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Development of an Innovative Modular Foam-Filled Panelised System for Rapidly Assembled Post Disaster Housing

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Abstract

In this paper the development process of a deployable modular sandwich panelized system for rapid assembly building construction is presented, and its structural performance under some different action effects is investigated. This system, which includes an innovative sandwich panel and its integrated connections, can be used as structural walls and floors in quickly assembled post-disaster housing, as well as load bearing panels for pre-fabricated modular construction and semi-permanent buildings. Panels and connections are composed of a pneumatic fabric formwork, and two 3-D high-density polyethylene (HDPE) sheets as the skins, filled with high-density rigid Polyurethane (PU) foam as the core. HDPE sheets manufactured with a studded surface considerably enhance the stress distribution, buckling performance and delamination strength of the sandwich panel under various loading conditions. The load-carrying behaviour of the system in accordance with some ASTM standards is presented here. The results show the system satisfies the codes criteria regarding semi-permanent housing.

Keywords: Post disaster housing; Rapid assembly systems; Foam filled sandwiches, Modular construction;

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Introduction

Natural disasters and emergencies can devastate the communities they hit, and the speed of a response can be crucially important. Crisis management after natural and non-natural disasters such as earthquake, flood, drought, bushfire, refugees, raid and even wars is one of the significant concerns of governments, where, fast decision making is an essential element of an effective crisis management system. When large amount of houses have suffered damages and become unusable, causing a high number of homeless people, rapid housing reconstruction programmes play a decisive role on the disaster recovery and providing temporary housing is a crucial step of these programmes. Experts estimate that on average, it can take 5 to 10 [1, 2] years for communities to recover from the effects of a major seismic event, which highlights the severity of the disaster and the importance of rapidly assembled buildings as an effective post disaster housing system. In addition to residential accommodation, rapid assembly buildings can be employed in several other applications such as, field hospitals, storehouses and other temporary and semi-permanent facilities. Some rapidly assembled systems have the potential to be used as temporary structures as well as providing long term serviceability.

Wise selection of rapid assembly building systems has an impact on their performance in an effective crisis management system. For instance, while use of big precast structural elements is very common for post disaster housing, as the dimension of precast elements increases, some significant construction problems will be appearing in transportation and erection phases. A temporary accommodation building can be any class of building as defined under the National Construction Code (NCC) [3]: class 1b (boarding house, guest house, hostel or the like), class 2 (residential units) or class 3 (motel) building, depending on its configuration [4]. Among the existing systems, air-liftable origami-inspired deployable systems, pliable structural systems with rigid couplings for parallel leaf-springs, scissor systems [5], elastic grid shell system[6], and structural panels are some popular types of mobile and rapidly assembled structures [7, 8]. However, most of these rapidly assembled structural systems suffer from low tolerance in the making and erection phases, and need skilled labors for installation that will result in an increase in the total construction costs and lower efficiency.

Light weight structural panels are one of the most popular types of mobile and rapidly assembled structures. Rapidly assembled panels are a form of modular construction, commonly used in residential buildings, as well as industrial structures [9-11]. A wide range of these panels are made from new lightweight components such as foams. Many types of

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foams are on the market and the Polyurethane (PU) foams are the most popular types [12]. Low self-weight and relatively high stiffness and durability have increased the demand for this type of composite structures [13]. 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 prefabricated building wall and floor systems.

With regard to the literature, a wide range of studies on the foam-filled composite panels are on those made of polyurethane (PU) foam-core [14]. The results of these studies indicate that the stiffness and strength of a majority of conventional foam-filled sandwich panels 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 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 [15]. The use of stitches for connecting the two side skins [16], or use of reinforcing ribs [17] are two popular strengthening techniques being employed for improving the mechanical performance of standard sandwich panels.

Despite their very competitive costs, conventional foam-filled 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 [15]. The use of stitches for connecting the two side skins [16], or use of reinforcing ribs [17] are two popular strengthening techniques being employed for improving the mechanical performance of standard sandwich panels.

In this study, in order to enhance the properties of the foam-filled sandwich panels with regard to such failure modes for application in semi temporary housing, a new sandwich system 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 Figure 1 with a total thickness of 100 mm. The system is casted in a pneumatic fabric formwork, which is used to accelerate the installation, and simplifying the transposition process. Using the HDPE sheets, manufactured with approximately 1200 studs per square

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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 debonding and increasing the interface strength between the foam-core and the face sheets.

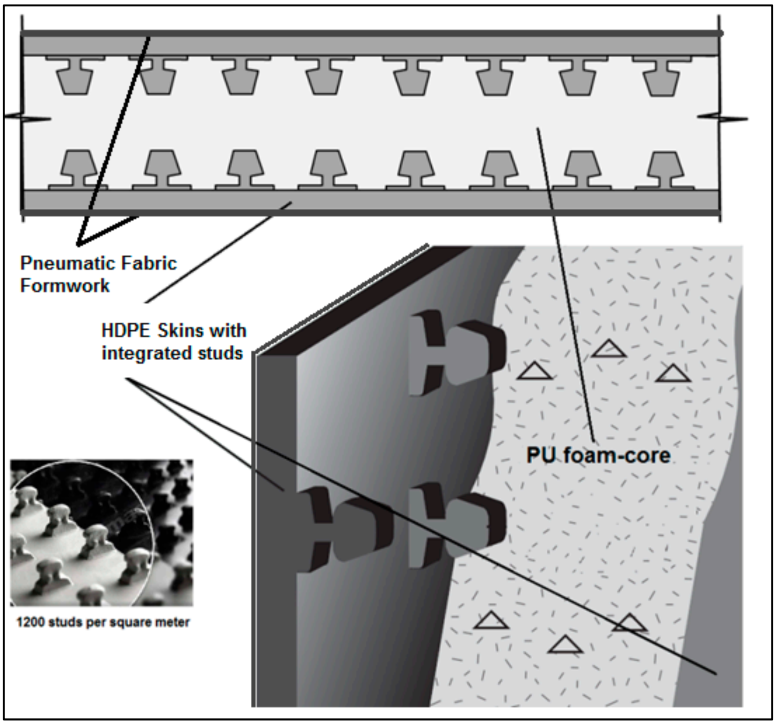

Figure 1. Sandwich with 3-D HDPE skins, PU foam-core, and pneumatic formwork

The fabrication of these sandwich panels takes place in a single step. Therefore, the face sheets and foam-core are integrated into one construction in to the fabric formwork. 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 system.

Material Properties

To evaluate the basic material properties, in addition to using the manufacturers' data, some experimental tests were performed.

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Foam Core

Rigid foam systems are energy efficient, versatile, high performance systems, where the liquid components are mixed together; and expand and harden on curing. The popular type of PU foam, being used for thermal insulation, refrigeration and water heater system is made of a 100:100-110 weight ratio mixture of AUSTHANE POLYOL AUW763 and AUSTHANE MDI [18]. This foam is formulated using a zero Ozone Depletion Potential (ODP), zero Global Warming Potential (GWP) and Volatile Organic Compound (VOC) exempt blowing agents. In this study, high-density rigid PU foam with a density of 192 kg/m^3 was selected for the core material, according to the results of the preliminary finite element models. Table 1 show and Figure 2 show the PU foam's manufacturing and mechanical properties, provided by the manufacturer, and validated in the laboratory according to the ASTM 1730 [19] standard specification for rigid foam for use in structural sandwich panel cores. It also meets the thermal conductivity, dimensional stability and flame resistance requirements of ASTM E1730 [19].

Table 1. Mechanical and manufacturing properties of the selected PU rigid foam

Mechanical Properties of the PU foam			
Density (kg/m^3)	Compressive yield strength (MPa)	Tensile yield strength (MPa)	Shear yield strength (MPa)
192	3.51	1.896	1.034
Manufacturing properties of AUW763			
Cream time	Gel time	Track free time	Free rise density
35-40 sec	94 ± 4 sec	115 ± 5 sec	280-300 kg/m^3

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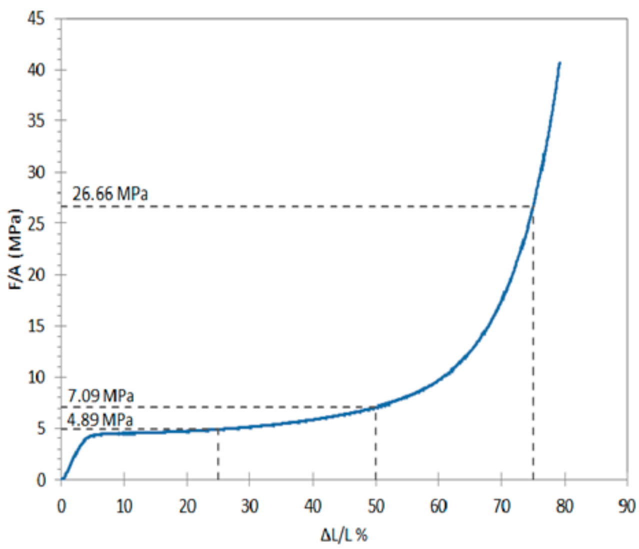

Figure 2. Results of the uniaxial load test on PU foam

The yield behaviour can be explained by the buckling of the foam's internal walls. Scanning Electron Microscopic images (SEM), provided before and after compression test, shown in Figure 4, substantiate such behaviour. A long and rather flat plateau was followed. Then, a densification (hardening) region was created by a gradual stress increase when the cell walls were stacked prior to final densification. In this range of loading, no visible signs of failure were observed. Residual displacement of the collapsed foam however, occurs once the unloading stage was complete.

Fabric Formwork

For the selection of formwork system some criteria are usually taken into account: quality (strength, rigidity, position, and dimensions); safety (of both workers and the concrete structure); efficiency (in operation, handling, erection and dismantling, and number of repetitions); and economy (life cycle cost to be consistent with quality and safety). Fabric formworks offer lower weight (approximately 1/300th that of a conventional rigid form), lower material cost, lower labour cost (no cost of stripping, placing, erection and waterproofing), better constructability (adaptable to uneven ground conditions, easier infill protection, and stakeless system). These make the use of fabric a viable option, especially for rapid assembly construction [20].

Although fabrics have been used as formwork for many years [21], thanks to recent advances in the textile material science, durable and low cost fabrics are becoming more and more

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available for construction purposes. Using fabric formwork as a mould in concrete structure, it is possible to cast architecturally interesting, structurally optimized non-prismatic structures that use up to 40% less concrete in comparison with an equivalent prismatic section [20], offering potentially significant embodied energy savings [22] and subsequently, a striking reduction in the CO_2 emissions [23] can be achieved.

There are two general types of fabric formworks: slack-sheet mould and energized (tensioned) formwork sheets [24]. Each type of fabric distributes force slightly differently depending on the material it is made of and the nature of its internal structures. This study will focus on the pneumatic fabric formworks, in which pneumatic force is used for the erection of the flexible fabric formwork. The critical aspect of fabric formwork for achieving desirable performance is the selection of the fabric itself. Although a wide range of woven fabrics can be used as formwork for fabric formwork, tensile strengths in both warp and weft directions must be sufficient to hold the infill material (which is polyurethane in this research) and a low creep modulus is desirable to limit formwork deformations during casting and curing/hardening.

For selection of the fabric criteria such as aesthetics, permeability, sew-ability or weldability, relative cost, durability and strength were considered [25]. Conducting some experimental tests to determine the selection indicators for the criteria like durability and strength for each candidate, 'Barrateen' as the most suitable pneumatic formwork candidate, we selected for foam-filled structural composite panels. 'Barrateen' fabric is a HDPE coated unbalance woven textile. The coating material is low density polyethylene and well inflatable. In addition, its tensile strengths in the wrap and weft directions are not the same. The result of tensile tests on 10cm wide and 20 cm length specimens according to ASTM D1980-89 showed that the module of elasticity of the principal direction is higher, but, in strain about 270%, it can have a sudden brittle rupture (Figure 3). A series of weldability tests was also conducted on the fabric. , the tensile bearing capacity of heat-welded connections can reach up to 13% of the average strength of the material. In addition, the maximum strain was measured as 90% at the failure point.

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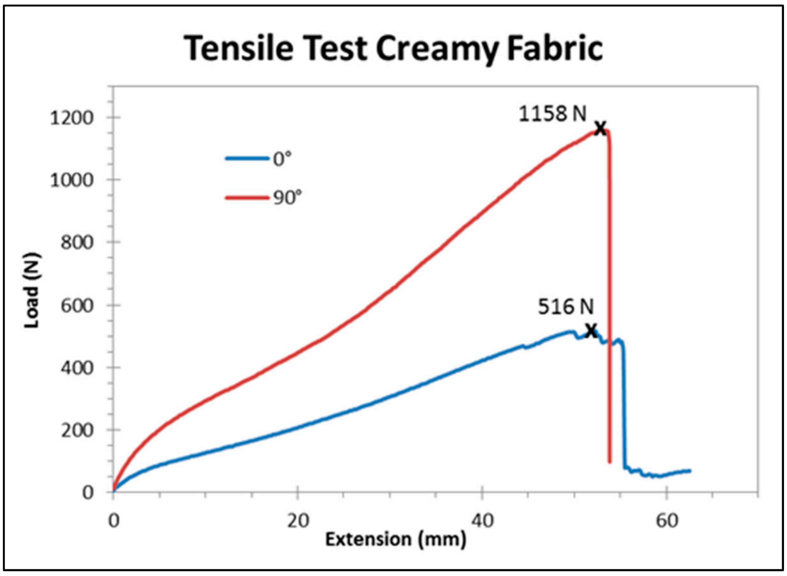

Figure 3. Barrateen fabric tensile behaviour in main and transverse directions.

With regard to the structural performance of the fabric formwork some experimental tests were conducted. Formwork should be designed for the ultimate as well as the serviceability limit states. Low yield stress and plastic viscosity of filling material increase the lateral pressure on the forms to a degree as high as the hydrostatic pressure. That is, formwork pressure exists as long as filling material is in a plastic state, and its rate of decay is related to the rate of the stiffening of filling material [26]. Figure 4 depicts the effects of fabric formwork thickness and foam density on the maximum lateral deflection of the fabric formwork. It shows the higher thickness will result in higher effects of density of the maximum lateral deflection.

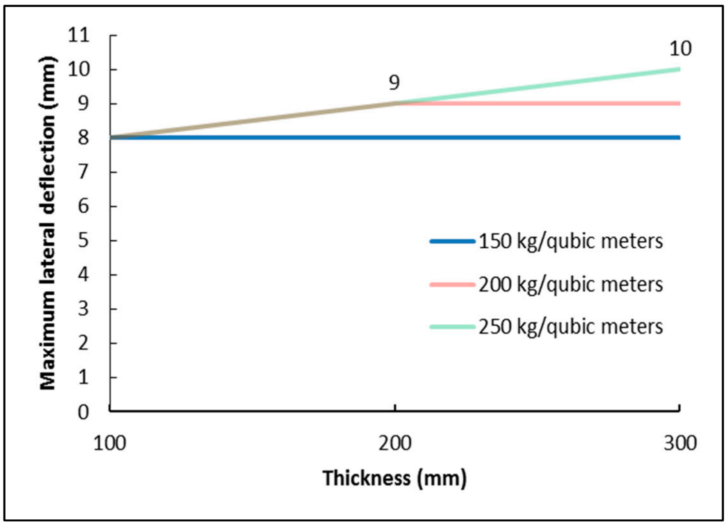

Figure 4. Effects of fabric formwork thickness and foam density on the maximum lateral deflection

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Skin Sheets

The face sheets of the sandwich panels are made of 3-D HDPE (High Density Polyethylene) 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 with approximately 1200 studs per square meter, can effectively contribute to the sandwich composites' structural performance by providing high pull out strength, minimum lateral movement of the skin, and stronger bonding. Four different thicknesses of the sheets were initially investigated (2mm, 3mm, 4mm and 5mm), and at the end the sheets with 2mm tackiness were selected for the sandwich composite. Table 3 shows some mechanical properties of the selected sheet, provided by the manufacturer and validated by experimental tests in the laboratory, in accordance with the ASTM D5199 , ASTM D1505 and ASTM D6693 provisions [27] 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, according to ASTM D6693 standard [27]. Figure 5 shows the coupon test results.

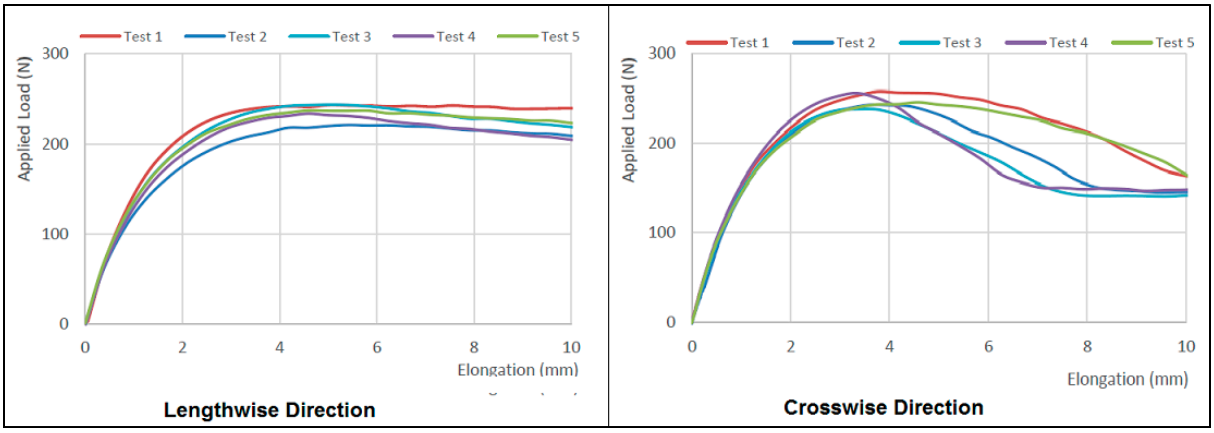

Figure 5. The HDPE's tension test results in the lengthwise and crosswise directions

Edgewise and Flatwise Compressive Behaviour

The edgewise compressive strength of sandwich construction is important as it provides the basis for the assessment of the load-carrying capacity [28]. The compressive properties of the sandwich composite along the direction parallel to the plane of the sandwich face skin were

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evaluated through edgewise compression tests on 100mm×200mm×300mm samples using a test rig (universal testing machine) in accordance with the ASTM C364 standard [29].

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 (Figure 6).

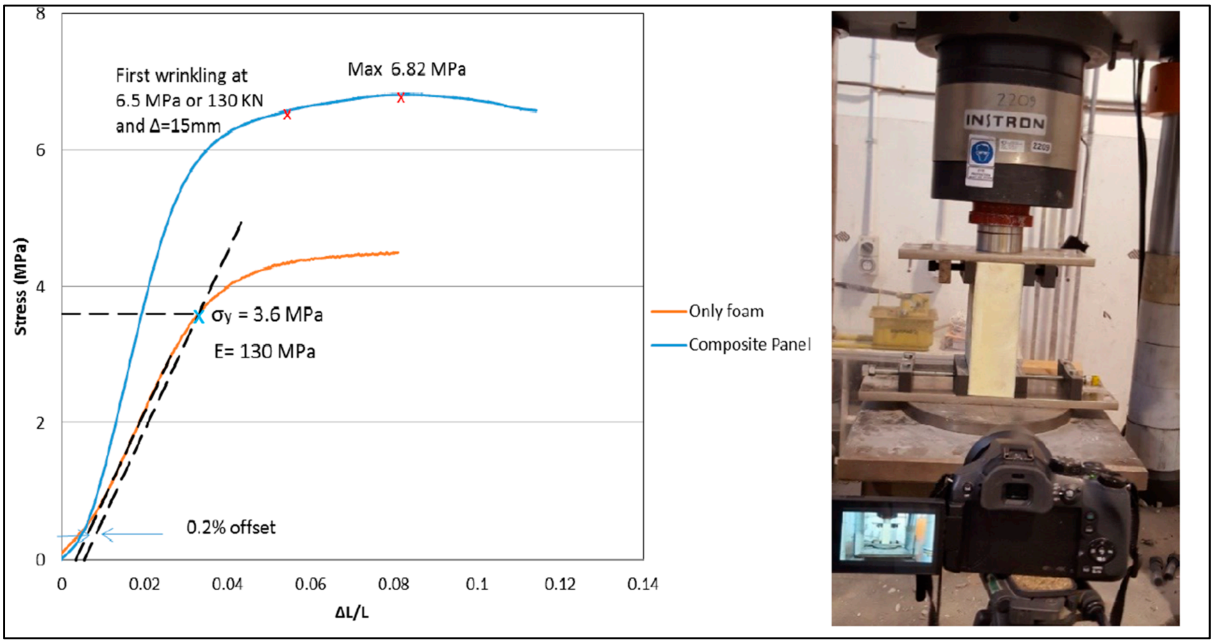

Figure 6. Test Setup and Design Elasto-Plastic diagram of composite panel under edgewise compression

The compressive strength of the composite was also assessed through the flatwise compressive tests [30, 31] 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. Flatwise compressive tests were performed until the load–displacement curve indicated a collapsed structure, i.e. with significantly high deformation of specimens. The results, shown in Figure 7, 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

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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. 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.

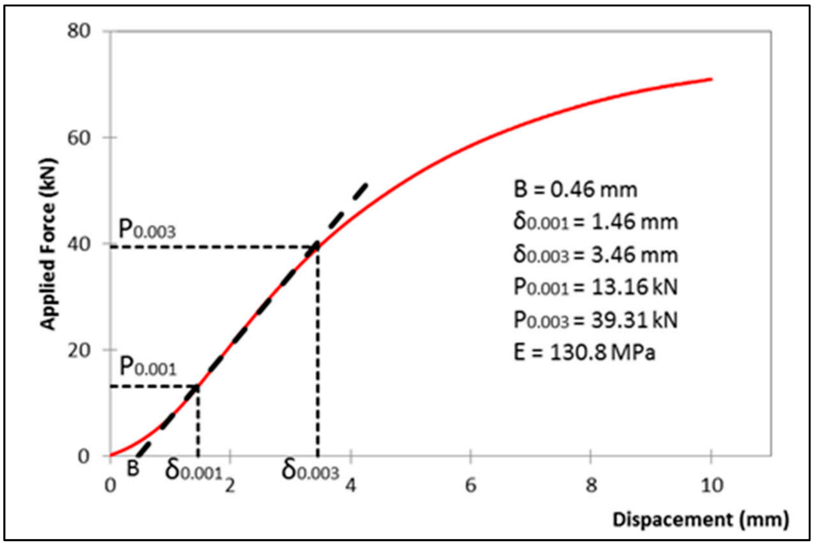

Figure 7. Description of flatwise compressive experiments calculation

Flexural and Shear Behaviour

The flexural stiffness of sandwich beams/panels that can be calculated using First-order Shear Deformation Theory (FSDT) [32-35], is used to estimate the shear stiffness of each sandwich beam type by fitting the results collected from four-point flexural tests. A perfect bond must be assumed to exist between the core and the facings. The bending stiffness can be computed accounting for the deflection components that are associated with bending and shear deformations [36, 37]. This study examined the core shear properties of introduced polyurethane infill-foam composite panels subjected to flexure in such a manner that the applied moments produce curvature of the sandwich facing planes. Also, in this regard, core shear ultimate stress, facing bending stress, transverse shear rigidity and core shear modulus of introduced sandwich panel are calculated based on ASTM C393/C393M [38] and ASTM D7250/D7250M [39] using six medium-scale sandwich specimens with 45cm length, 20cm width and 10cm as total thickness of composite section. The applied force versus crosshead

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displacement and mid-span deflection are shown in Figure 8, and transverse shear rigidity calculated based on ten load-deflection selective steps is shown in Table 2.

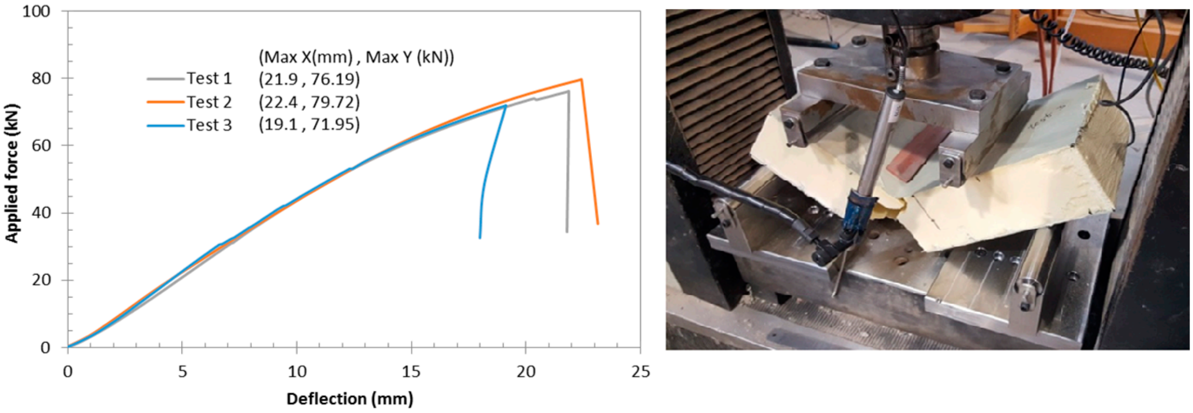

Figure 8. Four-point quarter-span loading flexural test results

Table 2. The least maximum applied forces and their related mid-span deflections

	4-Point Quarter Span Loading		3-Point Mid Span Loading	
	P_{max} (kN)	$\Delta_{midspan}$ (mm)	P_{max} (kN)	$\Delta_{midspan}$ (mm)
Specimen 1	76.19	21.9	56.23	24.9
Specimen 2	79.72	22.4	52.54 (minimum)	23.8
Specimen 3	71.95 (minimum)	19.1	53.98	24.2
Average	75.95	21.1	54.25	24.3
Standard deviation	3.89	1.8	1.86	0.56
CV (%)	5.12	8.42	3.5	2.3

Effects of Cold Joints

One of the most important construction problems of foam made panels is cold joints, which is also known as seams. When the placing of foam in the panels is delayed or interrupted for some reasons, the foam that has already been placed starts to condense, producing a kind of construction joint (seam) called a cold joint between it and newly placed foam. Seam is a plane under mixed material, or a fold that is developed within the rising foam mass, which appears as a line on the foam surface or section [40]. Such joints between new and old portions of foam that are formed when new foam is placed adjacent to the foam that has hardened or has started to harden, may have negative effects on the strength of rigid foam

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panel. Hence, attention must be paid to the position and direction of the joints, and the effects on the structural behaviour. For experimental investigation, three series of bending tests were carried out on two types of panelised specimens. Two types of 1500*1000*100 mm^3 rigid polyurethane panels were used: Type S (seamless) and type TS (with transverse seams) specimens. The expansion rate of this type of foam is 3.0, and the average weight of both types of panels is 29.0 kg.

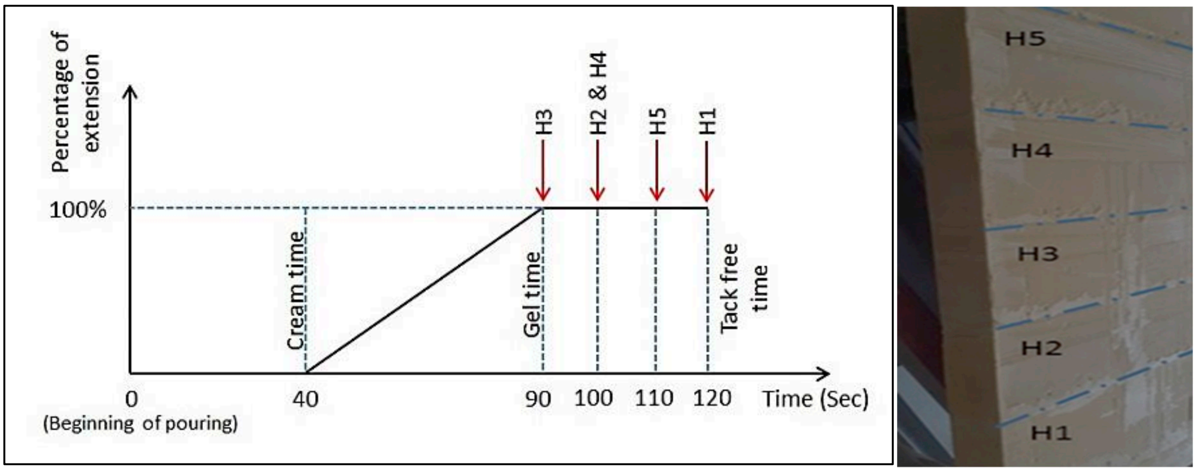

Fig3. Casting schedule of seams at TS specimens Locations of transverse seams

A comparison between the results of the tests shows that casting at the end of gel time instead the end of tack free time, resulted in % 80 increase in the tensile strength of the seams. Also, casting at about 20 sec before of the end of tack free time (120th sec), increased the tensile strength of the seams by %60. The seamed section exhibited about 33.1% of the maximum tensile strength of an intact section. In addition, the seamless panels showed a larger deflection capacity, as 20% more than that of TS panels.

Integrated Connections

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. For the composite sections in this study, the connections between the panels are constructed by continues foam casting to achieve better integrity. 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

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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.

For experimental investigation, six L shape specimens, representing the connections between adjacent sandwich panels, are 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. 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 Figure 9.

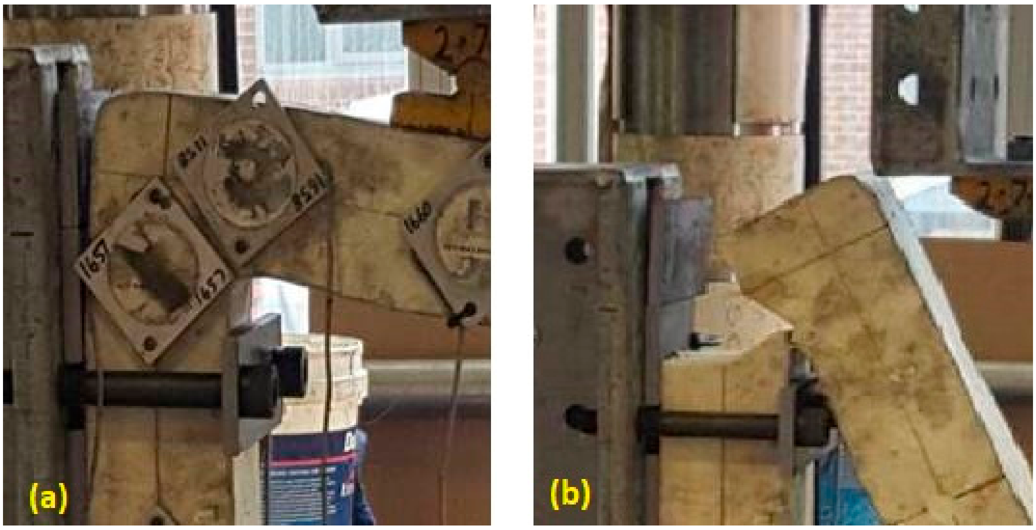

Figure 9**.** The ultimate deflection and the mechanism of collapse

As presented in Table 3, 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.

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Table 3. 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

Concluding Remarks

A new foam-filled sandwich panel and its integrated connections were developed at the Centre for Infrastructure Engineering of Western Sydney University, as a rapid assembly system for post disaster housing and semi-permanent accommodations. It is composed of 3-D high density Polyethylene (HDPE) sheets, as the skins with a thickness as 2 mm, high-density PU foam core with a total thickness as 100 mm, incorporated into a pneumatic fabric formwork. This paper investigated the structural performance of the panel and integrated connections, with respect to the material properties, edgewise and flatwise compressive behaviour, flexural and shear behaviour and the effect of cold joints (seams). The findings for each criterion indicate that the system fully complies with the relevant standards for semi-permanent and temporary accommodations, and meet their requirements for post disaster housing.

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