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Restoring and structurally reinforcing historic monuments by glass

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ABSTRACT: In this paper a pioneering, transparent restoration methodology is presented, introducing structural glass elements to substitute missing components of damaged monuments and simultaneously reinforce the original structure. To prove the feasibility of the concept, a damaged medieval tower in Toolse, Estonia is selected as a case study: Soil movements and over-consolidated clay layers result to a widening vertical crack, approximately one meter wide. Alternative designs, with float and cast glass components respectively, are proposed for restoring the crack and improving the wall's stability. The considerable differences in strength and stiffness between the original wall and the glass addition require connections that establish a coherent system. Specimens bonded with selected adhesives are tested in shear and evaluated. Finally, full-scale prototypes of a characteristic part of the wall are produced and tested in three point bending to compare the overall cooperation and compatibility of each design with the medieval wall.

1 INTRODUCTION

The discussion about restoration and preservation of historic buildings is an ongoing debate. Despite of the existence of several charters with conservation principles (*Athens Charter, Venice Charter, Nara Document*, etc.), there are no strict but only general guidelines on the degree of intervention in the restoration of historic buildings and monuments. Except for the colour and the nature of the materials used, arguments include the degree to which a building can be restored without losing its original aesthetic and historic value. Additions are allowed only if they do not detract from the interesting parts of the building, its traditional setting and the balance of its compositions, as well as its relation with the surroundings. After all, *how can one intervene in another's work maintaining its significance and authenticity*? (Stanley-Price 2009). Materialization is the key point in answering this question. Conservation approaches with traditional building materials, similar or identical to the original ones, bear the risk of conjecture between the original elements and the intervention. On the other hand, the restoration or structural reinforcement of historic monuments by modern techniques may undermine the aesthetical value of the building and impair its authenticity. A transparent restoration, using structural glass components, can be a promising answer to this materialization dilemma. An elegant, transparent restoration of the missing parts can exhibit at the same time the building at its original and current condition, preserving the original historical and aesthetical integrity of the building. But equally important, owing to the mechanical properties of glass, the glass addition can contribute to the structural preservation of the monument.

Towards this direction, the *Research Group of Structural Glass* at *TU Delft* has initiated a pioneering transparent restoration methodology introducing structural glass elements to reproduce the missing components of damaged monuments and simultaneously reinforce the existing structure. To prove the feasibility of the concept the hypothetical restoration of the damaged wall of the SW tower of the Toolse castle is chosen as a case study for further development and experimentation. Soil movements and over-consolidated clay layers have resulted to a widening vertical crack that has torn the tower in two parts. To explore the allowable degrees of architectural intervention three alternative designs are proposed implementing float and cast glass elements for restoring the wide crack. Aside of being minimally intrusive in terms of architectural context, the presented design alternatives should also attain the desired stability of the wall, by functioning as a rigid mass unit that connects the two separate parts of the stone wall. The considerable differences in strength and stiffness between the historic masonry and the glass addition call for special attention on the connections between the two structures in order to establish a coherent system. Specimens bonded with selected adhesives are tested in shear and evaluated. Finally, full-scale prototypes of a characteristic part of the wall are produced for all proposals and tested in shear to compare the overall cooperation and compatibility of each design with the medieval wall.

2 THE CASE STUDY

Dating back to 1471, the Toolse castle is registered as a national monument by the National Heritage Board of Estonia. The castle consists mainly of massive masonry walls, approximately 1.5 meter thick, constructed by a homogenous mixture of primarily local limestone and partially rubble stone bonded by a lime-based mortar with added crushed limestone as a binder. Based on origin, the limestone used in the structure falls under the *Lasnamäe Construction Limestone* grouping, which is considered relatively strong due to its minimal porosity with bulk density of circa 2660 kg/m^3 (Karron 2015). Over the last centuries, soil movements and over-consolidated clay layers have torn the SW tower of the castle in two parts (see figure 1), resulting to a widening vertical crack, between 0.3 and 1.0 meter wide. At present, tension rods and steel anchors have been installed to prevent the drifting walls from collapsing. However, these measures are structurally insufficient; moreover, they intervene with the aesthetical integrity of the monument. In the context of the pioneering restoration approach, the damaged wall of the SW tower will be used as the case study for a completely transparent restoration by structural glass components. In particular, the aim is to design a glass addition that:

- is respectful to and preserves the aesthetic and historic value of the building by being minimally intrusive.
- ensures reversibility by connections that do not adversely affect the original monument and can be removed without causing additional damage.
- structurally repairs the cracked wall and protects it from further degradation by attaining a coherent system, with good interaction and collaboration between the original and added structure.
- activates warning mechanisms in case of failure to prevent the monument from further damage.

3 DESIGN APPROACHES

Since restoration by glass is a novel concept it was decided to create three physical prototypes of distinct design approach in order to get an indication of the structural behaviour of each solution and conclude to which one has the most potential for further development. A simplified and geometrically rationalized section of the SW tower is selected for the further study of the design and physical testing (see figure 4).

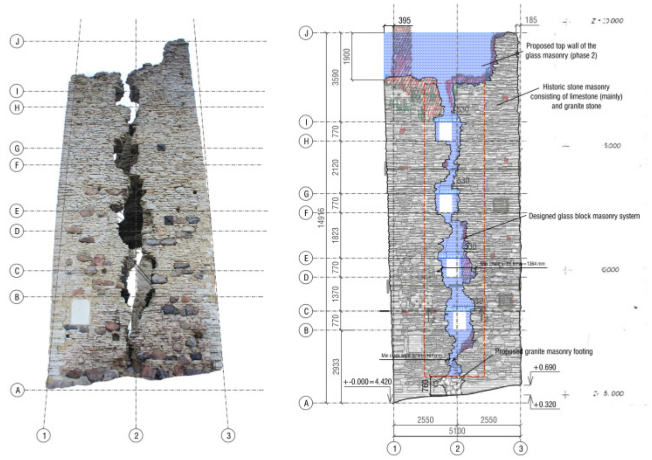

Figure 1. On the left the existing crack of the SW tower and on the right a schematic proposal of the glass restoration approach.

3.1 *Float design 1*

In this approach, laminated float pieces placed vertically and horizontally on both sides of the wall are used to reproduce the traditional masonry pattern. The reduced use of glass results to a lightweight, hollow addition and to a minimal contact surface between the glass intervention and the monument.

3.2 *Float design 2*

This design follows an hourglass shape in plan. In this way there is maximum contact surface between the original construction and the glass addition allowing for a more uniform transfer of stresses among the two structures. By reducing the amount of glass towards the centre of the glass addition, the total weight of the addition decreases considerably. Moreover, a middle zone with minimal thickness can function as a warning mechanism by being the first to crack in case of overload.

3.3 *Cast glass design*

This approach implements adhesively bonded solid cast glass bricks for restoring the crack. To reduce the weight, the glass addition is of smaller thickness than the wall and is placed in recession from both sides of the historic masonry.

4 EXPERIMENTAL

4.1 *Shear tests on adhesive connection*

Table 1. Properties of (soda-lime) glass and historic masonry.

Properties		Glass	Historic masonry
Young's Modulus	GPa	50-70	2.55*
Density	Kg/m^3	2520**	2250*
Poisson's ratio	-	0.22**	0.19*
Compressive strength	MPa	200	28**
Tensile strength	MPa	6-20	3**
Thermal exp. coeff.	10^{-6}/C°	9.5**	6.3**

* Source: (Karron 2015)
** Source: CES Edupack 2015

Apart from the density which is comparable, glass has much higher stiffness, tensile and compressive strength than a historic masonry. Table 1 shows the relation between the mechanical properties of glass and those of the historic masonry wall. These differences in mechanical properties highlight the importance of the connection between original structure and glass addition. The mechanical properties of the intermediate material and its interaction with both the original and the glass structure play a crucial role in the degree of collaboration between the two structures, determining the strength, stiffness and stress distribution in the entire construction. To attain a uniform stress distribution between the original and the additive structure an adhesive connection is chosen as the most suitable solution. Owing to its application thickness and its relatively soft nature as an intermediate layer, an adhesive connection can accommodate tolerances at the surface area and movements due to the different expansion of the materials that can result to induced stresses. On the contrary, a mechanical connection has the disadvantage of creating peak stresses that are unfavourable for both the historic masonry and the brittle glass. In specific, the adhesive connection has to:

- be discreet with a minimum visual impact
- be able to account for movements due to the different thermal expansion of the materials.
- be stiff enough to allow for collaboration but soft enough to distribute the stresses homogeneously between the structures
- be removable without damaging the historic wall.
- provide a warning mechanism and ensure that the historic part is not irreversibly affected in case of failure of the intervention.
- prevent the brittle, sudden failure of the glass addition or damage of the historic wall.

The last two points stress out the importance of designing the connection as the weakest link to prevent either structure from being damaged. To find an adhesive that fulfils all the aforementioned demands and investigate the adhesion between the different materials two categories of adhesives were tested in shear in a Zwick Z100 machine: rigid epoxy (*Araldite 2013*) and semi-rigid modified polymers (*Tec7 Brown, Sabatack 780* and *MD-MS polymer*). The experimental set up is shown in figure 2.

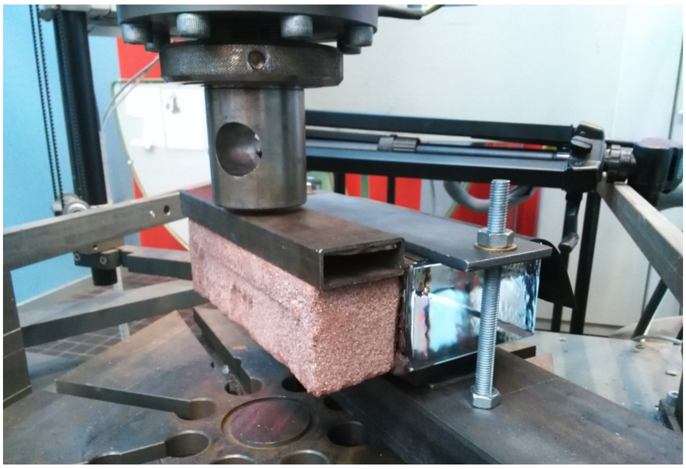

Figure 2. Experimental set-up.

Solid glass bricks are used for the glass addition and normal ceramic bricks to reproduce the historic masonry. After bonding, the specimens were left for two days to cure. A specially manufactured steel frame, connected by bolts to the base of the machine is used to clamp the glass brick to the base. A soft neoprene layer is applied as an intermediate to ensure an even load distribution. Load is introduced by the displacement of the crosshead against the top surface of the brick strip with a constant ratio of 10 mm/min. All specimens have the same shear-area of 12600 mm^2. The results of the experiments are summarized in Table 2.

Table 2. Shear tests results

Adhesive type	Sample number	Layer thick-ness	F_{max}	Dl at F_{max}	Nominal Shear stress
	#	mm	N	mm	MPa
Tec7 brown	1	3	3426.7	13.55	0.272
	2	3	3026.1	5.72	0.240
Sabatack 780	3	5	1509.6	15.03	0.120
	4	5	1446.8	10.81	0.115
MD-MS polymer	5	3	9727.7	19.10	0.772
	6	3	2436.7	16.06	0.193
Araldite 2013	7	0.1	26991.6	4.92	2.142
	8	0.1	8045.2	5.94	0.638
	9	0.1	10783.0	5.74	0.856

Figure 3 shows the typical failure mode of each type of adhesive. The specimens bonded with *Araldite 2013* and *MD-MS polymer* failed by damage of the brick component. Even though these two adhesives present the highest shear stress upon failure, their failure mode is unfavourable for the restoration purposes; when the adhesive is stronger than the masonry it results in damage of the historic wall in the

event of overload. Moreover, in the case of *Araldite 2013*, its optimum thickness of 0.1 mm is unrealistic for this application considering the rough outline of the actual crack and the movements due to the thermal expansion of the different materials.
The specimens bonded with *Tec7 Brown* and *Sabatack 780* failed by either cohesion of the adhesive or adhesion to glass after considerable deformation. These types of failure are the most favourable: by showing a gradual, visible deformation both adhesives provide by a ductile behaviour a warning mechanism before failure. Furthermore, the connection behaves us the weakest link, preventing the brittle failure of both glass and masonry. Moreover, the semi-rigid nature and considerable application thickness of these two adhesives can accommodate movements, and thus prevent the introduction of stresses due to the different thermal expansion coefficient of the two materials or due to settlement of the structure. For the same reasons, they can cover deviations in the rough surface of the historic wall, ensuring a uniform connection method.
Tec7 Brown was selected as the most suitable adhesive for constructing the full-scale prototypes since it exhibits a ductile connection and has approximately double the strength compared to *Sabatack 780*. In terms of reversibility, its semi-rigid nature allows for a relatively easy mechanical removal without damaging the monument. Moreover, this adhesive presents a good long-term performance as it is UV-, water-, saltwater- and moisture- resistant and shrinkage free.

Figure 3. Failure mode in shear of the different types of adhesives. Top Left: Tec7 Brown. Top Right: Sabatack 780. Bottom Left: Araldite 2013. Bottom Right: MD-MS Polymer.

4.2 *Construction and testing of the design prototypes*

One full-scale prototype of 0.21 m thickness is constructed for each of the three designs employing the selected adhesive, *Tec7 Brown*, for the connection between glass and masonry. Standard ceramic bricks bonded by a cement with calcium mortar are employed to approximate the historic material. The masonry part of each specimen was constructed a week prior to the glass structure, providing sufficient time for the mortar to harden. As for the glass elements in each addition, a UV-curing one-component acrylate is applied for bonding them together, already tested in the research conducted by (Oikonomopoulou et al. 2015) for an adhesively bonded glass brick wall. Previous experiments have proven that this clear adhesive of high stiffness ensures a completely transparent connection and a monolithic behaviour of the bonded glass system under loading. This simplifies the parameters that influence the collaboration between glass, adhesive and masonry by considering the glass addition as one solid mass under loading. The full scale prototypes built were thus tested under three point bending stress until failure in a force controlled hydraulic machine. The load was applied manually by a hydraulic hand powered pump. With every stroke of the lever the load increased approximately 5 kN. A metal plate was used to distribute the force onto a larger area and a wooden board was placed between the glass and the steel plate to prevent hard-to-hard material contact. The testing setup is shown in figure 4.

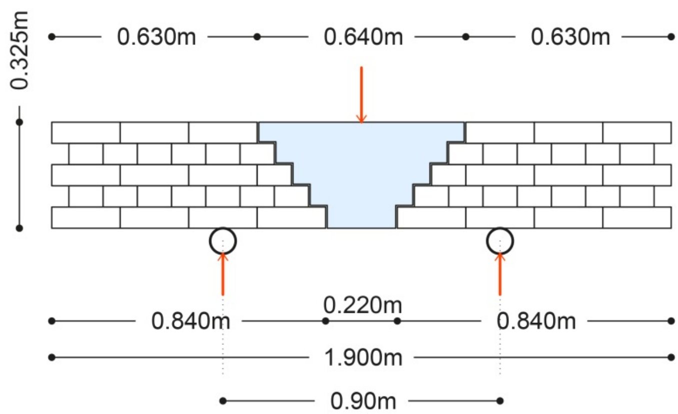

Figure 4. Testing set up.

4.2.1 *Float design 1*

In this specimen the glass addition is an assembly of pieces manually cut with a diamond oil glass cutter, comprising six layers of 6 mm thick float glass that resemble the original brick pattern of the wall. The already bonded units (of 36 mm total thickness) are then glued on site to form a shape that follows the outline of the wall on both sides, resulting in a hollow structure with limited contact surface to the masonry on both inner and outer faces (see figure 5). The advantage of this system is that it is a lightweight reproduction of the missing section and at the same time is a rather flexible solution, adapting the float pieces to the deviations in the geometry of the wall.

As the loading increased, initial cracks appeared at the masonry wall above the supports as a result of the reaction forces exceeding the stress limit of the masonry. Initiated by the crack in the masonry, the adhesive connection between masonry and glass started to deform visibly at the bottom part of the wall where the highest tensile stresses occur, until it failed by adhesion to glass at a load of 43 kN.

4.2.2 *Float design 2*

As a waterjet cutter was not available to obtain the solid hourglass shape of the design, alternating horizontal and vertical strips of float glass were cut manually and bonded together to match the elaborate shape of the wall's boundary surface (see figure 6). In this case, the glass addition had to be fully assembled into one unit and it was then inserted in the space between the two masonry parts, where it was bonded with *Tec7 Brown* adhesive.
With increasing testing load, the adhesive connection was visibly deforming at the bottom part of the specimen before the connection failed completely by adhesion to glass. When considerable deformation had already occurred, a crack initiated at the top part of the masonry which propagated due to increasing stress after the complete failure of the adhesive connection in a load of 68 kN.

4.2.3 *Cast glass design*

The construction of this design revealed some practical difficulties of filling the missing part with cast glass elements: Deviations in the height of each masonry layer can be easily accounted for when using float glass. However, in the case of cast glass elements dimensional deviations can only be compensated for by the thickness of the adhesive layer. The range of different size components has to be restricted due to high manufacturing cost. In this case, to follow the pattern of the masonry, float glass panes were inserted between the cast elements (see figure 7).
Increasing the test load, an initial crack occurred in the mortar at the bottom zone of the beam, close to one of the supports. It was observed that prior to testing the mortar at that location was very dry and brittle. The crack propagated as far as the glass addition, separating a small segment of the wall from the rest of the masonry. Still, the adhesive connection in collaboration with the glass insert sustained the separated segment until the complete failure of the beam due to increased deformation at a load of approximately 45 kN. Until failure, there was no considerable deformation observed within the adhesive connection.

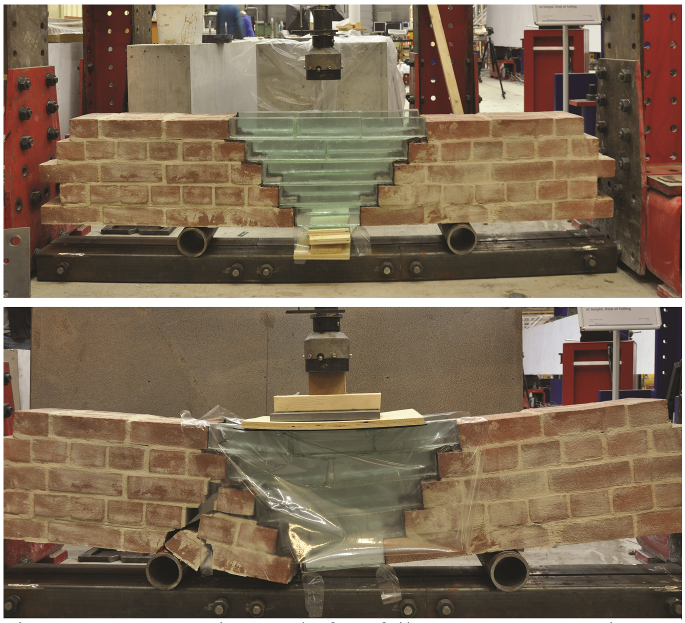

Figure 5. Top: Specimen 1 before failure. Bottom: Specimen 1 after failure.

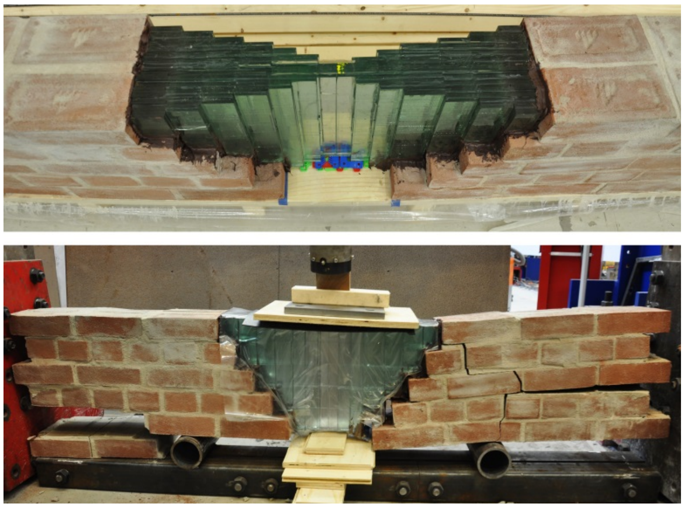

Figure 6. Top: Specimen 2 before failure. Bottom: Specimen 2 after failure.

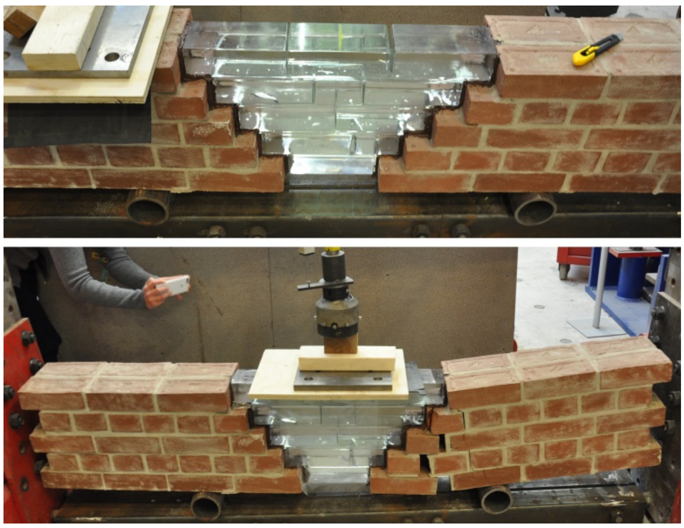

Figure 7. Top: Specimen 3 before failure. Bottom: Specimen 3 after failure.

5 CONCLUSIONS & DISCUSSION

A novel restoration system using structural glass components has been presented in this paper as an answer to the ongoing debate about the materialization of restoration. Although the experimental data are not sufficient for statistical purposes and cannot be considered conclusive for establishing mechanical properties, they highlight several important aspects of such a restoration scheme and can be used as the basis for future work.

The results of the shear tests point out that a semi-rigid adhesive, such as *Tec 7 Brown*, is the most favourable for the purposes of restoration: its large visible deformation can provide a warning signal before failure. Furthermore, its semi-flexible nature and its increased application thickness are essential for compensating displacements of the two structures due to different thermal expansion, loading or movements in the foundation, preventing the occurrence of high pick stresses in such events.

Table 3 summarizes the results of the three point bending experiments on each design specimen. Although the failure mode was not consistent the following conclusions can be deducted from the experiments:

Table 3. Summary of the real scale prototype testing

Spec. No.	Weight of glass	Connection surface	F_{max}	Dl at F_{max}	Failure mode
	kg	mm^2	kN	mm	
1 (float)	24.31	7560	43.0	41.3	Crack in masonry
2 (float)	38.60	13290	68.1	22.7	Failure of connection
3 (cast)	35.56	11025	44.6	18.7	Crack in mortar

- The glass addition is much stiffer and stronger than the masonry. Therefore it is important that the adhesive connection is designed as the weakest link to prevent the brittle failure of the historic masonry.
- Float glass is considered more applicable for the glass restoration scheme as it allows for more freedom in shapes and can account for dimensional tolerances.
- In the case of specimens 1 and 3, cracks initiated at the mortar or the masonry due to support reactions before a visible deformation of the adhesive. Still, the adhesive connection was strong enough to hold the specimen together and elastic enough to absorb the deformations created in the masonry. Only after a considerable load increase and visible deformation did the adhesive connection fail, leading to the complete detachment of the damaged part of the masonry. In reality, such cracks may occur to the masonry and it is important that the adhesive can hold the pieces together until the cracks can be fixed. Yet the failure of the masonry at its tensile zone indicates that a new experimental set-up is needed with support reactions that simulate a wall condition in order to derive consistent results.
- Specimen 2 failed in the most favourable way. First, the adhesive connection gave a warning by visibly deforming before failing by adhesion to glass in a load much higher than the other two specimens. This higher load can be attributed to the absence of any cracks in the masonry as well as to the maximized connection surface between the two structures. The latter leads to a uniform transfer of stresses within the construction. In addition, by reducing the mass towards its centre, the glass intervention becomes lighter, yet stiff enough to ensure the overall stability of the component. This design seems to be the most promising for further development.

Overall, the restoration of historic monuments by structural glass seems to be a compatible and promising solution. Further work will focus on testing the adhesive connection in different ambient temperature and moisture and radiation conditions to explore the effect of weathering on the adhesive connection. Cyclic tests are also going to be conducted to evaluate the creep behaviour and long-term performance of the adhesive. Based on these results, the design principle of specimen 2 will be further developed.

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