

# FEASIBILITY ANALYSIS OF THE USE OF RIGID POLYURETHANE FOAM IN MODULAR SANDWICH PANELS FOR RAPID ASSEMBLY STRUCTURES

Bijan Samali<sup>1</sup>, \*Saeed Nemat<sup>2</sup>, Phezhman Sharafi<sup>3</sup>, Farzad Yaghmaei<sup>4</sup>, Alireza Farrokhi<sup>5</sup>

<sup>1,2,3</sup> Centre for Infrastructure Engineering, Western Sydney University, Australia

<sup>4</sup> Faculty of Civil Engineering, ASIHE, Iran

<sup>5</sup> Faculty of Civil Engineering, Sharif University of Technology, Iran

\*Corresponding Author, Received: 18 April 2018, Revised: 3 May 2018, Accepted: 4 June 2018

**ABSTRACT:** Mobile and rapidly assembled structures play an important role in building temporary and semi-permanent accommodations and shelters in post-disaster management. One of the most efficient construction systems that can be used in rapidly assembled buildings is lightweight panelized systems. Use of rapidly assembled panelized systems is becoming very popular for cutting the construction time and transportation costs that make them suitable options for rapid assembly construction. In addition, when acoustic and thermal insulation of buildings is important, foam filled composite sandwich panels are an effective solution. Soft, semi-rigid and rigid Polyurethane (PU) foams, which are first introduced into the market in the 1950s, are most popular types of foams. Regarding the research performed in the last decade, the structural behavior of PU foam filled sandwich panels has been investigated by several researchers worldwide. There is a need for a comprehensive feasibility studies on the use of rigid PU foam in structural sandwich panel cores so that various aspects of this material is deeply investigated. In this paper, a feasibility study carried out on a commercial type of rigid PU foam with trading name AUW763, to be used as the core material of sandwich panels, based on ASTM E1730-15. Results show AUW763 meets the standards requirements and specifications for building constructions.

*Keywords: Polyurethane, rigid foam, Sandwich panel, modular construction, rapid assembly buildings*

## 1. INTRODUCTION

In building construction, polyurethane (PU) foams are used to make high-performance products that are relatively strong but lightweight, durable and versatile. PU products also can help enhance the aesthetic design of homes and buildings. In the last decade, the structural behavior of rigid PU foam filled sandwich panels is investigated worldwide. Yan et al. studied the Quasi-static and dynamic mechanical responses of hybrid laminated composites based on high-density flexible PU foam [1]. Wu et al. studied the energy absorption capacity of a simple and innovative foam-filled lattice composite panel using PU foams with various densities [2]. Nasirzadeh et al. investigated the effect of foam density variations in sandwich structure under high velocity impact loadings [3]. Sharma et al. studied all vibration modes of sandwich panels in order to ensure that debonding between facings and PU core with variation in density [4]. He et al. studied on the dynamic response of composite sandwich plates which are fabricated with carbon fiber-reinforced plastic (CFRP) skins and rigid PU foam cores, subjected to low-velocity impact [5]. Wang et al. performed experimental studies on the low-velocity impact behavior of PUR foam-core sandwich panels with

plain weave carbon fabric laminated face-sheets [6]. Feli et al. studied the low-velocity impact on sandwich panels with hybrid nanocomposite face sheets and rigid PU foams [7]. In a research undertaken by Mirzapour et al., an experimental study to investigate and optimize the processing conditions in the fabrication of the sandwich structures designed for flexural load bearing applications was carried out. Sandwich beams with two glass/epoxy faces and a rigid PU foam core were constructed under four different processing conditions [8]. Sharaf et al. studied the flexural behavior of a new sandwich panel proposed for cladding of buildings. The panel was fabricated by laminating two glass fiber reinforced polymer skins to a prefabricated PU foam core with two different densities 32 kg/m<sup>3</sup>, referred to herein as 'soft' foam, and 65 kg/m<sup>3</sup>, referred to as 'hard' foam [9]. Sharaf et al. also addressed the flexural performance of sandwich panels composed of a rigid PU foam core and glass fiber-reinforced polymer (GFRP) skins in their studies [10-12]. Mostafa et al. studied on behavior of PU-foam/glass-fiber composite sandwich panels under flexural static load using closed cell semi-rigid PU with a density of 62 kg/m<sup>3</sup> [13]. Berggreen et al. studied the skin delamination of FRP sandwich with low and high core density [14]. Tuwar et al. evaluated mechanical behavior of three core alternatives for GFRP foam-

core sandwich panels. The used foams were low density and high density closed PU [15]. Kakroodi et al. investigated the strengthening effects of soy-based rigid PU foam cores, neat and composite foams containing wood fiber, on the performance of small-scale wooden wall panels under monotonic and static cyclic shear loads [16]. Garrido et al. presented experimental and analytical investigations about the effects of elevated temperature on the shear response of Polyethylene Terephthalate and semi-rigid PU foams used in sandwich panels [17]. In addition, Garrido et al. presented the experimental assessment and the analytical modelling of the viscoelastic response of two types of sandwich panels, with and without reinforcement ribs using GFRP faces, cores of rigid PU foam, and longitudinal GFRP ribs are considered [18]. Also, Garrido et al. presented an experimental and analytical study about the effect of temperature on the shear creep response of a rigid PU foam within the scope of sandwich panel [19]. George et al. studied on sandwich panels fabricated using a fixed carbon fiber reinforced polymer truss and a variety of closed cell polymer and syntactic foams with density variations [20]. Also, the behavior of foam core sandwich and polymer reinforced rigid foam core sandwich panels (PRFCS) was experimentally explored for flatwise compression and flexural loadings by Abdi et al. [21]. Yanes-Armas et al. studied the structural creep behavior of rigid GFRP-PU web-core sandwich structures subjected to sustained loading was investigated [22]. Mohamed et al. studied the stiffness, load-carrying capacity and compressive strength of three designs of glass reinforced composite sandwich structures using PU rigid foam [23]. Mostafa et al. presented a semi-circular shear keys inserting between the skin and the foam core to improve the shear performance and skin-core debonding resistance for sandwich panels with Polyvinylchloride (PVC) and semi-rigid PU foam core [24]. In a recent study, Sharafi et al. [25-27] and Nemati et al [28, 29].

In this paper, a feasibility study is carried out on a commercial type of rigid PU foam with trading name A UW763 in order to use as the core material of sandwich panels, based on ASTM E1730-15 [30]. This PU foam is widely available in the market at a reasonable price that can be widely employed for the construction of modular sandwich panels [31-33].

## 2. AUW 763 RIGID FOAM

Rigid foam systems are energy efficient, versatile, high-performance systems, where the liquid components are mixed together; and expand and harden on curing. The common applications of this foam, which is made of a 100:100-110 weight

ratio mixture of AUSTHANE POLYOL AUW763 and AUSTHANE MDI by hand mixing, are thermal insulation and refrigeration, water heater system, continuous and discontinuous panel line systems, marine buoyancy, cavity filling of rotary moulded parts, pipe injection and Vessel insulation, packaging foam, moulding and structural systems. This foam is formulated using a zero Ozone Depletion Potential (ODP), zero Global Warming Potential (GWP) and Volatile Organic Compound (VOC) exempt blowing agent [27]. Table 1 shows the manufacturing properties of AUW 763 [27].

Table 1 Manufacturing properties of AUW763

Cream time	Gel time	Tack free time	Free rise cup density
35-40 sec	94 ± 4 sec	115 ± 5 sec	280 – 300 kg/m <sup>3</sup>

## 3. SPECIFICATION CHECK, BASED ON ASTM E1730-15

This specification covers rigid PU thermal insulation for sandwich panels used in shelter construction for exposure to ambient temperatures of -32 °C to 71 °C. Painted surfaces of shelters in actual field use reach temperatures of 93 °C.

### 3.1 Density

In this study, the density of used foam has been controlled in accordance with the test method D1622/D1622M [28]. In this regard, three cylindrical specimens (Fig. 1) were tested at 24 °C and 51 % relative humidity. The results are shown in table 2.



Fig.1 Obtained cylindrical specimens for a density test

Table 2 Dimensions and weights of cylindrical specimens for a density test

	First measurement	Second measurement	Third measurement	Average
Diameter (mm)	40.1	40	40	40
Height (mm)	80.1	80.1	8	80.1
Volume (mm <sup>3</sup> )				100605.6
Weight (gr)	19.3	19.6	18.8	19.3

Based on D1622/D1622M the density will be calculated as  $D = W_s / V$ , where:  $W_s$  is the weight of specimen (kg), and  $V$  is the volume of the specimen (m<sup>3</sup>). Therefore, the average density of the foam is 191.8 kg/m<sup>3</sup>, which meets the ASTM E1730's criteria for all types, shown in Table 3.

Table 3 Standard types of foams based on ASTM E1730

Requirement Procedure	Type 1	Type 2	Type 3	Type 4
Density (kg/m <sup>3</sup> ), max	41.6	55.7	72	192

### 3.2 Thermal Conductivity

Thermal conductivity shall be determined at mean temperatures of 5 °C, 24 °C and 52 °C after conditioning for 7±1 days at 24±2°C, and less than 60% relative humidity from the time of manufacture. The heat flow is to be measured parallel to the rise of the foam [26]. But, based on ASTM E1730, and because of the type of used foam (Type 4), carrying out this test is not required, as shown in Table 4.

Table 4 Thermal conductivity requirements based on ASTM E1730

Thermal conductivity, W/m-K, max	Type 1	Type 2	Type 3	Type 4
at approximately 5°C mean	0.25	0.257	0.257	not required
at approximately 24°C mean	0.25	0.257	0.257	not required
at approximately 52°C mean	0.25	0.257	0.257	not required

### 3.3 Dimensional Stability

Dimensional changes measured by this test method can be used to compare the performance of materials in a particular environment, to assess the relative stability of two or more cellular plastics, or to specify an acceptance criterion for a particular material [34]. Accordingly, ASTM E1730 provides some limitation on linear and volumetric stabilities of rigid foams, which are shown in Table 5.

Table 5 Dimensional stability requirements based on ASTM E1730

Dimensional stability	Type 1	Type 2	Type 3	Type 4
Linear Δ%	±1.5	±1.5	±1.5	±1.5
Volumetric Δ%	±2.5	±2.5	±2.5	±2.5

In this study dimensional stability was determined in accordance with ASTM test method D2126 [34], at 72 °C and ambient humidity. The test duration was 836 h (two weeks). In this regard, five 100mm × 100mm × 100mm cubic specimens were tested (Fig. 2). The faces of specimens were finished using # 0 sandpaper. The dust has been blown off the specimens with compressed air. Prior to the tests, specimens were conditioned to constant mass at the temperature of 23 °C and relative humidity of 52%. After exposure, allow the specimens to come to room temperature for 2h before measuring and testing.

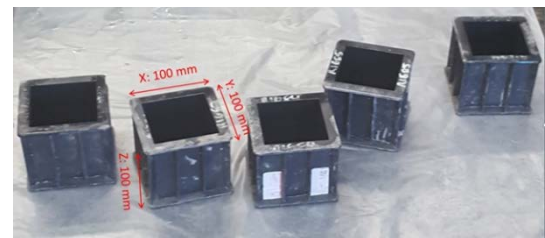


Fig.2 Empty cubic formworks (bottom) and foam filled ones (top) before been machined (mild)

The changes in dimensions are expressed as a percentage of the original measurement, as  $[(o_f - m_o) / m_o] \times 100$ , where  $m_f$  is the final measurement, and  $m_o$  is original measurement. Table 6 shows the results of tests and related calculations. In addition, some visual examination carried out on the specimens, whose results are shown in Table 7 and Fig. 3.

Table 6 Dimensional stability test results

Specimens No.	Original Measurement					Final Measurement					Change (%)				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
X dimension (mm)	100.23	100	100.24	100.22	100.2	98.99	98.98	99.07	99.51	99.81	-1.24	-1.02	-1.17	-0.71	-0.39
Y dimension (mm)	100.12	100.11	100.19	100.11	100.14	99.69	98.98	99.99	99.49	99.57	-0.43	-1.14	-0.2	-0.62	-0.56
Z dimension (mm)	100.19	100.38	100.33	100.16	100.1	99.38	99.99	99.13	99.07	98.92	-0.81	-0.39	-1.2	-1.09	-1.18
Volume (mm <sup>3</sup> )	1005409.4	1004904.2	1007618.8	1004907.7	1004406.2	980713	979606.1	981982.7	980817.8	983075	-2.46	-2.52	-2.54	-2.4	-2.1

Table 7 Dimensional stability visual test results

Specimens No.	1	2	3	4	5
General appearance	Minor darkening	Nothing	Minor darkening	Nothing	Nothing



Fig. 3 Minor darkening of specimens at 72 °C after 836 hours

### 3.4 Flame Resistance and Energy-Dispersive X-Ray Spectroscopy

The flame resistance of foam can be evaluated through tests according to the ASTM E1730 [26]. To that end, low-cost additive fire retardants can be used in PU foam. Nowadays a wide range of fire retardants is being used particularly for rigid foams. In contrast, it is difficult to impart fire retardants to flexible foams because of several factors such as open their cell structure, a low degree of crosslinking, and chemical structure impair [30]. Flame resistance test as well as heat and smoke release rate, are carried out by the manufacturer for all types of produced foams.

Based on the required flame resistance, a variety of resistance is achievable without any considerable change in the physical or mechanical properties, by using such fire retardant additives [31]. A major disadvantage is that they frequently cause shrinkage, which is mainly the case in flexible foams, not the rigid ones [30]. In this regard, Tris Chloroisopropyl Phosphate (TCPP) is a commonly used retardant used by many manufacturers. TCPP is a colorless or light yellow transparent liquid, whose molecular formula is C<sub>9</sub>H<sub>18</sub>Cl<sub>3</sub>O<sub>4</sub>P. TCPP is used as a low-cost flame

inhibitor and usually is used as a flame retardant rigid and flexible PU foam. Past studies show that by using TCPP any degree of fire resistant foam (even full fireproof rigid foams) are achievable [32, 33].

In order to further study the feasibility of using PU foam in structural members, an energy-dispersive X-ray spectroscopy investigation was carried out on AUW763 using a JSM-6510LV (Low Vacuum with EDS microanalysis) machine at western Sydney University (Fig. 4).

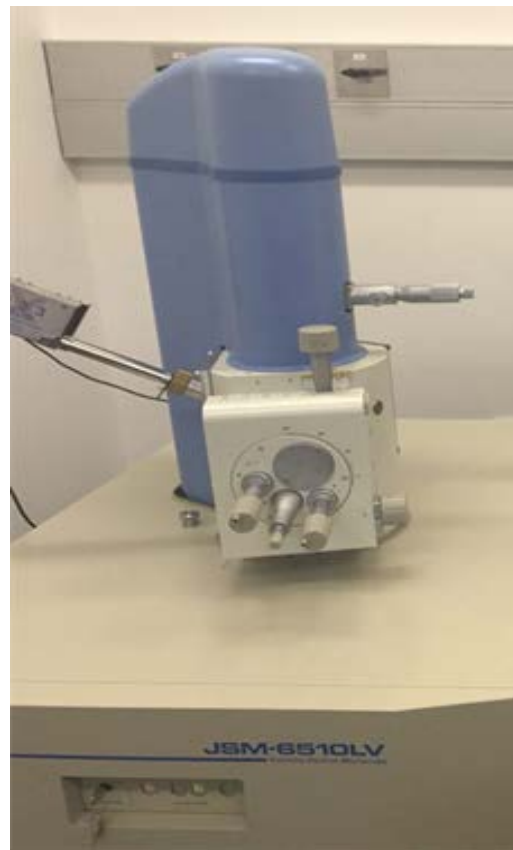


Fig. 4 JSM-6510LV machine

Energy-dispersive X-ray spectroscopy (EDS, EDX, EDXS or XEDS), or energy dispersive X-ray analysis (EDXA) or energy dispersive X-ray microanalysis (EDXMA), are analytical techniques used for the elemental analysis or chemical

characterization of a sample [34]. As the energies of the X-rays are characteristic of the difference in energy between the two shells and of the atomic structure of the emitting element, EDS allows the elemental composition of the specimen to be measured. The accuracy of the measured composition is also affected by the nature of the sample [34]. Fig.s 5 and 6 show the results of EDS analysis on the PU foam. No toxic components can be observed in investigated foam subsequently in its burned oxides.

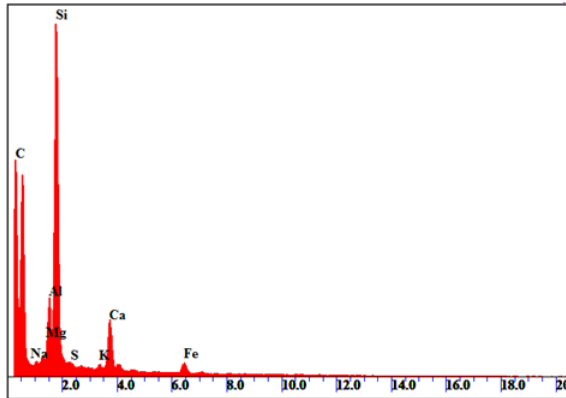


Fig. 5 Results of EDS analysis of presented foam

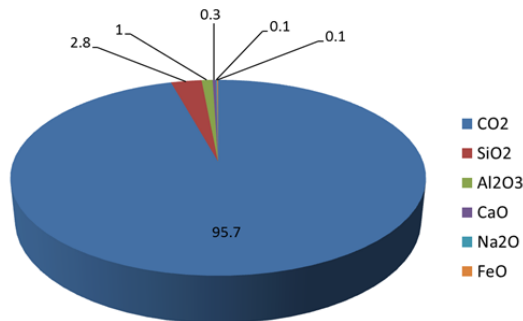


Fig. 6 List of oxides (weight %)

### 3.5 Impact Resistance

Materials such as masonry and concrete are robust and can generally be expected to resist normal impacts such as windborne debris or hailstone. However, many materials used in facades are more susceptible to damage and require testing to assess their performance. To examine the effect of transverse impact, a quasi-static impact test was used to simulate a low-velocity impact. The specimen of rigid PU foam (610 mm long, 610 mm wide and 50 mm thick) was used, as shown in Fig. 7. The face of the foam specimen is bonded to a 0.8 mm thick aluminum sheet. For determining the impact resistance a 31.7 kg steel hemispherical

cylinder of 80 mm diameter was dropped vertically from 762 mm distance so that the hemispherical end of the weight strikes the center of the outer skin of the specimen on a horizontal plane. The cylinder was not permitted to re-impact the specimen after the first impact. Specimens were supported along their four edges by a framework backed by concrete.

The frame was made of four pieces of lumber, rigidly connected together to form a 610 mm square on a side, as illustrated in Fig. 8. The panel specimens had their four surfaces bound with a channel frame of skin material attached through flanges. Impact did not result in rupture to either skin. No crushing of core is allowed outside a 3 in. radius from the center of the impact [34]. Fig. 9 shows the crushing areas of skin and core foam respectively. The maximum crushing radius was measured as 21 mm. Therefore, the result shows an acceptable impact resistance for the specimens.

### 4. CONCLUSION

Results of carried out tests on AUW763, based on ASTM E1730-15 show it meets the ASTM requirements and needed specifications as following:

- The used rigid foam is accordance with ASTM E1730 Type 4.
- Because of the used foam is accordance with ASTM E1730 Type 4, carrying out thermal conductivity test is not required.
- Dimensional stability visual test results show minor darkening of specimens at 72 °C after 836 hours.
- Dimensional stability test results show that the average of the maximum linear change in specimens was only -0.81% which is less than the allowed amount as +/-1.5%.
- Dimensional stability test results show that the average of the maximum volumetric change in specimens was only -2.4% which is less than the allowed amount as +/-2.5%.
- The results of carried out flame resistance test as well as heat and smoke release rate show the accordance of AUW763 with ASTM E1730-15.
- Based on energy-dispersive X-ray spectroscopy, no toxic components can be observed in investigated foam subsequently in burned oxides.
- The results of impact resistance test show the maximum crushing areas of skin was 21mm which is less than the allowed amount of 76.2 mm.

Therefore, the investigated foam is absolutely suitable for use in structural sandwich panel cores.

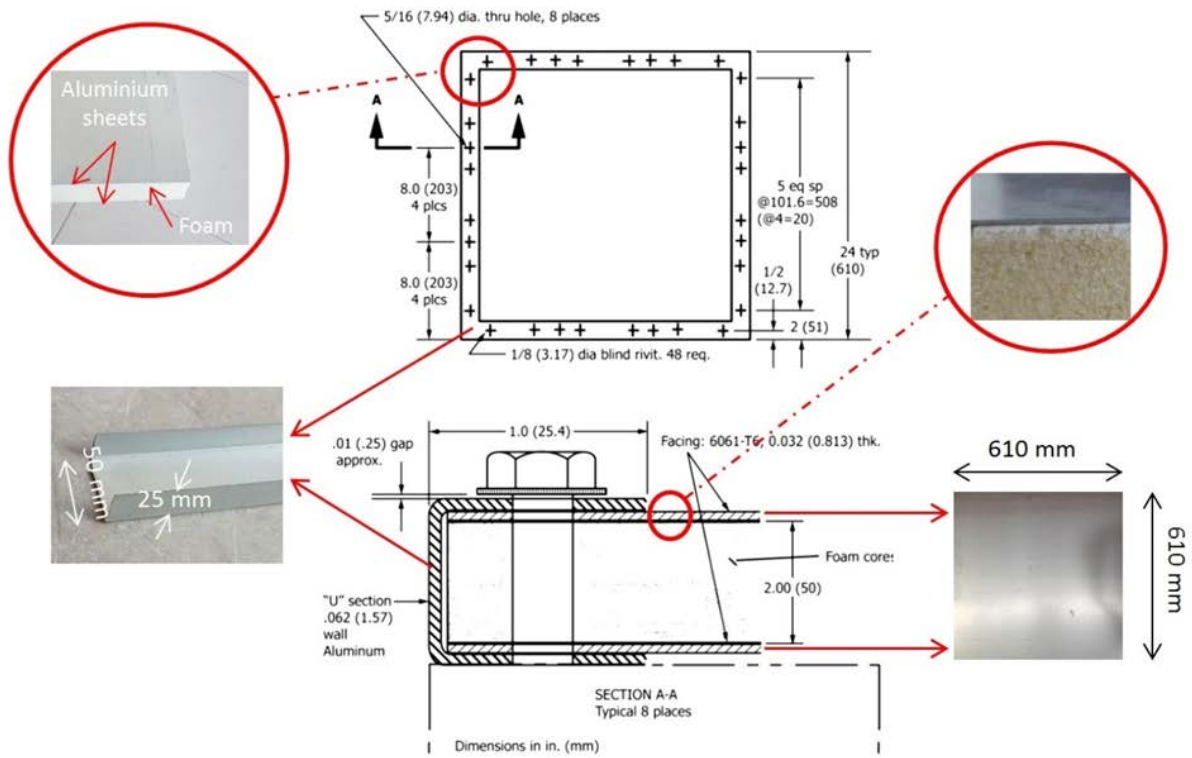


Fig. 7 Details and components of the specimen

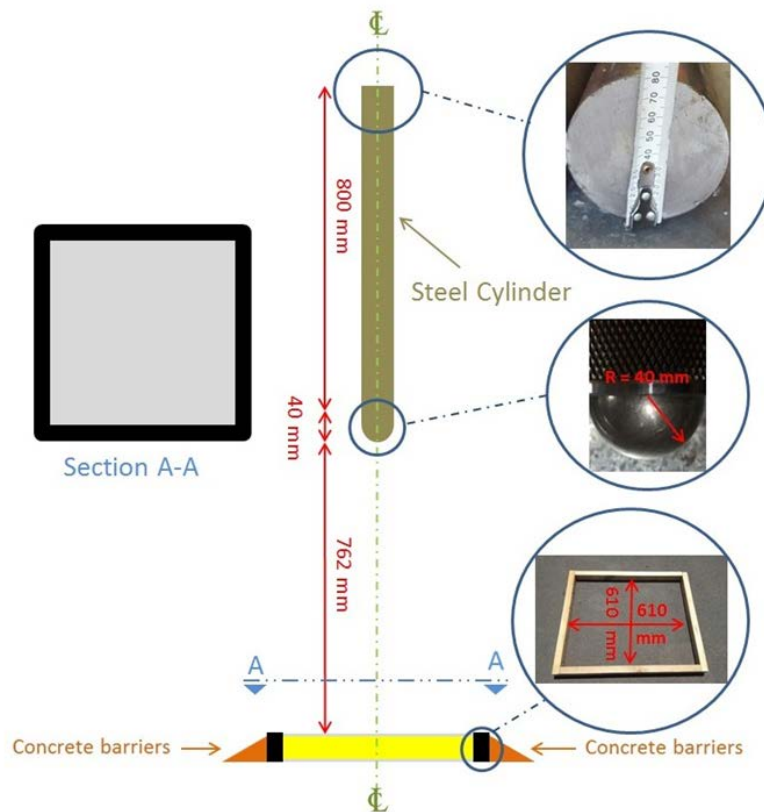


Fig. 8 Configuration of impact resistance test rig

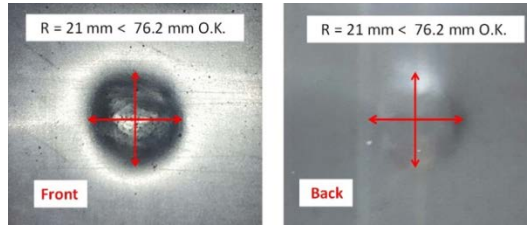


Fig. 9 Crushing areas of skin at impact resistance test

## 5. ACKNOWLEDGMENTS

The authors are thankful to Dr. Ghodrat for contributing to EDS analysis.

## 6. REFERENCES

- [1] Yan, R., Wang, R., Lou C. W. and Lin J. H., Quasi-static and dynamic mechanical responses of hybrid laminated composites based on high-density flexible polyurethane foam. *Composites Part B: Engineering*, 2015. 83: p. 253-263.
- [2] Wu, Z., Liu, W., Wang, L., Fang H., Hui, D., Theoretical and experimental study of foam-filled lattice composite panels under quasi-static compression loading. *Composites Part B: Engineering*, 2014. 60: p. 329-340.
- [3] Nasirzadeh, R. and A.R. Sabet, Study of foam density variations in composite sandwich panels under high velocity impact loading. *International Journal of Impact Engineering*, 2014. 63: p. 129-139.
- [4] Sharma, R.S. and V. Raghupathy, Influence of core density, core thickness, and rigid inserts on dynamic characteristics of sandwich panels with polyurethane foam as core. *Journal of Reinforced Plastics and Composites*, 2010. 29(21): p. 3226-3236.
- [5] He, Y., Zhang, X., Long, S., Yao, X., He, L., Dynamic mechanical behavior of foam-core composite sandwich structures subjected to low-velocity impact. *Archive of Applied Mechanics*, 2016. 86(9): p. 1605-1619.
- [6] Wang, J., A.M. Waas, and H. Wang. Experimental study on the low-velocity impact behavior of foam-core sandwich panels. in *53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference 20th AIAA/ASME/AHS Adaptive Structures Conference 14th AIAA*. 2012.
- [7] Feli, S. and M. Mahdipour Jalilian, Three-dimensional solution of low-velocity impact on sandwich panels with hybrid nanocomposite face sheets. *Mechanics of Advanced Materials and Structures*, 2017: p. 1-13.
- [8] Mirzapour, A., M.H. Beheshty, and M. Vafayan, The response of sandwich panels with rigid polyurethane foam cores under flexural loading. *Iranian polymer journal*, 2005. 14(12): p. 1082-1088.
- [9] Sharaf, T., W. Shawkat, and A. Fam, Structural performance of sandwich wall panels with different foam core densities in one-way bending. *Journal of Composite Materials*, 2010. 44(19): p. 2249-2263.
- [10] SHARAF, T., Flexural behaviour of sandwich panels Composed of polyurethane core and GFRP skins and ribs. 2010.
- [11] Sharaf, T. and A. Fam, Experimental investigation of large-scale cladding sandwich panels under out-of-plane transverse loading for building applications. *Journal of Composites for Construction*, 2010. 15(3): p. 422-430.
- [12] Sharaf, T. and A. Fam, Numerical modelling of sandwich panels with soft core and different rib configurations. *Journal of Reinforced Plastics and Composites*, 2012. 31(11): p. 771-784.
- [13] Mostafa, A., K. Shankar, and E. Morozov, Behaviour of PU-foam/glass-fibre composite sandwich panels under flexural static load. *Materials and Structures*, 2015. 48(5): p. 1545-1559.
- [14] Berggreen, C., B.C. Simonsen, and K.K. Borum, Experimental and numerical study of interface crack propagation in foam-cored sandwich beams. *Journal of composite materials*, 2007. 41(4): p. 493-520.
- [15] Tuwaira, H., Hopkins, M., Volz, J., A.ElGawady, Mohame, M., Evaluation of sandwich panels with various polyurethane foam-cores and ribs. *Composites Part B: Engineering*, 2015. 79: p. 262-276.
- [16] Kakroodi, A.R., Khazabi, M., Maynard, K., Sain, M. and Kwon, O., Soy-based polyurethane spray foam insulations for light weight wall panels and their performances under monotonic and static cyclic shear forces. *Industrial Crops and Products*, 2015. 74: p. 1-8.
- [17] Garrido, M., J.R. Correia, and T. Keller, Effects of elevated temperature on the shear response of PET and PUR foams used in composite sandwich panels. *Construction and Building Materials*, 2015. 76: p. 150-157.
- [18] Garrido, M., Creep of Sandwich Panels with Longitudinal Reinforcement Ribs for Civil Engineering Applications: Experiments and Composite Creep Modeling. *Journal of Composites for Construction*, 2016: p. 04016074.
- [19] Garrido, M., J.R. Correia, and T. Keller, Effect of service temperature on the shear creep response of rigid polyurethane foam used in composite sandwich floor panels. *Construction and Building Materials*, 2016. 118: p. 235-244.
- [20] George, T., Hybrid core carbon fiber composite sandwich panels: Fabrication and mechanical

- response. *Composite structures*, 2014. 108: p. 696-710.
- [21]Abdi, B., Azwan, S. and Li, X., Flatwise compression and flexural behavior of foam core and polymer pin-reinforced foam core composite sandwich panels. *International journal of mechanical sciences*, 2014. 88: p. 138-144.
- [22]Yanes-Armas, S., J. de Castro, and T. Keller, Long-term design of FRP-PUR web-core sandwich structures in building construction. *Composite Structures*, 2017.
- [23]Mohamed, M., S. Anandan, Z. Huo, V. Birman, J. Volz and K. Chandrashekhara, Manufacturing and characterization of polyurethane based sandwich composite structures. *Composite Structures*, 2015. 123: p. 169-179.
- [24]Mostafa, A., K. Shankar, and E. Morozov, Effect of shear keys diameter on the shear performance of composite sandwich panel with PVC and PU foam core: FE study. *Composite Structures*, 2013. 102: p. 90-100.
- [25]Sharafi, P., Nemati, S., Samali, B., Aliabadizadeh, Y. and Khakpour, S., Edgewise and flatwise compressive behaviour of foam-filled sandwich panels with 3-D high density polyethylene skins. *Engineering Solid Mechanics*, 2018. 6(3): p. 201-208.
- [26]Sharafi, P., Nemati, S., Samali, B., Aliabadizadeh, Y. and Khakpour, S., Flexural and shear performance of an innovative foam-filled sandwich panel with 3-D high density polyethylene skins. *Engineering Solid Mechanics*, 2018. 6(2): p. 113-128.
- [27]Sharafi, P. and Samali, B., Interlocking system for enhancing the integrity of multi-storey modular buildings. *Automation in Construction*, 2018. 85: p. 263-272.
- [28]Nemati, S., Sharafi, P., Samali, B. and Aliabadizadeh, Y., Non-reinforced foam filled modules for rapidly assembled post disaster housing. *International Journal of GEOMATE*, 2018. 14(45): p. 151-161.
- [29]Nemati, S., M. Rashidi, and B. Samali, Decision Making On The Optimised Choice of Pneumatic Formwork Textile for Foam-Filled Structural Composite Panels, *International Journal of GEOMATE*, 2017. 13(39): p. 220-228.
- [30]ASTM, Standard Specification for Rigid Foam for Use in Structural Sandwich Panel Cores. E1730, 2015.
- [31]P Sharafi., Identification of Factors and Multi-Criteria Decision Analysis of the Level of Modularization in Building Construction. *ASCE Journal of Architectural Engineering-Special Collection on Housing and Residential Building Construction*, 2018. (accepted).
- [32]Sharafi, P., Samali, B., Ronagh, H. and Ghodrat, M., Automated spatial design of multi-story modular buildings using a unified matrix method. *Automation in Construction*, 2017. 82: p. 31-42.
- [33]Sharafi, P., L.H. Teh, and M.N.S. Hadi, Conceptual design optimization of rectilinear building frames: A knapsack problem approach. *Engineering Optimization*, 2015. 47(10): p. 1303-1323.
- [34]ASTM, Standard Test Method for Response of Rigid Cellular Plastics to Thermal and Humid Aging. Test Method D2126, 2015.