Journal of Architectural Design and Construction Technology
Volume 3 | Issue 1

Research Article Open Access

Behavior of Polyhedral Built-Up Glass Compression Members

Joseph Robert Yost[1], Masoud Akbarzadeh[2], Mohammad Bolhassani[3], Liam Ryan[4], Jens Schneider[5], Philipp Amir Chhadeh[6]

[1] Professor, Villanova University, USA
[2] Assistant Professor, University of Pennsylvania, USA
[3] Assistant Professor, City College of New York, USA
[4] Graduate Student, Villanova University, USA
[5] Professor, Technische Universität Darmstadt, Germany
[6] Research Assistant, Technische Universität Darmstadt, Germany

***Corresponding author:** *Joseph Robert Yost, Professor, Villanova University, USA, E-mail: joseph.yost@villanova.edu*

Citation: Yost JR, Akbarzadeh M, Bolhassani M, Ryan L, Schneider J, Chhadeh PA. (2021) Behavior of Polyhedral Built-Up Glass Compression Members. J Arch Des Cons Tech. 2021;2(3):1-7.

Received Date: August 08, 2021; **Accepted Date:** August 23, 2021; **Published Date:** August 25, 2021

Abstract

This research presents an experimental program executed to understand the strength and stiffness properties of hollow built-up glass compression members that are intended for use in modular construction of all-glass, compression-dominant, shell type structures. The proposed compression-dominant geometric form has been developed using the methods of form finding and three-dimensional graphical statics. This research takes the first steps towards a new construction methodology for glass structures where individual hollow glass units (HGU) are assembled using an interlocking system to form large, compression-dominant, shell type structures thereby exploiting the high compression strength of glass. An individual HGU has an elongated hexagonal prism shape and consists of two deck plates, two long side plates, and four short side plates. In this study, systematic fabrication of an individual HGU is described, including component and overall geometry, methods of glass cutting, and connecting individual glass plates to form the HGU. This is followed by presentation of the experimental program and corresponding strength and stiffness results. The research concludes that individual HGU strength is governed by simultaneous flexural buckling of the deck plates at force levels well in excess of that required for system strength. Strain and deformation measurement clearly shows regions of first order and second order behavior, with a zone of transition between these two regions.

Introduction

Glass is a transparent and brittle material with significant strength in compression and relatively little strength in tension. Therefore, structural systems that are designed as all-compression or compression-dominant can exploit the strength properties of glass to create large transparent open space structural forms. It is proposed that this vision can be achieved by using the methods of form-finding and three-dimensional graphic statics (3DGS) together with assemblies of individual flat plate three-dimensional glass units, referred to as hollow glass units (HGU). The resulting structure system is modular in construction and with an overall geometric form such that force flow through the structure is primarily axial compression and the presence of tensile force is minimal or absent. The use of 3DGS analysis technology and modular construction using assemblies of HGUs is proposed for design and construction of an all-glass pedestrian bridge of 10m span, as is conceptually shown in Fig. 1. The proposed structure is unique in that it exploits the high strength and stiffness of glass in compression allowing for a long span transparent structure that can be assembled or disassembled using the proposed modular construction methodology.

The geometric form of the bridge will ultimately be determined using 3DGS, which is a geometry- based method of structural analysis allowing exploration of funicular structural solutions in three dimensions. The method is graphical where loads and geometry of the structure are represented using a form-diagram, and the corresponding member forces are represented in a force-

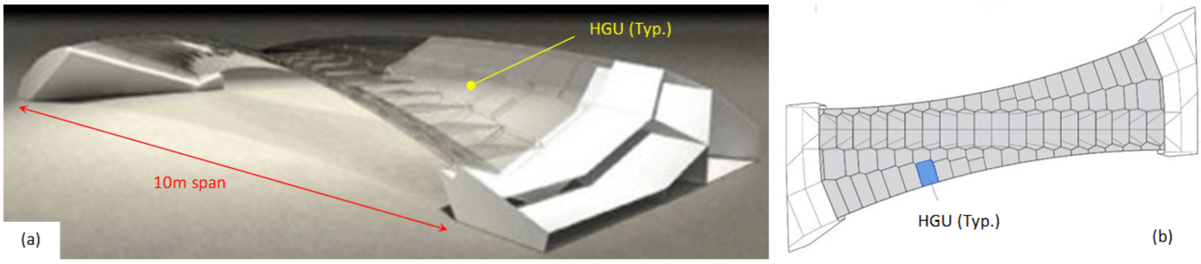

Figure 1: Proposed all-glass pedestrian bridge. (a) Isoparametric view, (b) Plan view

diagram. Using this method, the force-diagram is a collection of polyhedral shapes, the areas of which represent force in the respective members (Bolhassani etal. 2018). The resulting structural forms are polyhedral geometries with planar faces. Importantly, the planarity of the method facilitates the use of flat plate materials such as glass. The proposed compression-dominant geometric form has been developed using the methods of form finding and three-dimensional graphical statics as described in Nejur and Akbarzadeh (2021), Bolhassani, et al. (2018), Akbarzadeh et al. (2015a) and (2015b). Furthermore, a full description of numerical study using finite element method of the proposed 10m span pedestrian bridge can be found in Akbarzadeh et al. (2019).

The HGU represents the fundamental structural component of the proposed building technology. It istherefore necessary to understand its behavior under axial loading, so that the system behavior can be determined. In this research, four individual prototype HGUs are assembled as elongated hexagonal prism fabricated with two deck plates and six side plates. All plates are 10mm thick annealed float glass and a transparent double-sided structural tape is used to connect individual plates to form the HGU. The prototype HGUs are tested in axial compression to establish strength and stiffness properties.

Hollow glass unit detail and fabrication

The prototype hollow glass unit is shown in Fig. 2 and consists of two deck plates, two long side plates and four short side plates. All glass is 10mm thick annealed float glass. Individual plates were cut to the required dimension using a 5-axis abrasive waterjet, with a surface texture corresponding to this cutting technology. Sharp corners were eliminated with a 5mm radius fillet at all corners (Fig. 2). Connections between all glass plates were made using a double sided transparent structural tape manufactured by the 3M Corporation and known as VHB tape (3M, 2020). A total four HGUs were assembled and designated HGUa, b, c, d. Samples HGUa and HGUb were fabricated using 2mm thick VHB tape, and samples HGUc and HGUd were fabricatedusing 1mm VHB tape. All glass surfaces on which VHB tape was placed were degreased using a solution of 50% isopropyl alcohol and 50% water. This was then followed by cleansing with a 3M priming solution Silane Glass Treatment AP115 (3M, 2006), which was used to increase bond strength as well as protecting the bondin high humidity areas.

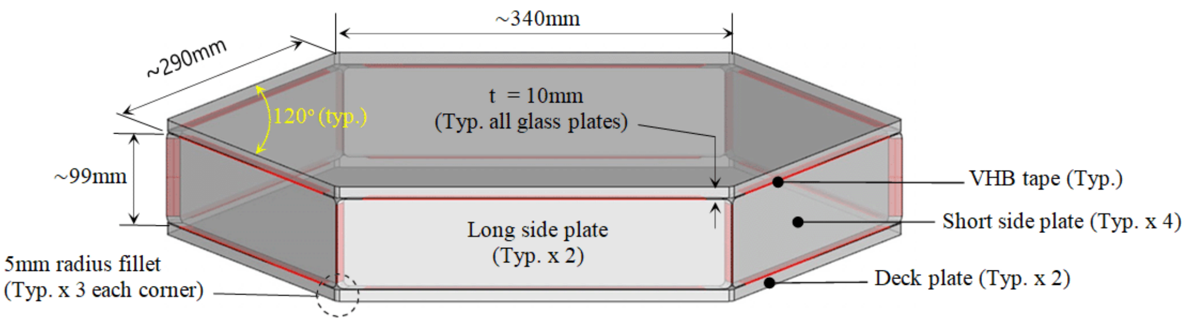

Figure 2: Typical HGU detail

Sample fabrication is shown in Fig. 3 and started with connecting two short side plates to one long side plates, forming a 3-side plate unit (Fig. 3a). Side plate clips, that were 3D printed, were used to ensure the required 120-degree corner angle was maintained. Next two 3-side plate units were connected forming the side-wall unit. Again, side plate clips were used to maintain the required 120-degree corner angle. This was followed by placement of VHB tape on the long dimension of all six side plates in the side-wall unit (Fig. 3c)and placement of the first deck plate. To ensure the deck plate was exactly aligned with the side wall unit 3D printed deck plate clips were used on all six corners of the deck plate as it was lowered onto the side-wall unit (Fig. 3c). Finally, the second deck plate was placed with the HGU inverted (Fig. 3d) and following the same procedure of placement as used with the first deck plate.

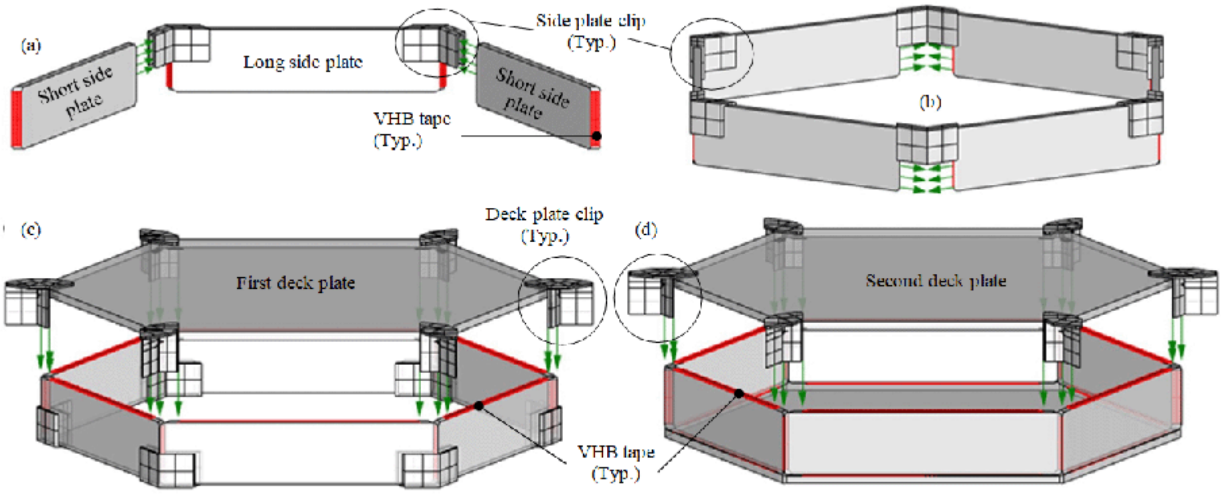

Figure 3: HGU assembly. (a) 3-side plate unit, (b) Side-wall unit, (c) Placement of first deck plate, (d) Placement of second deck plate

To ensure all tape between deck and side plates was securely attached to the glass and no air voids existed at the glass-tape interface, the assembled HGU was then clamped on each deck plate edge using handclamps and dimensional lumber to uniformly distribute the clamping pressure along the tape length. This procedure is shown in Fig. 4a and b, and a fully assembled HGU is shown in Fig. 4c. It should be noted that as a consequence of the deck plate clips and 5mm corner radius, there existed a void space at all corners where VHB tape was not present, as shown in Fig. 4c.

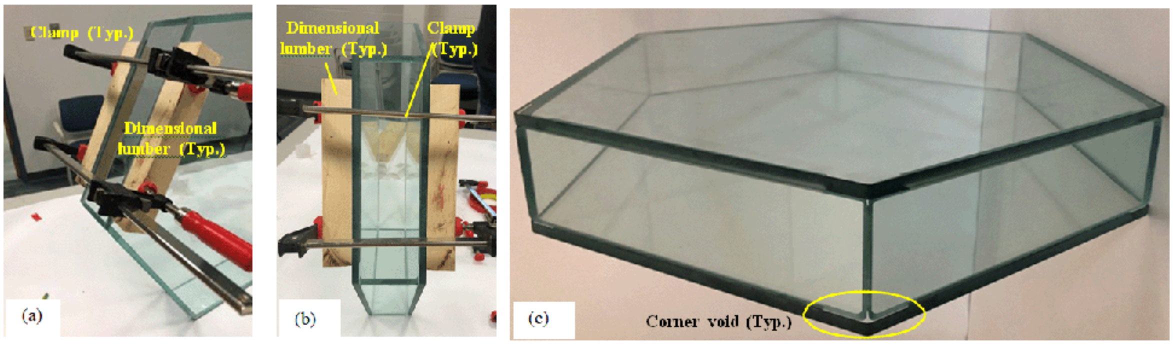

Figure 4: HGU. (a) Clamping procedure, (b) Fully assembled HGU

Experimental program

The experimental program consisted of testing four individual HGUs in axial compression. As mentioned earlier, samples HGUa and HGUb were fabricated with 2mm VHB tape, and samples HGUc and HGUd werefabricated with 1mm VHB tape. For testing the HGU was oriented vertically with load applied in the plane ofthe deck plates along the short side (Fig. 5). This asymmetric load arrangement resulted in an eccentricity between the top and bottom centerlines of 24mm and was intentionally selected as being more critical than a symmetric orientation.

Load was applied to the samples using a servo-hydraulic actuator programed in displacement control at a rate of 0.25mm/minute. The load and support assemblies consisted of steel plates bolted to the actuator swivel and grouted to the laboratory strong floor, as is shown in Fig. 5. To avoid direct contact between the HGU glass and steel plates at the load and support locations, 10mm oriented strand board (OSB) was used as an interface material. This was a critical part of the test setup, and the interface function was to prevent premature cracking on the loaded edges (top and bottom, east and west) of the deck plates resulting from local stress concentrations that would occur at the glass-steel interface. Instrumentation included seven equally spaced deflection sensors located on the vertical centerline of both HGU deck plates (Fig. 5b). Sensors 1-to-7were located on the west deck plate, and sensors 8-to-14 were located on the east deck plate. Note sensors 4 and 11 are located at the centroid of the west and east deck plates, respectively. These deflection sensors measured deformation perpendicular to the plane of the deck plate, representing buckling deformation. Also, a 90-45-0 strain rosette was located at the centroid of each deck plate and on the outside glass surface. Actuator force, deformations and strains were acquired using a 16-bit data acquisition system at a rate of 10 Hz.

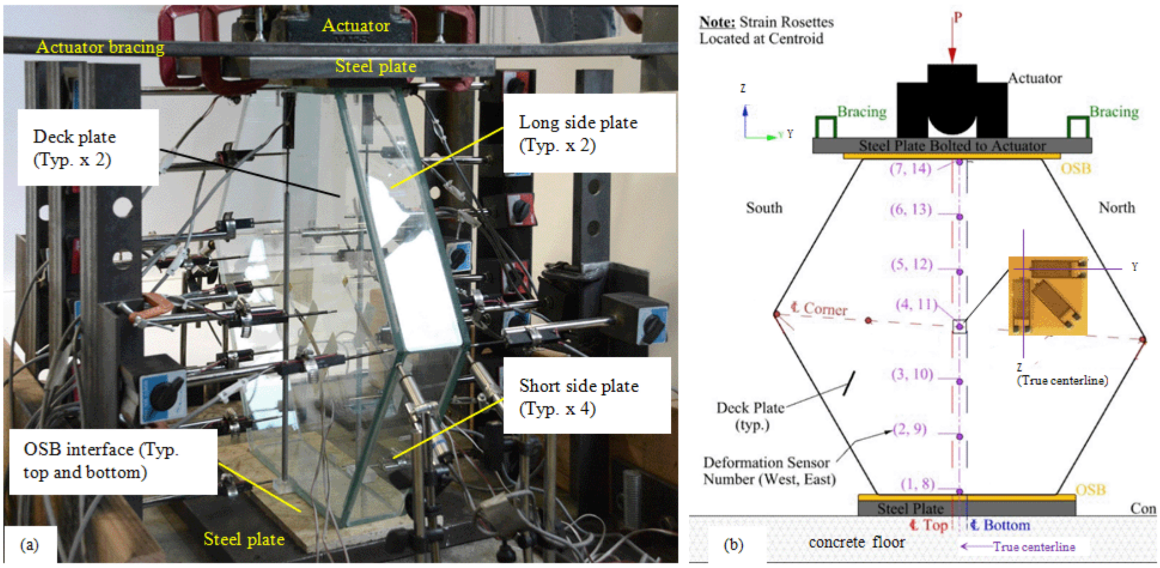

Figure 5: Experimental setup. (a) Photo, (b) Detail

Test results

Typical results are shown using sample HGUb in Fig. 6a in the form of applied force vs. center deck plate deflection (i.e., deformation sensors 4 and 11 in Fig. 5b), and in Fig. 6b as applied force vs. center deck plate vertical strain. In Fig. 6a, deflection is positive for 'push', which corresponds displacement towards the sensor, and negative for 'pull', where displacement is directed away from the sensor. Also, note that vertical strain has direction Z in Fig. 5b, and responds directly to axial force and y-axis bending due to flexural buckling. Time elapsed photos of the HGUb test from start to post failure are shown in Fig. 7.

The observed behavior can be represented by three characteristic regions related to axial force and eccentricity. First, in the force range between zero and about 150 kN, axial force behavior is noted as dominant. This is identified in Fig. 6a by the very small amount of lateral deformation on both the east and west deck plates. The axial dominant condition is perhaps better represented in the applied force vs. vertical strain results of Fig. 6b. Here it is noted that the strains increase in compression at a linear rate and are approximately equal for both the east and west deck plates. This represents equal force distribution to each deck plate and a strain increase in compression that is simply related to axial force divided by glass cross-sectional area. This axial dominant behavior transitions rapidly to an eccentric axial region between about 150 and 180 kN. In this force span Fig. 6a shows nonlinear behavior with an increasingly accelerating deflection rate. It is noted that the east and west deflections are approximately the same but with directions pull and push, respectively. This means that both deck plates are deforming (i.e., buckling) in the same direction, which for sample HGUb is towards the west. It is noted that on the outside surface of the deck plates, when deformation is push, strain associatedwith bending is tension and for pull displacement, bending strain is compression. This is exactly the behaviornoted in Fig. 6b, where strains on the east and west deck plates trend in opposite directions for loads in excess of 150 kN. For the east deck plate (in 'pull') axial force and bending strains are both compression and add. For the west deck plate (in 'push'), axial force and bending strains are compression and tension, respectively, and subtract. Eventually the eccentric axial region transitions to an impending failure region where deformation and strain increase rapidly with little increase in applied load. Eventually the deck plates fail as a consequence of cracking from flexural buckling and associated tensile stresses resulting from force eccentricity and second- order bending. Load at failure was 185 kN, deflection was about 5mm and vertical strain in tension and compression was 385 and -1,100 microstrain, respectively. Importantly, at failure no debonding of the VHB tape between deck and side plates was noted, and all side plated remained in an uncracked condition. Also, the OSB interface between the steel load and support plates and the loaded edge of the HGU deck plate glass was effective in preventing cracking on the glass bearing surface. Bearing stress at failure on the glass loaded edge was about 35 MPa.

Test results at the maximum condition for all four HGU samples are provided in Table 1. As is notedall samples failed explosively in the same way by flexural buckling and load at failure ranged from 165 to 202 kN, with no clear trend between 1mm VHB tape (samples HGUc and HGUd) and 2mm VHB tape (samples HGUa and HGUb). For all samples both deck plates buckled in the same direction, which was west for HGUa,b,c and east for HGUd. Furthermore, there was no cracking on the loaded edge of any HGU deck plates and bearing stress at this location ranged from 31 to 38 MPa. These bearing stress results are very important, and represent a target that must be achieved by an appropriate interface material if the flexural buckling capacity of the HGU is to be achieved (as was done in this experimental program using OSB). Vertical tensile strains ranged from 304 to 542 microstrain and in compression between -1,014 and -1,213 microstrain. These maximum strains are the result of axial force and second order bending, with the latter contributing a

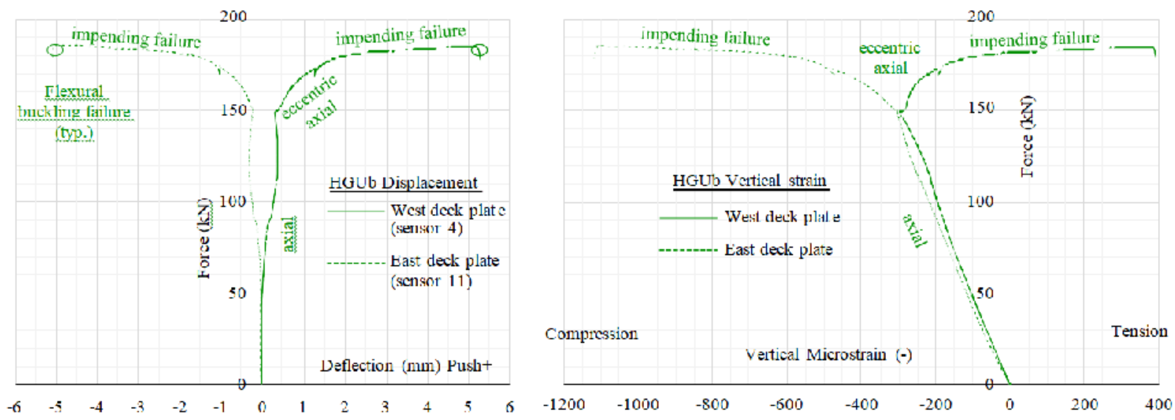

Figure 6: HGUb test results at deck plate centroid.
(a) Force vs. deformation, (b) Force vs. vertical strain

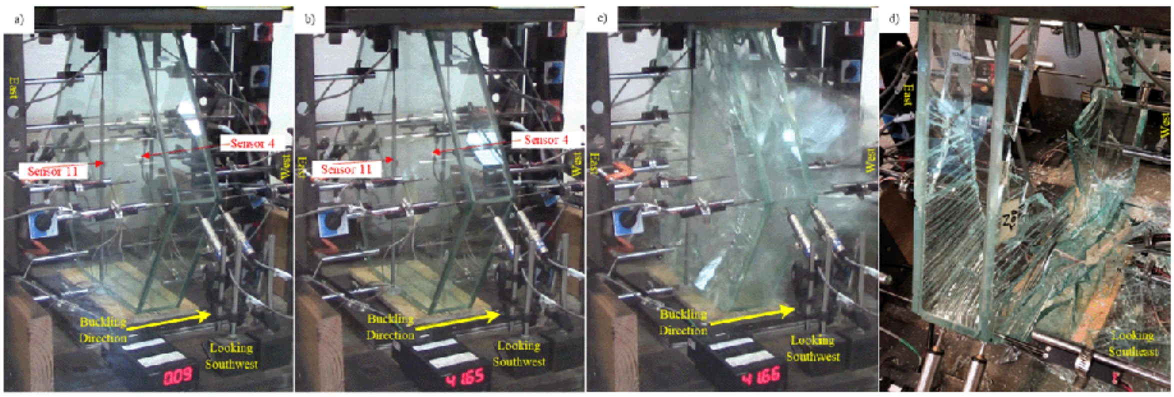

Figure 7: HGUb test to failure. (a) Test start, (b) 100% Load, (c) Failure, (d) Post failure

larger amount to the total. Transverse deflection related to flexural buckling was significant and ranged between 4.7and 6.7mm. Normalized relative to the HGU height of 566.5mm, the ratio of height to maximum buckling displacement ranges between 85 and 120.

Table 1: Summary of maximum test results

Sample (ID)	Failure limit state	Load (kN)	Deflection (mm)	Tesnile strain (µ)	Comp. strain (µ)	Bearing stress (Mpa)
HGUa	Flexural buckling	165	4.7	304	-1,014	31.0
HGUb		185	5.25	385	-1,109	34.8
HGUc		186	6.7	542	-1,213	35.0
HGUd		202	5.35	443	-1,095	38.0

Future research

The strength and stiffness properties on an individual HGU have been presented in this publication. As was shown, the HGU strength capacity as limited by flexural buckling is significant and well in excess of that required for the proposed pedestrian bridge application. However, to achieve the vision of modular construction using assemblies of HGUs it is necessary to develop the connection detail between neighboring HGU parts. This connection must allow for the transfer of axial and shear forces as well as using an appropriate interface material that can allow for the transfer of these forces without any cracking due to local stress concentrations at the glass-interface surface. From the results of this research, this translates to an interface material capable of resisting bearing stresses against glass of between 31 to 38 MPa. Furthermore, the interface material must be transparent to maintain the wholistic transparent clarity of the structural system.

A proposed connection detail is shown in Fig. 8. The side plates have mirrored male and female geometry for the transfer of shear force, and an interface material is proposed through the entire HGU depth to avoid any glass-to-glass contact. The interface must be transparent and form fit to the side plate geometry, and importantly resist bearing stresses of sufficient magnitude so that deck plate cracking associated with local stress concentrations does not occur before the full flexural buckling capacity of the HGU is realized. The interface material actually plays the central role of allowing the individual HGUs to function as a structural system. Importantly, the failure limit state of the global structural system should relate to the HGU strength as a semi rigid three-dimensional frame, with flexural buckling of the deck plates limiting capacity.

The feasibility of the connection detail will be investigated by extensive experimental testing of the interface material (Fig. 9b) followed by construction and testing of a reduced scale bridge, as is hypothetically shown in Fig. 9b.

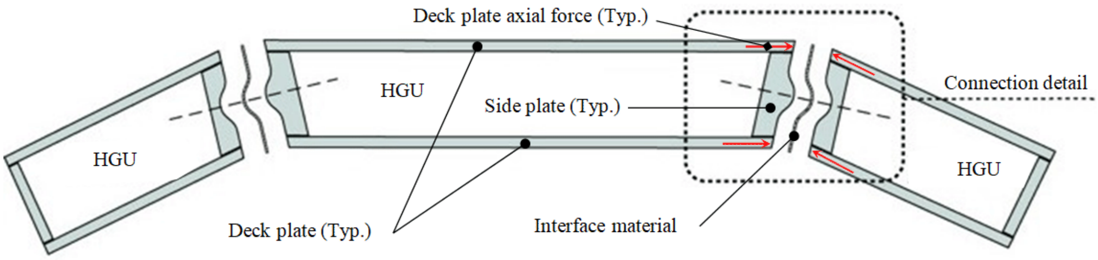

Figure 8: Connection detail between neighbouring HGUs

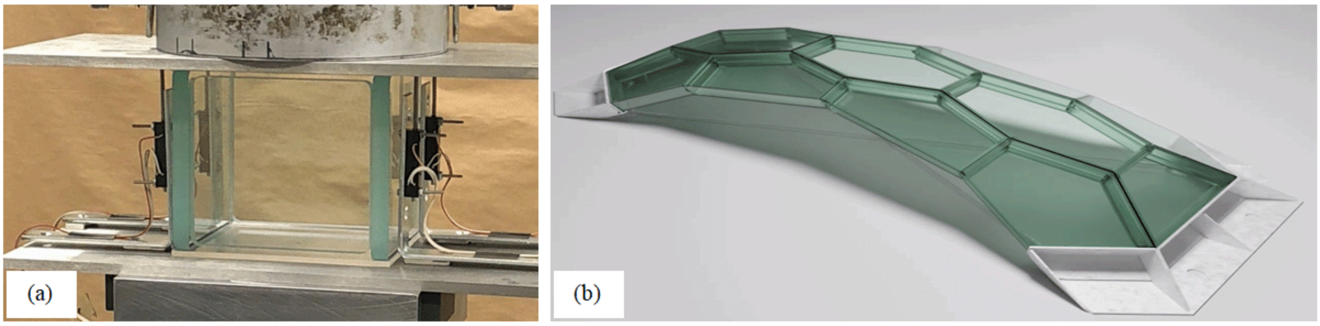

Figure 9: Future testing. (a) Interface material testing, (b) Small scale bridge testing of HGU connection detail

Importantly, the proposed structural assembly of all-glass HGUs to function collectively as a compression dominate shell type structure is not limited in application to the proposed 10m pedestrian bridge. Rather, the efficient exploitation of modular HGUs in compression allows for the construction of large open-space glass structures with limited or absent intermediate column supports. The described methodology of compression-dominate geometric design using 3DGS together with modular assemblies of HGUs hasapplication in a wide variety of structural needs where large span transparent structural systems are desired. It is the vision of this research to fulfill this need.

Conclusions

From the experimental program presented, the following conclusions are offered.

- All samples failed in a flexural buckling mode with both deck plates displacing in the same direction.
- Failure was sudden and explosive, with shattered deck plate glass ejected in the direction of buckling.
- Failure was a consequence of bending deformation related to second-order flexural buckling and associated deck plate cracking resulting from tensile bending stress on the outer fiber of the deck plates.
- Load at failure ranged from 165kN to 202kN.
- There was no real difference in behavior of HGU samples fabricated with 1mm or 2mm VHB tape.
- At failure there was no observable debonding between the glass and VHB tape, and all side plates remained in an uncracked condition.

- Structural behavior can be characterized by three distinct regions: 1) axial (concentric), 2) eccentric axial (2nd order bending), and 3) impending failure (rapid increase is stress/deflection with little force increase).

References

Bolhassani M, Akbarzadeh M, Mahnia M, Taherian R. On structural behavior of a funicular concrete polyhedral frame designed by 3d graphic statics. Structures. 2018;14:56–68.

Akbarzadeh M, Van Mele T, Block P. Spatial compression-only form finding through subdivision of external force polyhedron. In Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium, Amsterdam. 2015.

Akbarzadeh M, Van Mele T, Block P. On the equilibrium of funicular polyhedral frames and convex polyhedral force diagrams. Computer-Aided Design. 2015;63:118–128. doi: 10.1016/j.cad.2015.01.006

Akbarzadeh M, Bolhassani M, Nejur A, Yost JR, Byrnes C, Schneider J, Knaack U, Borg Costanzi C. The Design of an Ultra-Transparent Funicular Glass Structure. Proceedings American Society of Civil Engineers Structural Engineering Institute Annual Conference, Orlando, FL. USA. 2019.

Nejur A, Akbarzadeh M. Polyframe, efficient computation for 3d graphic statics. Computer- Aided Design. 2021;134:103003.

3MTM. 3mTM VHBTM structural glazing tape. multimedia.3m.com/mws/media/1267925O/vhb-tape- specialty-tapes.pdf. 2020.

3MTM. 3mTM VHBTM silane glass treatment. multimedia.3m.com/mws/media/413153O/silane-glass- treatment-ap115.pdf. 2006.