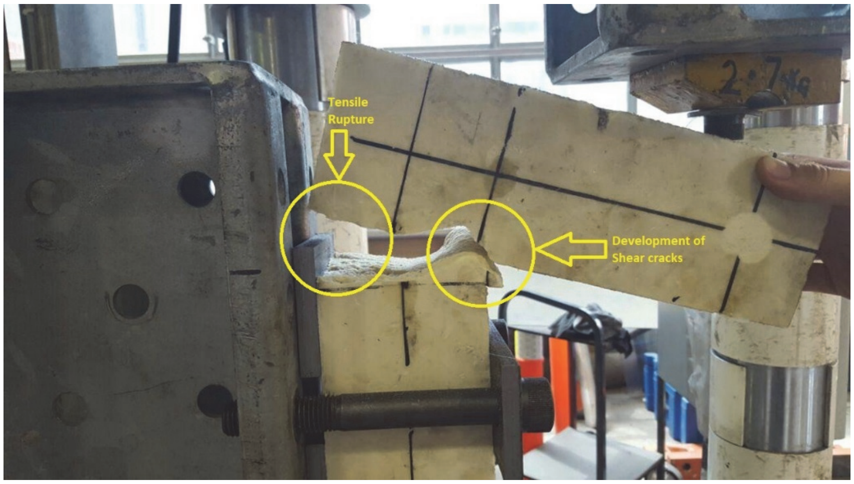

Fig. 8. The failure modes and brittle fracture of foam-only connections

4.2. Behaviour of composite connections

The composite connection specimens showed relatively similar behaviour as those for the foam-only specimens, with respect to rotation. Meaning that the composite action and the effect of skins are relatively negligible in rotation, and the major rotational stiffness is provided by foam. Table 4 shows the structural properties of the composite connection, calculated based on the experiment results.

Table 4. The connections' structural properties

Bending ultimate strength (kN.m)	Rigidity (%)	Rotational stiffness (kN.m/Rad)	Relative ultimate cantilever deflection (%)
2.018	95	26.901	16.4

Composite connections had the same failure modes as simple connections. The failure modes and collapse mechanism observed in these series of tests are shown in Fig. 9. The first sign of failure occurred at the vertical side of internal edge. Bearing stresses were the reason of this matter. The connections were still able to carry some load yet but, lower than the failure load. Although collapse had still not occurred, specimens exhibited very large deformations at this stage (Fig. 9a). Then, by applying more pressure to the specimens, connections collapsed in a gradual manner at the external side of vertical arm and approximately at the level of bottom surface of horizontal arm. Therefore, the tensile strength of external HDPE sheet was the reason of gradual fracture despite caused by a sudden reduction of foam tensile area. In addition, remained internal facing sheet prevents the connection from falling (Fig. 9b).

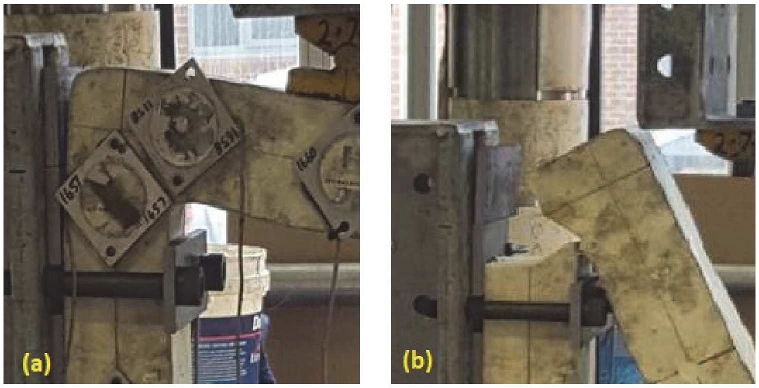

Fig. 9. The composite connection behaviour. (a) the ultimate deflection (b) the mechanism of collapse

4.3. Comparison of results

A comparison between the results indicates that in composite sections the bending ultimate strength increases by 25% compared to simple connections. The composite connections also show 2.2% greater rigidity. More importantly, the composite action resulted from HDPE facing sheets increases connection rotational stiffness by 85%. With regard to the relative ultimate cantilever deflection, composite connections presented better performance by 12% in comparison with foam-only connections. In the other words, the bending stiffness of composite connections is 12% greater than that of foam-only connections. Fig. 10 compares the performance and failure mechanisms. Both simple and composite connections showed very similar failure modes and the fracture surface of them are fairly similar to each other. The most important difference therefore was their ductility; i.e. the foam-only connections show a relatively brittle sudden failure, while composite connections managed to undergo rather larger deformations before collapse.

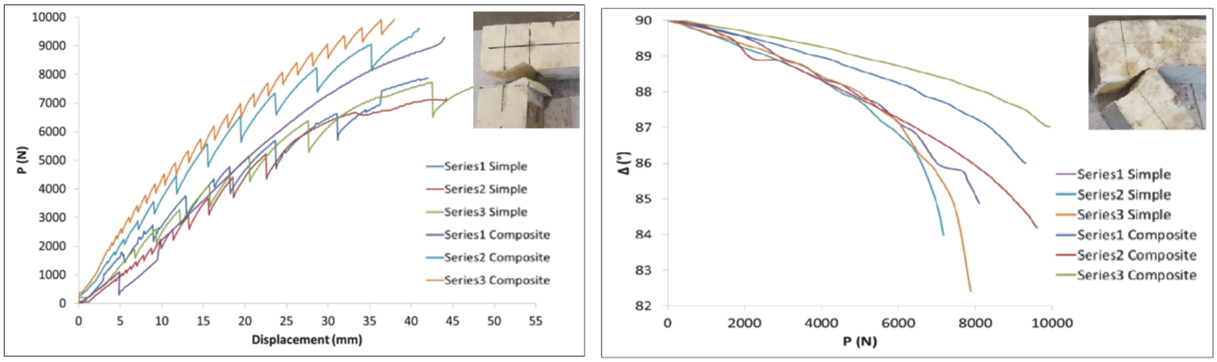

Fig. 10. A comparison between behaviour, ultimate loads and collapse for two connections

5. Numerical simulation

The integrated connection system in this study, were numerically modelled using a nonlinear FE modelling approach in order to simulate the stress distributions within the connection. In addition, the maximum deflections of connections components estimated while they were to be supported in a perfect cantilever (clamped) configuration, and the experimentally observed failure modes were compared with those of numeric results. Three-dimensional (3D) FE models were developed using the commercial package ANSYS R15.0 to simulate the foam-only and composite connection systems. The HDPE sheets and PU foam were modelled using hyperelastic isotropic material (Mooney-Rivlin) properties (Sharafi et al., 2012a,b). The PU foam and HDPE properties were obtained from strain energy density function, confirmed from results of material characterisation tests which carried out in Centre for Infrastructure Engineering of Western Sydney University as well as manufacturing specifications. The contacts between all contact surfaces with different material properties were modelled using the ‘‘Bonded” boundary condition in ANSYS 15. This method can be defined as surfaces which are fixed or glued together (Kaveh and Sharafi, 2007; Kataoka and El Debs, 2014). Quadratic ten-node tetrahedral solid elements were used to model the different components of the panels and connections. Sensitivity checks were performed regarding the influence of the mesh density/refinement on the results obtained with the FE models, leading to the selection of the adopted meshes.

In the foam-only connections, the stress concentration causes the foam reaches to tensile yield under the loading point. When the tensile stress is 1.896 MPa, the compressive stress is lower than the ultimate 3.51MPa. Fig. 11 and Fig. 12 show the equivalent strain and stress distribution, as well as shear stress and strain distribution, at the ultimate stage, respectively. By applying more load, the connection collapse occurs, which is shown in Fig. 13.

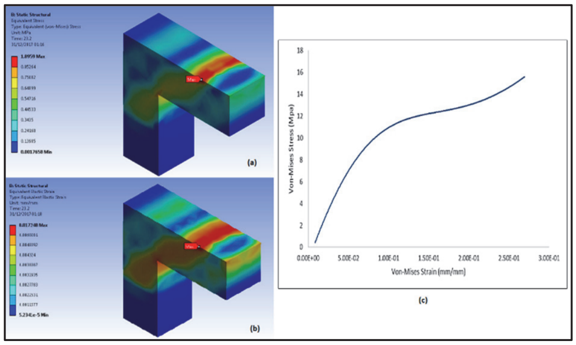

Fig. 11. Von-Mises (a) stress, (b) strain distribution, and (c) their relation, in the foam-only connections

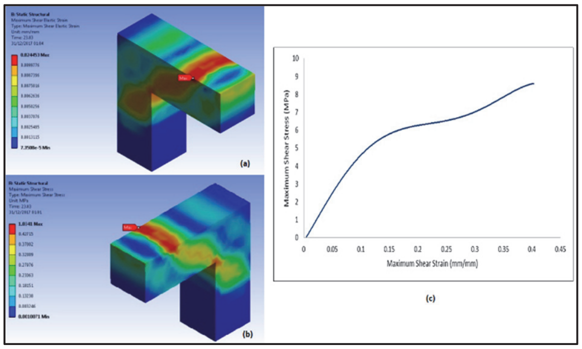

Fig. 12. Ultimate shear (a) stress, and (b) strain distribution in foam-only connections

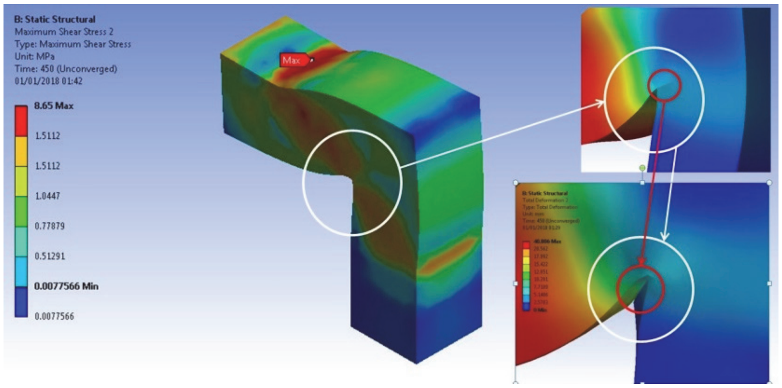

Fig. 13. Shear stress distribution on the foam-only connection at failure

Unlike the foam-only connections, no early tensile yielding occurs under loading point in the composite sections. At the ultimate state, as shown in Fig. 14, foam reaches to its shear yield point at the edge of supporters, and it develops through the foam towards the edges. By applying more loads, shear yielding occurs at the inner corner of the lower HDPE sheet, as shown in Fig. 15. Before failure, the top layers of HDPE sheets reaches tensile yield point at the edge of loading surface, and the inner side of lower HDPE sheet enters a local high compressive stress zone. FEM results confirm that the failure happens at the inner corner of connection, similar to the experimental results. The maximum displacement at loading point is 40 mm, which has good agreement with experimental results (Fig. 4). The equivalent stress distribution in the connection components (core and facings) at collapse are shown in Fig. 16 and Fig. 17.

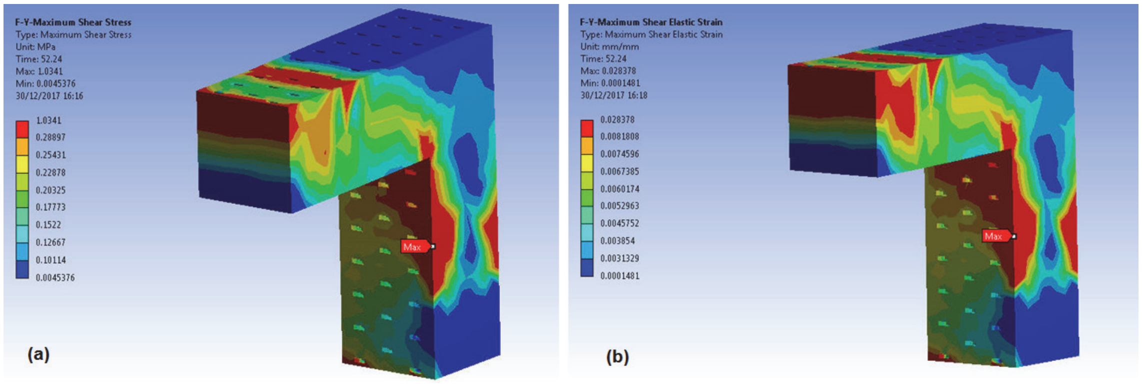

Fig. 14. Ultimate shear (a) stress, and (b) strain distribution in foam in the composite connection

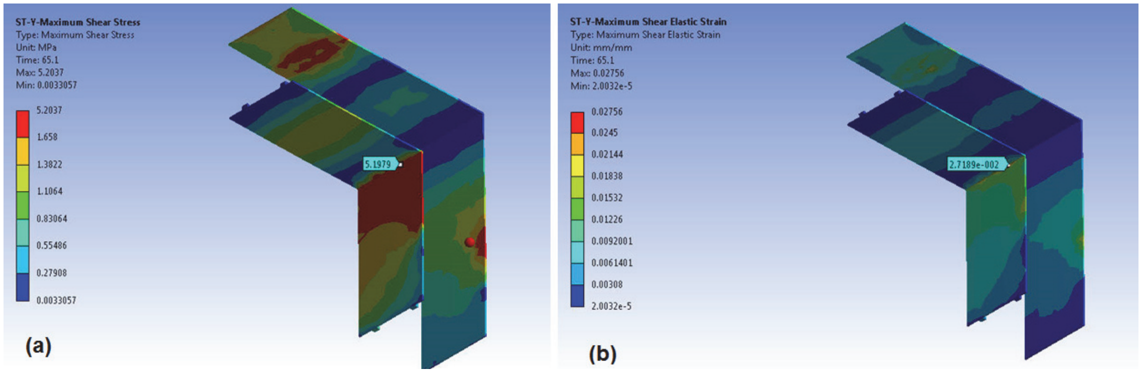

Fig. 15. Shear stress (left) and strain (right) contours at shear yielding time, 65.1th second

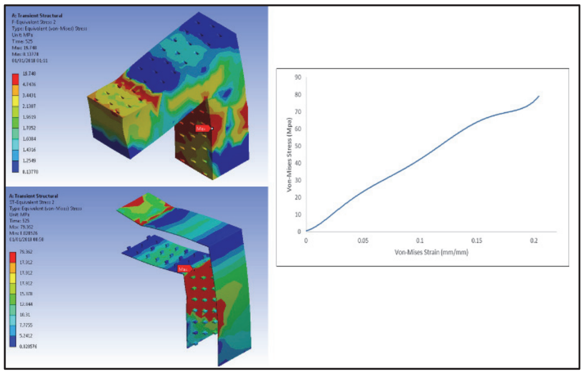

Fig. 16. Von-Mises stress distribution, and stress-strain relation in the composite connections' components

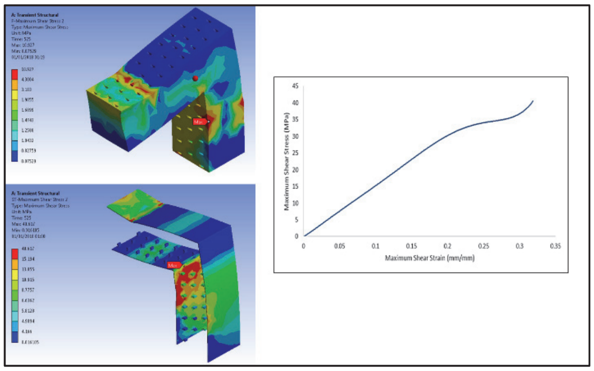

Fig. 17. Shear stress distribution, and stress-strain relation in the composite connections' components

6. Conclusions

Experimental and numerical investigations were conducted on an integrated connection between adjacent foam-filled sandwich panels composed of 3-D high density Polyethylene skins and high-density Polyurethane foam core. The overall mechanical response, and the stress distributions, and failure modes, moment resistance, initial rotational stiffness and rotational capacity of the connections were studied. The experimental test results indicated that in composite sections the bending ultimate strength increases by 25% compared to foam-only connections. The composite connections also show 2.2% greater rigidity, and increased rotational stiffness of 85%. With regard to the relative ultimate cantilever deflection, i.e. bending stiffness, composite connections presented better performance by 12% in comparison with foam-only connections. Both simple and composite connections showed very similar failure modes and the fracture surface of them are fairly similar to each other. The first failure mode was a shear crack occurred at the vertical side of internal edge. By applying more pressure to the specimens, connections collapsed due to the development of shear stress and consequently the tensile stresses at the edges. The most important difference therefore was their ductility; i.e. the foam-only connections show a relatively brittle sudden failure, while composite connections managed to undergo rather larger deformations before collapse. Comparison of finite element model and experimental results of all specimens showed that the load versus displacement were similar. Furthermore, the failure modes, ultimate load and ductility capacities correlated well with experimental observations.

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