Dry interlayers out of cast polyurethane rubber for interlocking cast glass structures experimental exploration and validation

Oikonomopoulou, Faidra; Bristogianni, Telesilla; Barou, Lida; Veer, Fred

DOI
10.1201/9780429426506-295

Publication date
2019

Document Version
Accepted author manuscript

Published in
Advances in Engineering Materials, Structures and Systems: Innovations, Mechanics and Applications

Dry interlayers out of cast polyurethane rubber for interlocking cast glass structures: experimental exploration and validation

F. Oikonomopoulou, F. Veer
TU Delft, Faculty of Architecture, Department of Architectural Engineering + Technology

T. Bristogianni, L. Barou
TU Delft, Civil Engineering and Geosciences, Structural Engineering Department

ABSTRACT: A novel, reversible structural system comprising interlocking, dry-assembled cast glass components is currently being developed at the TU Delft Glass & Transparency Lab. This paper, in continuation of the research conducted by (Oikonomopoulou et al. 2018a), investigates the mechanical properties of different materials that function as dry interlayers for interlocking cast glass structures. The interlayers should be preferably transparent, able to be pre-formed to the desired shapes, and resistant to UV-radiation-induced colour shifts, long-term compressive loads and creep. Based on the above criteria, polyurethane (PU) rubber with a shore hardness between 60A - 80A is chosen as the most suitable material. Accordingly, different readily available PU interlayers are selected and cast in the desired shape. Each interlayer is introduced between two interlocking osteomorphic cast glass components (bricks) and the assembly is tested under compression in series of 3 specimens. The experiments indicate that for the harder interlayer variants, failure mainly occurs due to peak stresses occurring at the shortest section of the brick, where the manufacturing tolerances of the concave-convex surface are the highest, leading to mismatch, i.e. incomplete contact at that area of the interlayer with the glass units. The stiffer interlayers further contribute to the failure due to the increased shear stresses induced at the edges of the interlocking surface while they are deforming. This is evident by the radial breaking pattern of the failed glass blocks. Interlayer variants with low tear resistance fail due to the perforation of the interlayer leading to glass-to-glass contact. Still, all specimens with interlayer in between presented a considerably higher failure stress than an assembly with no interlayer, highlighting the critical contribution of the PU to the structural performance of the system.

1 INTRODUCTION

The structural use of cast glass components in architecture remains at present a largely unexplored field. Yet, applications such as the *Atocha Memorial (Schober et al. 2007)*, *the Optical House (Hiroshi 2012)* and the *Crystal Houses façade* (Oikonomopoulou et al. 2015) exhibit the great potential of this production method for attaining 3-dimensional all-glass structures. Currently there are two realized building systems employing cast glass components: either a metal substructure is employed or the glass blocks are adhesively bonded with a rigid, colourless adhesive. Whereas the first solution compromises transparency, the second results into a permanent, irreversible and non-recyclable construction. Moreover, multiple engineering challenges occur in the construction due to the extreme dimensional accuracy required for achieving an adhesively-bonded transparent structure of satisfactory visual and structural performance (Oikonomopoulou et al. 2017).

A novel system out of dry-stacked interlocking cast glass components has been introduced by (Oikonomopoulou et al. 2018b) that tackles the drawbacks of both previous systems: It avoids the use of adhesives, while allowing for a reversible full-glass structure; eventually the components can be retrieved intact and reused or recycled. Furthermore, towards an enhanced circularity of the system, the possibility of using glass waste for the manufacturing of the components (fig.1) has been explored by (Bristogianni et al. 2018).

Two key features guarantee the successful structural performance and integrity of the system:

- the *interlocking geometry* of the components, essential for attaining the desired stiffness and stability.
- the application of *a dry interlayer* as intermediary, to compensate for dimensional discrepancies and surface micro-asperities and allow for a homogeneous load distribution and an easy assembly and disassembly process.

Various interlocking geometries for solid cast glass components have already been explored by the authors in (Oikonomopoulou et al. 2018a) concluding that osteomorphic blocks (Figure 1), such as described by (Molotnikov et al. 2007) are the most promising shape for the further validation of the system.

Figure 1: Prototype made by the authors of osteomorphic blocks out of recycled glass waste exhibited at the Dutch Design Week 2018.

This paper comes in continuation of the research described by (Oikonomopoulou et al. 2018b) and focuses on the design criteria and selection of the dry interlayer material for the osteomorphic interlocking assembly (similar to Figure.1).

2 DESIGN CRITERIA FOR THE DRY INTERLAYER

Due to the inability of glass to deform plastically, any unevenness at the contact surface of the components can yield local high tensile stresses, even when the interlocking glass structure is loaded in compression. The brittle nature of glass can respond to such peak stresses with crack propagation and eventual failure, compromising the overall strength of the interlocking assembly. This has been well demonstrated by the results of axial compressive tests performed on soda-lime cast glass blocks by (Oikonomopoulou et al. 2015): Solid cast components tested in compression presented obvious cracks in a nominal compressive stress between 20 – 30 MPa, when the glass came in direct contact with the steel surfaces of the testing machine. In comparison, specimens where a softer intermediary was introduced between steel and glass presented a considerably higher nominal compressive strength, of at least 135 MPa.

Accordingly, a resilient (dry) interlayer between the glass blocks is essential for their structural application. The interlayer can accommodate surface asperities by deformation and can evenly redistribute the stresses across the contact area. Indeed, (Dyskin et al. 2001) and (Estrin et al. 2015) confirm that the ductility and the fracture toughness of interlocking assemblies out of brittle components can be improved if the interlocking components are interleaved with soft, rubber-like polymers.

For a contact application as the one examined, the hardness[1] and tear resistance of the interlayer are considered the most important parameters for choosing the material. To allow for an even load distribution, it is crucial that the interlayer material is neither too flexible nor too stiff. The interlayer should be stiff enough to avoid penetration, yet sufficiently flexible so that it can adapt to the micro-asperities of the glass surface. For common polymer and rubber materials the hardness is expressed through the durometer shore hardness scale, which essentially measures the resistance of a material to indentation. Fig.2 provides an illustration of the two most common shore hardness scales (A, D), ranging from very soft, flexible rubbers to semi-rigid and rigid plastics. The shore scale index of common applications is as well indicated as a comparative guideline.

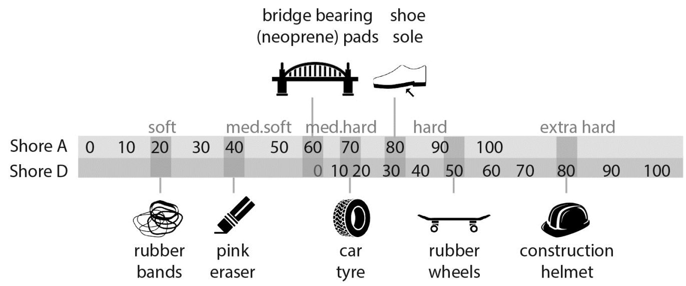


Figure 2: Diagram of the shore hardness scales, indicating as well the shore hardness of common objects.

From Figure 2 it can be directly deducted that for the discussed application an interlayer material with a shore hardness between 60A – 80A/50D seems to be the most suitable. Interlayers softer than 60A are expected to easily creep under compression, whereas interlayers with a shore hardness higher than 80A will be too stiff, preventing an even spread of the stresses by deformation.

Another important factor for consideration is that the interlayer should be able to resist constant compressive loads without creeping. As a first estimation, the surfaces of the interlayer and glass should be in full contact before reaching an average compressive stress of 20 MPa, for preventing the early failure of the assembly, as suggested by the experimental work of (Oikonomopoulou et al. 2015).

Finally, for good contact, the material should be able to be shaped into the particular interlocking shapes of the glass blocks with an accurate, constant thickness. In this direction, the interlayer's thickness plays a crucial role in the overall performance as well. A thickness of min. 2 mm is proposed to accommodate dimensional tolerances. In general, the interlayer material should be as thin as possible, as thicker interlayers compromise the stiffness of the assembly. Summing up these properties, the follow-

[1] Unlike the Young's Modulus, hardness shows size dependence in materials with near surface hardness being different from bulk hardness.

ing requirements are considered for the selection of the interlayer:

- Shore hardness between 60A - 80A.
- Compressive strength ≥20 MPa
- Good creep resistance and controlled deformation under static long-term compressive load
- Ability to be pre-formed in a consistent thickness (t_{int}) in the desired shapes
- 2 mm ≤ t_{int} ≤ 4 mm
- Transparency and durability to UV-lighting
- Water resistant
- Service temperature between -20 °C and +50 °C
- Fire-resistant

According to *CES Edupack 2015* program (Granta Design Limited 2015) the following thermoplastic and elastomer polymers, listed in Table 1, fulfil the above-mentioned criteria:

- PEBA – Polyether block amide
- PU - Polyurethane (rubber/cast)
- PVC – Polyvinyl Chloride (soft)
- TPU – Thermoplastic polyurethane

Table 1: Mean properties of the selected material families by (Granta Design Limited 2015)

Material	PEBA	PVC	PU	TPU
Poisson's ratio	0.48	0.47	0.48-0.50	0.49
Yield Strength [MPa]	34	19-20	25-51	38-50
Transparency	clear	clear	clear	clear
UV-resistance	fair	fair	fair	fair
Flammability	Slow burning	Slow burning	Slow burning	Slow burning

These materials can be processed to the desired shape either by injection moulding or extrusion. The mean properties of the chosen material families can be seen in Table 1. From these, PU, PVC and TPU have already been applied in the building industry and are considered the most promising candidates. Experimental work by (Aurik et al. 2018) on a vertical assembly of dry-stacked rectangular cast glass blocks with PV), PU 70 Shore A (PU70) and PU 90 Shore A (PU90) interlayers as intermediary, each tested in 1,2,3 and 4 mm thick variants, has indicated that:

- The thicker interlayer variants (3-4 mm) allow for a more homogeneous spread and an increased stiffness. Essentially the interlayer becomes stiffer as the contact area increases.

- Under compression, the PVC interlayers achieve a more homogeneous contact area compared to the PU ones, due to high lateral deformation of the material. PU interlayers behave as more stiff materials and do not spread so evenly upon pressure and thus are considered more sensitive to failure due to surface imperfections than PVC. PU90, which is the stiffest material, does not achieve full contact with the glass surface. The thicker variants of PU70 present an almost complete contact area under pressure.

- PVC's performance is strongly time-dependent and creep occurs under static loads. PVC interlayers of 3 and 4 mm thickness were flowing out of the edge during compression. On the contrary, PU remains relatively stable over time.

- After removing the load, the residual deformation of the PVC interlayer remains considerable, whereas PU interlayers restore their thickness relatively quick.

Table 2: Material properties used by (Aurik et al. 2018)

Property	Unit	PVC	PU70	PU90
Shore-hardness	Shore A	80 (±5)	70 (±5)	90 (±5)
Tensile resistance	N/mm^2	16	≥ 40	≥ 45
Elongation at break	%	340	≥ 550	≥ 575

Although in the specific tests, PVC achieves a more homogeneous and consistent contact area than PU, it is considered unsuitable for this research due to its considerable creep under pressure and marginally acceptable yield strength (see Table 1).
As a good compromise, for this research it is concluded that a PU interlayer is most fitting. Despite the fact that the tested PU specimens showed a comparatively non-homogeneous load distribution, they exhibited good creep-resistance and stable stiffness.
According to the experimental work by (Aurik et al. 2018) and the established design criteria, a thickness of 3-4 mm proved the best for allowing a consistent contact area while absorbing surface irregularities. This minimum acceptable interlayer thickness is preferred over thicker variants that can further compromise the stiffness of the interlocking assembly.
Lastly, PU interlayers with a shore hardness between 60A - 80A are considered to be the best candidates, as stiffer interlayers (such as PU90) fail to achieve complete contact under pressure even with cast glass surfaces flat to a precision of ±0.25 mm (Aurik et al. 2018).

3 EXPERIMENTAL TESTING

3.1 *Prototype Manufacturing*

Based on the above, readily available PU interlayers with a shore hardness between 60A - 80A were sought that could be cast in the desired shape. Table 2 gives an overview of the selected interlayer materials for the experimental validation of the system. Due to practical reasons (availability of materials in the Netherlands as resins, etc.) some of the selected interlayers do not meet the transparency criteria. Even so, at this research stage the most crucial factor to examine is the most favorable shore hardness of the interlayer and thus, non-transparent interlayers were also considered when no alternative could be found.

Table 2: Properties of a selection of cast PU interlayers available in the market as provided by the manufacturer.

Material	Shore Hardness	Break El. %	Tensile Strength MPa	Die C tear strength N/mm	Colour
PMC 746	60A	650	4.8	17.5	Transl. amber
PMC 770	70A	750	5.2	35.1	Transl. amber
Permacol 5450	75A/ 25D	unk	unk	unk	Clear
Task 16	80A/ 30D	233	15	34.5	Light yellow

A two-part 3d printed mould out of polylactic acid (PLA) was used for casting each PU resin to a constant 3 mm thick interlayer matching the osteomorphic geometry of the blocks. Each specimen was manually poured into the mould and was left to cure for 24 h prior to removal.
Each interlayer was placed between two half osteomorphic glass blocks to be tested in compression (see Figure 3). The latter were kiln-cast at the TU Delft Glass & Transparency Lab, using disposable Crystalcast M248 moulds. Schott B270 modified soda-lime silica glass was employed for the production of the glass components. The bottom face and the side face from where the glass was poured into the moulds were ground and polished up to 400 grit. There was no post-processing on the other 4 sides of the blocks, including the interlocking surface. It should be noted that the interlocking surfaces presented more than 3 mm deviation at their middle. A *Dremel* rotary tool with diamond pad was used to round the edges of the interlocking mechanism.

3.2 *Compression tests*

Figure 3 shows the typical set-up of the experiment. All specimens were tested under compression in a *Zwick Z100* universal testing machine at a rate of 250 kN/s. A max. load was set (between 40-60 kN), after which the load is maintained constant for 900 s (15 min). Each interlayer material was tested in a series of 3 specimens in order to be able to derive statistical data. The specimens have been named according to their shore hardness. 3 mm thick neoprene interlayers were placed between the steel plates of the machine and the glass assembly to prevent the failure of the system due to peak tensile stresses from the direct contact of glass with steel. It should be noted that the neoprene is anticipated to have an influence on the graphs of total deformation and creep performance.

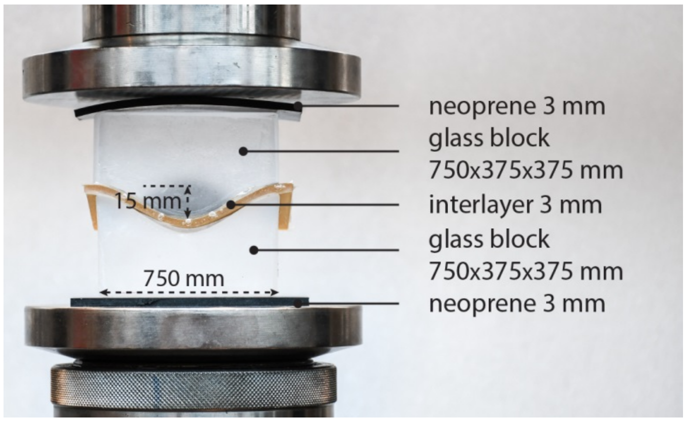


Figure 3: Experimental set-up.

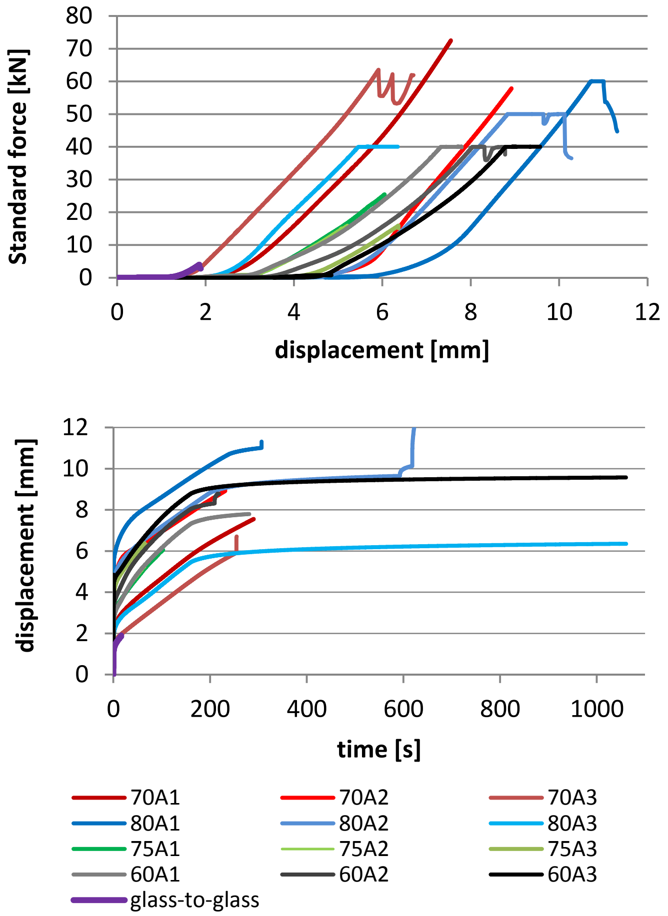
In order to evaluate the contribution of the interlayer to the structural performance of the interlocking system, an assembly of two glass blocks without interlayer in between was also tested in compression.
Graphs 1 and 2 give the force vs displacement and displacement vs time curves of all tested specimens respectively. Table 3 summarizes the main results.

Table 3: Summary of experimental results.

Specimen	$F_{max\ set}$	$F_{fail.}$	u_{atmaxF}	u_{max}	T_{creep}	Failure mode
	kN	kN	mm	mm	s	
$70A_1$	-	72.5	-	7.55	-	(a), (i)
$70A_2$	-	57.8	-	8.9	-	
$70A_3$	-	63.5	-	6.7	-	
$80A_1$	60	60	10.7	11.3	66	(a), (ii)
$80A_2$	50	50	8.8	16.3	426	
$80A_3$	40	40	5.45	6.35	900	(c)
$75A_1$	40	25.4†	6	6	-	(b), (i)
$75A_2$	40	15.9†	5.2	5.2	-	
$75A_3$	40	15.9†	6.4	6.4	-	
$60A_1$	40	40	7.3	7.8	121	(b), (ii)
$60A_2$	40	40	8	8.8	58	
$60A_3$	40	-	8.8	9.5	900	(c)
glass	40	4	-	1.9	-	(i)

(a) Failure of the glass blocks at their shortest section. No tearing of the interlayer observed.
(b) Perforation of the interlayer leading to glass to glass contact.
(c) assembly successfully withstood the max. set load for 900 sec.
(i) failure at increasing load
(ii) failure under creep mode
† Test stopped when visible tearing of the interlayer was observed.

Initially, different max. loads were set for the interlayers. In specific, the first series of specimens, with *PMC 770* (70A) as an interlayer was tested on increasing load until failure. For the rest of the series, different max. loads were set based on the performance of the previous specimen. Accordingly, 40 kN was eventually set as the max. load and then the machine was programmed to maintain this as a constant load for 900 s to evaluate the performance of the interlayer-assembly under creep.



Graph 1(top): Force vs displacement curve of all specimens.
Graph 2(bottom): Displacement in time of all specimens.

In summary, the specimens failed either from:
(a) peak tensile stresses occurring at the shortest section of the block due to insufficient contact with the interlayer, combined with increased shear stresses occurring due to the continuous deformation of the interlayer.
(b) the tearing of the interlayer leading to direct glass-to-glass contact.
In specific, specimens interleaved with *PMC 770* (70A) and *Task 16* (80A) failed due to peak tensile stresses at the middle of their concave (shorter) section with a consistent Y breaking pattern, with the tip of the crack always originating at the apex of the concave (and shorter) section (see Figure 4). The peak stresses are anticipated to have been caused by an insufficient contact of the interlayer at that area due to the increased manufacturing tolerances of the kiln-cast components. The shear stresses occurring in the plane of the interlayer due to its increasing deformation further contributed to failure (Figure 5), as was evident especially for the specimens which failed when loaded under constant load.

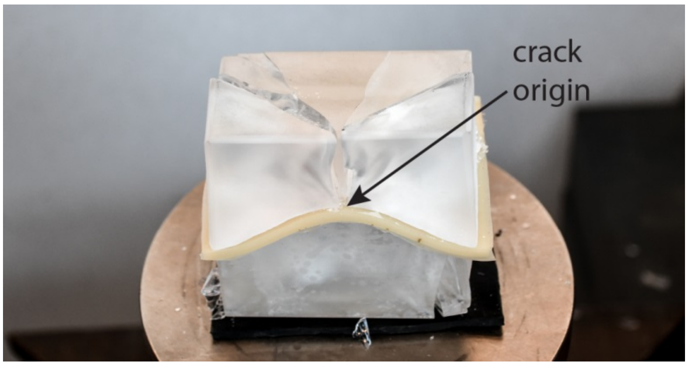


Figure 4: Typical Y breaking pattern, originating at the shortest section of the block (specimen 80A$_1$)

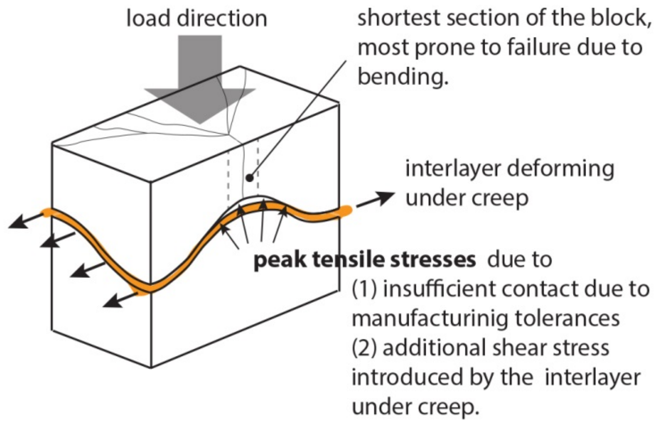


Figure 5: Possible explanation of the cause of failure of the specimens interleaved with PMC770 (70A) and Task16 (80A).

The assemblies interleaved with *Permacol 5450* (75A) and *PMC 746* (60A) failed due to the tearing of the interlayer which lead to glass-to-glass contact. The *Permacol 5450* tests were interrupted once visible perforation of the interlayer was noticed. The interlayer was always first torn at the sharpest edges of the interlocking blocks as can be seen in Figure 6.
The only specimens that completed the testing without cracking were specimen 80A$_3$ and specimen 60A$_3$. From these, specimen 60A3 reached an almost stable deformation during the constant 40kN testing.

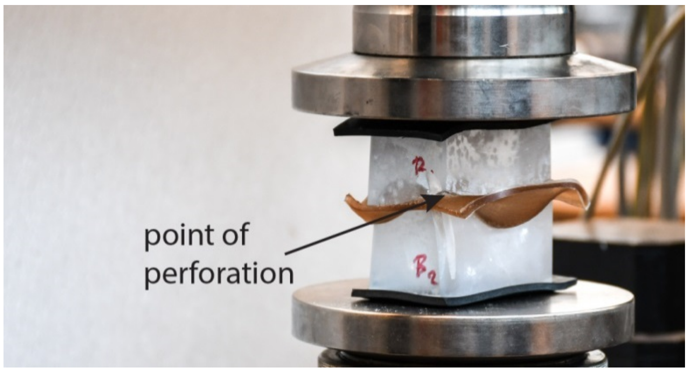


Figure 6: Typical failure at the edge of the assembly caused by the perforation/tearing of the interlayer (specimen 60A$_1$)

Finally, in comparison to the specimens with interlayer in-between, the specimen with direct glass to glass contact failed at a considerably lower load of just 4 kN, at the sharpest edge of the assembly, similar to the specimens that failed due to tearing of the interlayer (Figure 7). This highlights the necessity of a soft-interlayer for enhancing the structural performance of the assembly.

Figure 7: Failure of glass specimen without interlayer used.

4 CONCLUSIONS

Series of three specimens out of kiln-cast glass interlocking blocks interleaved with different cast PU interlayers were tested under compression up to a max. set load; upon reaching that value the load was set to be constant for 900 sec. The specimens failed due to peak tensile stresses occurring either because of:

(1) the penetration of the interlayer and the eventual glass-to-glass contact at lower stress values or

(2) insufficient contact of the interlayer at the concave-convex interlocking area of the blocks, combined with the shear stresses occurring at the interlocking surface due to the increasing deformation of the interlayer under constant or increasing load.

Although in most tests the assembly reached the maximum set load without cracking, the continuous deformation of the interlayer introduced further tensile stresses that eventually lead to failure.

Therefore, the creep and tear resistance of the interlayer and the manufacturing tolerances of the components are of crucial importance to the structural performance of the interlocking assembly.

The geometry of the interlocking system is equal or more critical to the interlayer used. As the experiments demonstrated the sharp inclination at the edges of the assembly can lead to the local perforation of (some of) the interlayers and lead to early failure of the assembly due to glass-to-glass contact. Thus, smoother curves along the interlocking surfaces are preferred.

Another conclusion regarding the interlocking geometry derived from the tests is that the more excessive the amplitude of the interlocking system, the more prone is the assembly to manufacturing intolerances and thus to the introduction of peak tensile stresses because of insufficient contact (mismatch) and collaboration between the interlayer and the glass units. This can be improved either by introducing a thicker interlayer (4-5 mm), which however would further compromise the stiffness of the assembly or by a smoother interlocking mechanism of reduced wave amplitude.

In conclusion, interlayers with low tear resistance, such as *Permacol 5450* and *PMC 746* are considered improper for further investigation. The creep resistance of the interlayer variants with sufficient tear resistance and suitable Shore hardness needs to be further validated under lower load/stress in order to establish design values. Interlayers with a thickness of 4 mm and the redesign of the osteomorphic unit so that it presents smoother curvatures will be also considered for the further improvement of the design.

REFERENCES

Aurik, M., Snijder, A., Noteboom, C., Nijsse, R., Louter, C.: Experimental analysis on the glass-interlayer system in glass masonry arches. Glass Structures & Engineering 3(2), 335-353 (2018). doi:10.1007/s40940-018-0068-7

Bristogianni, T., Oikonomopoulou, F., Justino de Lima, C., Veer, F.A., Nijsse, R.: Structural cast glass components manufactured from waste glass: Diverting everyday discarded glass from the landfill to the building industry. HERON 63 (1/2), 57-102 (2018)

Dyskin, A.V., Estrin, Y., Kanel-Belov, A.J., Pasternak, E.: A new concept in design of materials and structures: Assemblies of interlocked tetrahedron-shaped elements. Scripta Materialia 44, 2689-2694 (2001)

Estrin, Y., Molotnikov, A., Simon, G.P., Kaloshkin, S., Senatov, F., Maksimkin, A.: Flexible ceramics with self-stiffening capability. In: European Symposium on Intelligent Materials 2015, Kiel, Germany 2015

Granta Design Limited: CES EduPack 2015. In. Granta Design Limited, Cambridge, (2015)

Hiroshi, N.: Optical glass house. Architectural Review (2012)

Molotnikov, A., Estrin, Y., Dyskin, A.V., Pasternak, E., Kanel-Belov, A.J.: Percolation mechanism of failure of a planar assembly of interlocked osteomorphic elements. Engineering Fracture Mechanics 74, 1222-1232 (2007)

Oikonomopoulou, F., Bristogianni, T., Barou, L., Jacobs, E.A.M., Frigo, G., Veer, F.A., Nijsse, R.: A novel, demountable structural glass system out of dry-assembly, interlocking cast glass components. In: Louter, C., Belis, J., Bos, F. (eds.) Challenging Glass 6 : Conferece on Architectural and Structural Applications of Glass, The Netherlands 2018a

Oikonomopoulou, F., Bristogianni, T., Barou, L., Veer, F.A., Nijsse, R.: Interlocking cast glass components, exploring a demountable dry-assembly structural glass system. HERON 63 (1/2), 103-138 (2018b)

Oikonomopoulou, F., Bristogianni, T., Veer, F., Nijsse, R.: The construction of the Crystal Houses facade: Challenges and Innovations. Glass Structures and Engineering(online) (2017). doi: 10.1007/s40940-017-0039-4

Oikonomopoulou, F., Veer, F.A., Nijsse, R., Baardolf, K.: A completely transparent, adhesively bonded soda-lime glass block masonry system. Journal of Facade Design and Engineering 2(3-4), 201-222 (2015). doi:10.3233/fde-150021

Schober, H., Schneider, J., Justiz, S., Gugeler, J., Paech, C., Balz, M.: Innovations with glass, steel and cables. In: Glass Performance Days, Tampere, Finland 2007, pp. 198-201