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Reversible joinery methods for full glass vaults made of cast or 3D printed glass components

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Abstract

Glass's high compressive strength makes it ideal for compressive-only structures such as vaults. Float glass, the most common type in architecture, is limited by its planar form, often resulting in buckling-induced tensile stresses that undermine glass's compressive potential. 3D-printing and casting are alternative fabrication methods that enable the production of volumetric glass components that can better utilize glass's compressive capacity. Due to fabrication limitations, both 3D-printed and cast glass assemblies in building-scale require segmentation, calling for specialized joinery solutions. Existing built projects rely on permanent adhesives. However, towards circular construction, a reversible connection is needed that can transfer the desired loads, enable customization, allow for disassembly, and preserve recyclability. Accordingly, this research investigates two novel, reversible joinery methods for dry-stacked glass vaults composed of either cast or 3D-printed interlocking units: (i) a Velcro-inspired, polymer interlayer, directly 3D-printed onto the glass and (ii) a dry, laser-cut expandable metal interlayer. We first assess the fabrication constraints of cast and 3D-printed glass bricks and their implications for joinery design. The two joinery methods are then evaluated based on criteria linked to manufacturability and structural performance. Finally, we present preliminary feasibility testing and discuss the practical challenges and potential of each connection type in relation to both glass fabrication methods and overall vault design.

Keywords: cast glass, 3D-printed glass, glass vaults, glass structures, dry assembly, construction techniques, dry connection, reversible joinery, glass additive manufacturing, glass bricks

1. Introduction

Glass possesses high compressive strength, exceeding that of even steel, rendering it an excellent candidate for compressive-only structures such as arches and vaults. Although a few shell-like structures constructed from float glass have been realized [1,2], the inherently planar geometry of float glass panes often constrains the scale of such constructions and typically necessitates additional substructures (e.g. framing) to resist out-of-plane tensile stresses, leaving glass's compressive strength underutilized. Casting and 3D-printing/Additive Manufacturing (AM) are two emerging fabrication methods for volumetric glass components, offering high potential for creating free-form, fully glass structures that can effectively utilize glass's compressive capacity.

Due to inherent fabrication constraints, namely the long annealing times required for large cast glass components [3] and the restricted build volume of AM equipment [4,5], both cast or 3D-printed glass elements are typically restricted to the size of a large masonry brick. As a result, architectural-scale applications necessitate segmentation and assembly of multiple smaller units. Direct glass-to-glass contact can induce stress concentrations from surface imperfections, risking the failure of the structure. An intermediate material is therefore essential to ensure a safe and effective glass assembly. To date,

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relevant (cast) glass structures have relied on permanent bonding techniques, which hinder disassembly and significantly limit reuse and recyclability [6]. Towards circular construction, it is crucial to engineer reversible joinery methods that enable both reuse and eventual recycling of the glass units. Prior research at TU Delft introduced dry-stacked, interlocking cast glass units providing kinematic constraint and enhanced stability, using cast or thermoformed dry PU/TPU interlayers to accommodate surface asperities and distribute contact stresses [7,8]. MIT has explored how to achieve similar interlocking geometries in 3D-printed glass units [5], shown in Fig.1. Both approaches have demonstrated the feasibility of using 100% recycled waste glass as feedstock [4,5,9], further promoting circularity.

(a) (b) (c) (d) (e)

Fig.1: (a),(b): Interlocking cast glass bricks made from various glass waste by TU Delft. (c): 3D-printed glass bricks following a similar geometry, developed by MIT and *Evenline*. Impressions of (d) the proposed Velcro-inspired connection for cast glass bricks and (e) the laser-cut, expandable metal interlayer for 3D-printed glass bricks

Building on this work, in this paper, we present two novel reversible joinery methods for compressive-only glass vaults constructed from either cast or 3D-printed glass components: (i) a Velcro-inspired polymer interlayer, directly 3D-printed onto the glass surface, and (ii) a laser-cut, expandable metal interlayer based on Kirigami principles (Fig. 1). We first examine the fabrication constraints of cast and 3D-printed glass bricks and their impact on joinery design. The two joinery methods are then evaluated on criteria relevant to manufacturability and structural performance, followed by preliminary testing and a discussion of their practical challenges and design potential on cast and 3D-printed glass assemblies.

1.1 Cast and 3D-printed glass bricks: Potential and considerations

Solid cast glass bricks have already been used in several built architectural projects [6]. Their key characteristics are summarized in Table 1. The bricks typically weigh between 2.5 - 20 kg to allow for feasible annealing times manual handling in construction.

Table 1. Key characteristics of cast glass bricks and chosen intermediate of realized glass brick structures

	Project	Qaammat Pavilion	Glass Vault	Crystal Houses	Atocha Memorial	Qwalala Sculpture
	structure type	semi-circular	vault	flat wall	cylinder	free-form wall
component	dimensions [mm]	240x110x53	246x116x53	210x210x65	300x200x70	320x160x160
	tolerances [mm]	±1.00	±1.00	±0.25	±1.00	unknown
	weight [kg]	3.5	3.8	7.2	9.2	20.5
	shape	rectangular	rectangular	rectangular	horseshoe	rectangular
	mold type	metal open	metal open	metal open	metal pressed	metal open
	post-processing	none	none	cnc polishing	none	none
joint	max. d [mm]	3	20	0.25	2.5	7
	selected material	silicone + PU adhesives	epoxy adhesive	UV-curing adhesive	UV-curing adhesive	silicone adhesive

Bricks are generally cast solid to maximize compressive strength, simplify mold design and ensure uniform, controlled cooling during production. In all realized applications, high-precision metal molds have been used to achieve smooth, glossy surfaces requiring minimal post-processing and tight dimensional tolerances (±1 mm); top surface deviations may be greater due to shrinkage during the initial cooling of the glass. Higher dimensional precision (<1 mm) is attainable through post-processing (e.g., CNC polishing), as seen in the *Crystal Houses* Project, though at higher cost [10]. Due to the high costs of custom high-precision molds, cast glass bricks are generally limited to simple, repetitive shapes, restricting design flexibility and largely defining the assembled structure's geometry. For example, in the *Glass Vault* the structure's geometry and pattern were adapted to allow fabrication using a single, non-tapered glass block type. This resulted in wedge-shaped joints optimized to remain below 17.5 mm to comply with the chosen epoxy's 20 mm gap-filling limit [6,11]. Similarly, in the *Qaammat Pavilion*, structural overhang was reduced to enable assembly with uniform units [12]. To enable variation at lower costs, adjustable molds offering dimensional variation along a single axis have been explored [13,14,15]. Additional design considerations for cast glass units include avoiding sharp edges and keeping uniform cross-sectional thickness to ensure even cooling and reduce residual thermal stresses.

Additively manufactured (AM) hollow glass bricks are still in early development, with no built architectural examples to date; however, they offer great potential for freeform glass structures due to their highly customizable shape. Architectural-scale AM of glass is achieved by extruding molten glass through a heated nozzle in a continuous bead. The glass printer is based on a dual kiln concept: a material reservoir consisting of a kiln and crucible above and a larger kiln for a heated build chamber below, where the glass is printed onto a moving build platform [16]. The size of 3D-printed glass elements is limited by the printer's crucible and build chamber dimensions. The largest in scale application so far, the *Glass II* project, features 3 m tall, free-standing hollow glass columns, each made of fifteen printed segments [17]. Ongoing research at MIT, in collaboration with *Evenline Inc.*, explores the fabrication via AM of interlocking hollow bricks for architectural applications [5]. The current *Glass 3D Printer 3* (*G3DP3*) supports a max. print volume of 320 × 320 × 380 mm with a deposition rate of maximum 6-20 mm/s or 5.2 kg/h, and components of up to ~30 kg [5]. Printing a 10 kg component requires ~2h, followed by 8 hours of annealing [5,18]. The G3DP3 nozzle supports a nominal layer thickness of up to 13 mm [5]; although it should be possible to further adjust this by modifying the settings and nozzle. As with other AM processes, the geometry of the printed glass units is constrained by overhang angles and the requirement for continuous bead deposition. Typical manufacturing tolerances are approximately ±0.5 mm in the x- and y-directions. Post-processing (e.g., cutting, polishing) is required to remove residual features of the bead lead-in and -out at the top and bottom surfaces of printed elements [5].

1.2. Considerations for compressive-only vault design using cast and/or 3D-printed glass bricks

To enable self-alignment and dry assembly, compressive-only glass vaults can be built using discrete, interlocking bricks. Both cast and 3D-printed glass bricks can incorporate such interlocking features that enhance stability and reduce construction-induced eccentricities.

Table 2: Guideline of design limitations of the two fabrication methods for brick-sized units

Fabrication method	advised max. brick size	Volume	unit shape flexibility	mean dim. tolerances	Transparency	Other fabrication considerations
Cast	320x160x160*	solid	difficult†	±1.00	high	even mass distribution sharp edge prevention
3D-printed	320x320x380*	hollow	easy	±0.50	moderate	limited overhang continuous printing path

*Size based on existing applications - larger bricks are possible if required

†Customized units are feasible but incur high costs due to the need for customized high-precision molds

Weatherproofing - particularly at joints - is another key consideration. This can be addressed by integrating an overlapping weathering lip into the brick geometry in both fabrication methods. However, each method has distinct manufacturing limitations and characteristics (see Table 2), which influence design flexibility, overall form and structural performance at brick scale. Table 3 highlights the main advantages and disadvantages of 3D-printed and cast glass bricks for compressive-only vault construction, and how these could affect the dry-assembly joinery method.

Table 3. Main pros and cons of the use of 3D-printed vs. cast glass bricks in compressive vault design

Fab. method	Compressive strength	Unit design flexibility	Optical quality	Surface quality	Structural reliability	Joint considerations
Cast	high	low	high	smooth	high	increased and variable thickness
3D-printed	moderate	high	moderate	layered	moderate	rough glass surface produced open in two sides

1.2.1. Cast glass bricks

Solid and isotropic, cast glass bricks are well-suited for compressive applications, offering uniform strength and high optical clarity with minimal distortion. Their substantial mass enhances structural stability by increasing self-weight, which is beneficial for resisting uplift and other destabilizing loads in compression-only vaults.

However, their applicability in non-standard or freeform geometries is limited due to the high costs of custom precision molds which restricts their production to simple, repetitive shapes. Thus, it is advised to use a standardized global brick shape and resolve dimensional tolerances of both bricks and construction at the interface [15]. Standardized bricks also lack the flexibility to accommodate the variable angles typical in vaults, often requiring thicker or variable joints that may compromise both the structural performance and visual quality of the resulting vault assembly (see Fig.2)

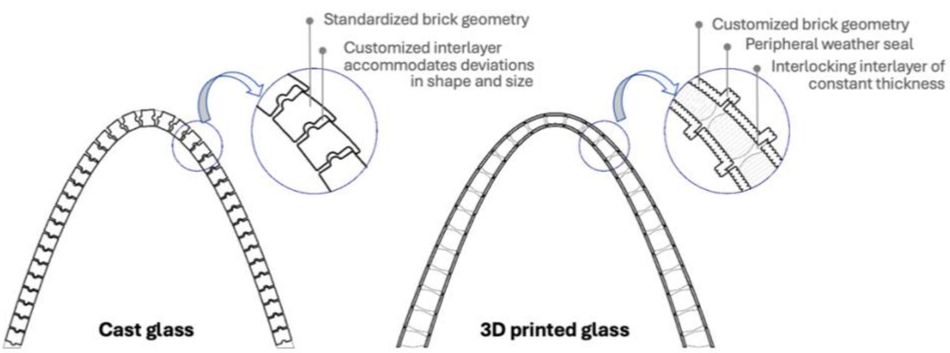

Fig.2: Schematic diagram of key considerations on joint design in cast vs 3D-printed glass vault assemblies

1.2.2. 3D printed glass bricks

3D-printed glass bricks offer high design flexibility, allowing for geometry-specific, non-standard units without the need for custom molds, making them ideal for freeform vaults. Their geometry can be further tailored to maintain a consistent interlayer thickness, accommodating tolerances and minimizing the need for variable joints.

Nonetheless, several limitations exist. Their hollow form reduces unit weight, potentially compromising the stability of compression-only assemblies under variable loads. Additionally, 3D-printed glass exhibits anisotropic strength properties, with reduced performance perpendicular to print layers [16]. Accordingly, units should be oriented so that compressive forces align with the outer shell and are parallel to the print direction (i.e., perpendicular to the print bed). In this orientation, large angles between the top and bottom surfaces must be created with post machining, though it may be possible to incorporate this capability to a limited extent in future generations of the printer architecture. Visually, 3D-printed bricks tend to show reduced transparency due to visible layer lines. A key technical challenge lies in the fabrication of 3D-printed glass bricks incorporating fully enclosed internal cavities, as current AM technologies do not allow for mid-print pausing or large unsupported overhangs, resulting in units with two open faces. Recent research by *Evenline* and MIT explored partial sealing strategies, such as direct printing onto float glass, casting into printed parts, or printing a closure layer [4,5]. A method for sealing both ends while integrating interlocking features remains unresolved. A promising alternative involves developing a structural interlayer that provides the interlocking functionality between adjacent units, eliminating the need to seal the open faces. Incorporating a peripheral weathering lip can further aid alignment, prevent assembly errors, and ensure water resistance (see fig.2). Such a feature can be efficiently fabricated using a graphite base mold, as demonstrated in [5].

2. Reversible Joinery methods

2.1. Design criteria

As outlined in [6], selecting intermediate materials for volumetric glass assemblies is guided by four key criteria: (i) visual performance (transparency, optical clarity), (ii) structural performance (strength, creep resistance, service temperature), (iii) constructability (assembly ease, gap-filling capacity), and (iv) economic feasibility (low post-processing costs). Based on adhesively bonded built projects and prior experimental work at TU Delft with dry interlayers (PETG, PVC, PU, PMC), [19] classifies these criteria as either primary (structurally critical) or secondary (less structurally impactful and more flexible). Table 4 summarizes the adapted criteria for dry interlayers in compressive glass structures.

Table 4. Design criteria of intermediate material based on [19] adjusted for glass vault structures

key criteria for intermediate material		primary	secondary	requirements
visual	transparency		x	may require transparent interlayer
structural	compressive strength	x		≥ 1MPa
	creep resistance	x		satisfactory
	Stiffness	x		E<50 GPa (less stiff than glass)
	shore hardness	x		70-80A, 20-40D
	thermal. expansion		x	α value close to applied glass
	Durability		x	water, fire, UV-resistance durability
	Service T	x		case dependent
ease of assembly	shaping freedom of intermediate	x		ability to be shaped in desired geometry thickness ≥ 3 mm
cost constraints	reduce post-processing		x	interlayer to account for dimensional deviations of glass units and construction

Primary criteria emphasize satisfactory compressive strength, creep resistance, and a lower stiffness than glass for stress redistribution, as well as thermal expansion compatibility to minimize internal stresses. Ease-of-assembly (constructability) - an important factor in overall construction costs - requires an intermediate material that can accommodate dimensional tolerances and can be easily shaped into the desired shapes and thicknesses to reduce or eliminate post-processing. Additional considerations - such as UV resistance, durability, non-toxicity - depend on the joinery method.

2.2. Velcro-inspired, polymer interlayer directly 3D-printed on the components

A promising joinery method is the direct 3D-printing of a Velcro-inspired polymer interlayer onto glass components, offering highly customizable joint shapes and thicknesses. A preliminary feasibility experimental study is conducted to address the following key challenges: (i) the adhesion of the printed material to glass; (ii) its printability in the desired pattern on non-planar surfaces; (iii) the failure mode of the resulting connection under shear.

2.2.1. Direction adhesion of the printed material to glass – material selection

The material selection for 3D-printed interlayers must balance printability with mechanical performance: the chosen material must be mechanically compatible and be able to directly adhere to glass. Relevant requirements include low printing temperature, high geometric fidelity, rapid curing and ability to adhere to glass. While materials like PETG (Vivak), Neoprene, PU/TPU, and aluminum have been used for thermoformed dry interlayers [19], 3D-printing imposes stricter constraints. Neoprene and aluminum are excluded due to AM incompatibility and high-temperature processing, respectively. TPU and PETG are viable options, offering good printability via FDM and mechanical compliance. 3D-printing of PETG to glass has been explored by [20] for creating composite panels of thin glass sheets attached to a 3D-printed PETG core structure using a UV-curing adhesive to bond the polymer core and the thin glass cover layers. However, such a bond hinders the eventual recyclability of the glass. Other promising material options include heat-cured silicone, *Surlyn*, and PLA, all offering the desired formability and adequate compressive strength. Nonetheless, for initial feasibility testing, silicone was excluded due to incompatibility with the printers available at TU Delft’s LAMA lab, and *Surlyn* was unavailable in filament form. Instead, a PC-ABS blend and *FlexPolyester* were added in the preliminary material selection based on availability and application potential.

Thus, based on the key performance criteria and on material availability, five materials - PETG, TPU, PC-ABS (Polycarbonate/Acrylonitrile Butadiene Styrene), *FlexPolyester* and PLA - were tested for printability on glass. Float glass samples of 100 × 100 mm were waterjet cut and used as print beds on an *Anycubic* 3D-printer (1.0 mm nozzle). A honeycomb pattern design was printed under varying bed/nozzle temperatures on the glass surface, with and without wood glue as an adhesive layer. The key findings are summarized in Table 5 and characteristic samples are shown in Fig. 3.

Based on adhesion to glass, printability and mechanical strength, PLA and PETG emerged as the most promising interlayer materials for this joinery method. In specific, PETG offers superior mechanical and chemical performance, forming strong bonds with glass at high bed (90°C) and nozzle (240 °C) temperatures, with slow cooling and wood glue application. However, it shows significant warping due to thermal contraction during rapid cooling, occasionally cracking the glass substrate, indicating a need for further optimization of printing parameters and geometrical patterns. An alternative approach involves printing the PETG interlayer separately and bonding it to the glass when cold using an intermediate layer, as in [20]. While effective, this method complicates assembly and may hinder glass recyclability due to material contamination. PLA showed strong, direct adhesion to glass at moderate bed temperatures (60 °C, with 210°C set as nozzle temperature), with low shrinkage and high dimensional accuracy, making it suitable for precise, stable prints. It should be noted though that its lower strength and poor weather resistance may limit long-term or outdoor use.

Fig. 3: Samples from left to right: (i) PETG with wood glue exhibiting strong adhesion and no warping; (ii)TPU showing severe warping and poor adhesion; (iii) FlexPolyester with moderate adhesion and corner warping, (iv) PC-ABS that warped of the bed immediately; (v) PLA with high adhesion and no warping

Table 5. Key observations from experiments on adhesion of 3d-printed materials on glass

Material	CTE $\times10^{-6}/°C$	Adhesion to glass	Warping	Printability	Strength
PETG	100-120	excellent (at high nozzle/ print bed T)	moderate to high	moderate (needs tuning)	high (can induce stress in glass) high chemical resistance
TPU	160-200	poor	severe	low (difficult to control)	low (flexible, not rigid)
FlexPolyester 40D	150-180	moderate	moderate (corner lift)	moderate (needs tuning)	medium
PC-ABS	70-110	poor	severe	low (needs enclosure)	high
PLA	60-75	excellent	low	high (very reliable)	medium (stiff but brittle) poor weather resistance

2.2.2. Printability in desired pattern on non-planar glass surface

To test the printability in a Velcro-inspired pattern, PETG and PLA were 3D-printed on 50×50 mm flat glass plates (Fig.4 left). The interlock design uses elastic averaging to enable self-alignment of components with slight print deviations. PETG showed strong adhesion yet induced stress fractures in glass due to the significant thermal expansion (CTE) mismatch. Design modifications to reduce stress - such as isolated prints or reduced contact areas - were ineffective. In contrast, PLA, which has circa 40% lower CTE compared to PETG, showed better dimensional stability owing to its lower shrinkage and processing temperature, with minor warping limited to sharp corners; this can be further reduced by filleted designs (e.g., 15 mm radius). Although PETG is a promising material, reliable direct printing onto large glass surfaces without an intermediate adhesion layer requires further optimization to address thermal stresses arising during cooling. To evaluate feasibility of this novel connection, PLA is selected as the preferred material due to its lower thermal expansion and more stable adhesion to glass.

A custom robotic printing setup is required for the precise conformal of Velcro-inspired interlayers onto non-planar (e.g. curved and/or interlocking) glass units. Due to fabrication tolerances, each glass brick may need to be 3D-scanned (using an opaque spray to enhance surface capture) to create accurate mesh models, so that interlayer geometry can be adapted in *Grasshopper/Rhino*. Non-planar slicing can be performed via specialized software, like the 5-axis slicer by *Dotx*, with custom scripts to ensure smooth toolpaths (e.g., min. blend radius). Robot motion can be simulated and programed offline using a software like *RoboDK*. As a proof of concept, a 6-axis *UR5* robotic arm with a direct-drive extruder and an *Arduino*-controlled stepper motor is being explored at TU Delft to print PLA filament directly onto the curved glass surface via a custom workflow (see Fig. 4 middle and right).

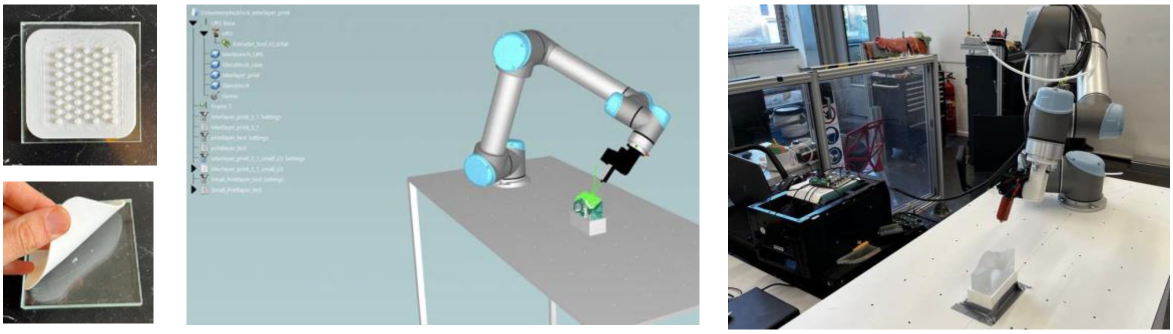

Fig. 4: Left: Successful printing of Velcro-inspired pattern in PLA connection on glass substrate. The connection can be removed if heated at 80 °C (middle). Middle & Right: Programming in *RoboDK* and robotic arm set-up at TU Delft for non-planar printing of the polymer onto the glass.

2.2.3. Failure mode of the connection

To evaluate the shear capacity and failure mode of the developed 3D-printed PLA connection on glass, eight specimens were tested under shear using a horizontal actuator, with Digital Image Correlation (DIC) employed for displacement tracking. Each specimen consists of two interlocked 100x100x8 mm float glass plates with directly printed interlocking PLA interlayers. A controlled normal preload (~0.3 kN) simulates the self-weight of a glass vault assembly. The horizontal actuator imposes a lateral displacement of the top plate until failure, while the lower plate remains fixed. Both force-displacement curves and DIC imaging are recorded.

Peak shear forces range between 1.77 - 6.13 kN, with corresponding average friction coefficients (μ) up to 1.80, significantly exceeding those of conventional material interfaces specified in Eurocode (e.g. $\mu_{timber-timber} = 0.40$). All specimens failed via the PLA's sudden delamination from the glass surface, indicating that adhesive failure at the interface is the limiting factor, and not the interlock geometry. These preliminary results demonstrate the mechanical efficiency of interlocking features under compression, while highlighting the need for further research on the glass–polymer adhesion to prevent sudden failure and achieve ductile behavior.

2.3. Dry, metallic laser-cut expanded interlayer

Dry metallic interlayer materials have a high potential for reclaiming and recycling upon disassembly of a glass vault structure. Expanded metal mesh is a commercial product made from sheet metal slit in a regular pattern and stretched using a sheet metal stamping process. The sheet thickness increases as beams of the mesh bend out of plane. The expansion out-of-plane can be adjusted by varying the cut pattern and magnitude of stretch [21]. The effective stiffness of the mesh as an interlayer can also be tuned via the metal and alloy selection, the thickness of the flat stock used, as well as the cut pattern and degree of expansion. Depending on loading of the vault structure and the resulting stress concentration at the metal to glass interface, the metal can be used as the sole interlayer material or coupled with PU sheets. A PU sheet can reduce contact stresses while the expanded metal mesh can fill large gaps while maintaining high overall stiffness.

Aluminum and steel sheet stock materials were considered for the interlayer application. The lower Brinell hardness 5000 and 6000 series aluminums are advantageous for avoiding contact damage with glass components, but are not available in as many discrete thicknesses as 301 stainless steel sheets. The latter allows for greater customization of the mesh's bulk mechanical properties, namely buckling strength and stiffness [22,23,24]. To demonstrate the ability to match the effective modulus of previously tested polyurethane interlayers [19] with expanded metal meshes, prototypes of custom aluminum and stainless steel meshes were created using a fiber laser (*Fablight FL4500*) and then expanded with the use of an *Instron 5969* universal testing machine (fig.5, left). Focusing on the aluminum, 0.04 mm thick 6061 aluminum once cut and expanded, reached a mesh thickness of 5 mm +/- 0.2mm. Compression tests on this expanded interlayer (fig.5, center) show that the expanded mesh has an effective Young's modulus of 6 MPa. With a bulk density of 18kg/m^3, this is effectively a less dense material when compared to a solid sheet of PU, (40-1740 kg/m^3) [25]. With optimization, the metal mesh can be used as a metamaterial with a tunable bulk Young's Modulus.

Preliminary compression tests on three identical glass–aluminum interlayer samples showed that the aluminum interlayer deformed visibly before any glass damage occurred, demonstrating the feasibility of engineering a flexible expanded metal interlayer using a material with a similar Young's modulus to glass. Each specimen consisted of two 8 mm thick, 100×100 mm float glass panes and an 8.7 mm thick expanded aluminum interlayer (from a 0.5 mm sheet). 2 mm MDF plates separated the glass from the machine interface. The samples were tested using an *Instron* universal testing machine with a 10 kN load cell and a loading head of 60 x120 mm. At the maximum 10 kN load (corresponding to >1.5 MPa compressive stress at the loaded surface) the glass remained undamaged, and the interlayer sustained minor deformation. Following these compression tests, the samples were then loaded in a manual compressive machine until the visible compression and buckling of the interlayer at circa 2 kN (see fig.5, right) without damaging the glass.

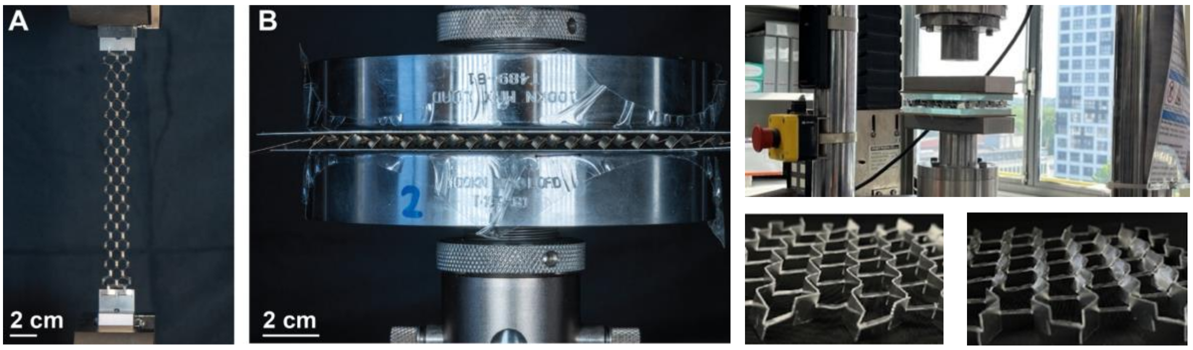

Fig 5. Photos of aluminum expanded metal created for concept evaluation. Left: Activation of expanded metal in tensile grips. Center: Compression testing of expanded metal. Top right: Compression testing of aluminum expanded interlayer between glass plates (right). Bottom right: the same interlayer before (left) and after (right) being loaded until visible deformation/buckling.

Some of the limitations that should be considered in the implementation of expanded metal meshes include thermal expansion, stress concentration in contact points, positioning and interlocking with glass components, and preventing moisture infiltration and corrosion. Stress from contact points and thermal expansion may be alleviated with the inclusion of a PU sheet, or tuning the metal mesh dimensions to create a softer bulk behavior and allow for exemption in the internal open space of the mesh. Using aluminum alloys also has the benefit of a lower hardness than the glass components. Interlocking with glass components and moisture infiltration (rain) will depend on the application and glass component geometry, but as discussed above in regard to joint design and indicated in Fig 5, could be addressed in the geometry of both the mesh and glass components.

Conclusion

This study introduces two novel, reversible joinery methods for dry-assembly, compression-only vaults from cast or 3D-printed glass bricks: (i) a Velcro-inspired, 3D-printed polymer interlayer and (ii) a laser-cut, expandable metal interlayer. Both glass brick fabrication techniques - casting and additive manufacturing - offer distinct benefits and limitations regarding geometry and performance. While cast glass bricks offer high strength and optical clarity, their application is restrained by the high cost of precision molds to standardized units, limiting design flexibility. Subsequently, cast glass vaults require substantial joints that resolve dimensional tolerances and variable angles - often at the expense of the structure's overall transparency. In contrast, 3D-printed bricks provide geometric freedom, enabling standardized, thinner joints that can yield a highly transparent structure, despite 3D-printed glass's visible layering. On the downside, 3D-printed bricks have a non-uniform strength, and fabricating fully enclosed forms is challenging. This necessitates a joinery method that can potentially serve as the interlocking mechanism. The proposed reversible joinery concepts address these challenges by allowing flexibility in the joints' size and shape, crucial for tolerance accommodation and constructability.

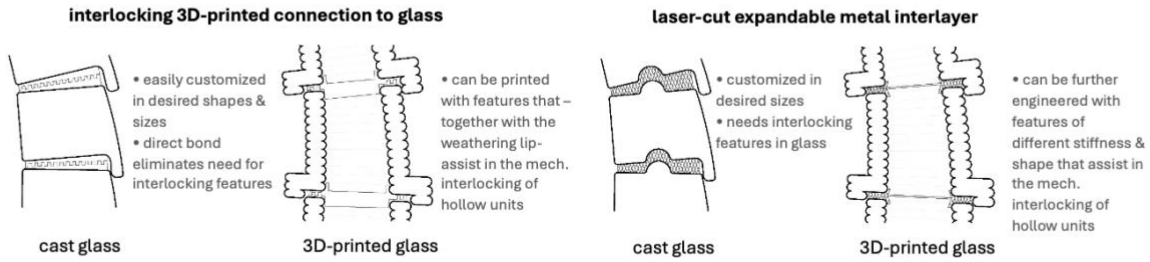

Fig. 6: Graphic illustration of potential adaptations of the two joinery methods for cast and 3D-printed vaults

The direct 3D-printing onto the glass of a polymer in a Velcro-inspired interlocking pattern, supports custom joint geometries, rendering this joinery method particularly suited to cast brick assemblies. As the printed polymer pattern provides a mechanical interlocking, it can be also suitable for assembling simple shaped glass units without interlocking features (see Fig.6). Thanks to its high printing fidelity, the method could also enable interlocking, self-aligning features on hollow 3D-printed glass bricks and adapt to their textured surfaces. Printability tests on five polymers, identified PLA and PETG as the most suitable, with PLA preferred for its accuracy and strong direct adhesion to glass without warping. For full recyclability, the polymer can be removed by heating it above its glass transition temperature. A practical challenge is the need to scan each brick for dimensional variations, particularly true for cast glass, which may require applying and later removing an opaque spray on transparent bricks.

The laser-cut expandable metal interlayer solution suits both cast and 3D-printed glass vaults but requires effective interlocking by the glass units; it is not effective on flat panes due to insufficient friction. In 3D-printed assemblies, brick geometry can be tailored to accommodate a standardized interlayer, while cast assemblies can use metallic sheets of varying thickness to adapt to joint dimensions and desired angles (see Fig.6). Overall, it offers a sustainable, fully reversible and material efficient joint, achieving sufficient stiffness with minimal material.

Discussion

While preliminary results are promising, further research is required to fully engineer both systems. For the Velcro-inspired connection, further research should focus on refining polymer selection (e.g., with a CTE closer to that of glass, such as glass-reinforced PETG) and printing parameters, enhancing polymer-glass adhesion (e.g. via surface or thermal treatment), and optimizing the interlocking geometry to align with load paths and support reversibility. The latter can be achieved by designing the printed interlayers in a pattern that triggers detachment when subjected to forces acting in directions outside the intended load path. A systematic investigation into debonding behavior is needed to assess the system's circularity potential.

For the laser-cut, expandable metal interlayer additional material testing - particularly using aluminum and titanium- is recommended. Titanium's thermal expansion coefficient closely matches that of soda-lime glass, making it a promising candidate. Future studies should explore pattern variations, assess out-of-plane shear performance, and investigate hybrid configurations, where part of the where parts of the sheet act as folded interlayers and others as rigid interlocks (Fig.6, right).

The performance of both joinery systems under dynamic and eccentric loading, as well as their effectiveness on the corrugated surfaces of 3D-printed bricks, should be experimentally investigated. In terms of assembly, the Velcro-inspired connection depends on off-site preparation, while the metal interlayer allows for on-site activation without strict environmental controls. The latter also offers logistical advantages, being lightweight and flat-packable.

At assembly scale, hybrid vaults combining cast and 3D-printed glass present a promising strategy: cast bricks can serve structurally critical zones, while 3D-printing accommodates complex geometries in curved or transitional areas. Future work can explore dry stacking via the Nubian vault principle.

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