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Reinforced glass: Structural potential of cast glass beams with embedded metal reinforcement

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ABSTRACT: The shaping freedom of cast glass in combination with the robustness of the resulting voluminous components opens up new, exciting directions in the field of structural glass. Yet, cast glass components remain brittle, limiting their structural applications in hyper-static compressive structures designed with conservative safety factors. Stretching these limits, this work investigates the reinforcement of cast glass by incorporating metal bars during the casting process, in a similar principle to reinforced concrete. Aim is to increase the ductility of the composite glass component, provide a warning mechanism prior to ultimate fracture and secure a post-failure load-bearing capacity. The development of hybrid glass components involves kiln-casting experiments using different metal-glass combinations, of similar thermal expansion coefficients. The method of introducing the metal bar in the glass during casting, and the effect of the selected forming temperature are investigated. The resulting metal-glass interfaces are examined for micro-cracks using a digital microscope, and for internal stresses using cross-polarized light. Two material combinations are found successful; soda lime silica with titanium and alkali borosilicate with Kovar. A hybrid borosilicate-Kovar 30*30*240mm beam is further tested in 4-point bending until failure, while its displacement is measured by Digital Image Correlation. The flexural response of the composite component is compared to the performance of unreinforced cast glass beams of similar composition. Although reinforced and unreinforced specimens show a comparable flexural strength, the reinforced specimen exhibits a warning mechanism well before failure, a gradual fracture and a post-failure load-bearing capacity. These attributes encourage the further exploration of cast glass reinforcement.

1 INTRODUCTION

Cast glass can play a promising role in structural applications, as through casting, three-dimensional, even free-form, monolithic load-bearing glass components can be created that can take full advantage of the high compressive strength of glass (Oikonomopoulou, 2018b). However, due to its brittleness and unpredictable failure behavior, glass is considered a structurally unsafe material. In the case of float glass, several safety strategies have been developed to reduce the inherent risk in the event of collapse, such as: (i) tempering or chemical treatment of glass for increasing its tensile strength and (ii) lamination, which also allows for (iii) over-dimensioning of the load-bearing components and incorporation of sacrificial layers to provide redundancy. Another approach that provides redundancy, a visible warning mechanism, and post-breakage load-bearing capacity is the (iv) mechanical reinforcement of laminated float components. Prior research on hybrid glass-steel systems, where the metal reinforcement is introduced in laminated float beams either at the tensile edge, on both tensile and compressive edges, or as a surrounding metal strip, has been conducted by among other Veer et al. (2003), Nielsen and Olesen (2007), Belis et al. (2009), Feldmann et al. (2010), Louter (2011), Martens et al. (2016) and Cupać et al. (2017, 2021). In prior art, the reinforcement is responsible for the ductile behaviour of the hybrid glass components, and is activated upon glass fracture. It retains the fractured glass pieces connected, carries the tensile forces, and increases the residual resistance of the beam.

Considering the above mentioned safety strategies, methods (i)-(iii) are difficult to implement in cast glass structural components. In specific, tempering of cast glass is particularly challenging to control due to the considerable volume of the component; this is even more complex in free-form components of variable cross-section. Chemical strengthening targets only a small portion of the component, considering its overall volume. Regarding lamination, the inherent shrinkage of cast glass components, larger than ±1mm even in components of a standard brick size (Oikonomopoulou et al. 2018a), impedes the lamination process as the latter requires a virtually flat surface (a standard Polyvinyl Butyral or SentryGlas Plus lamination foil has 1.52 mm thickness). Over-

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dimensioning is so far the most common safety practice in the case of cast glass, however, it does not prevent the complete collapse of the component in case of damage, given the monolithic nature of cast glass. However, an embedded metal reinforcement in the cast glass component can be a promising solution. The direct incorporation of the reinforcement in the glass during casting can allow for a high composite action, where the metal reinforcement works in tension and the glass in compression; in essence, an approach similar to that of reinforced concrete. A direct bond between the two materials, without the aid of a lamination foil, further enhances the recyclability of the component, as the two materials can be mechanically separated and the glass remains non-contaminated. To achieve such a direct bond without the implementation of an adhesive medium, it is crucial that the chosen glass recipe and metal composition present an almost identical thermal expansion coefficient so as to prevent cracking occurring due to thermal stresses. Thermal stress breakage appears either during the cooling process of the glass or over the service life of the component, and is the main reason why the incorporation of metal (particularly steel) in molten glass is commonly avoided. Nonetheless, direct embedment of metal components in glass already exists in applications such as wired safety glass, while the compatibility of glass and metal compositions has been researched in the field of electronics, for example for glass-to-metal seals in electronic devices (e.g. lightbulbs) or for soldering microcircuits, but hybrid cast glass components have not yet been reported in the literature.

2 EXPERIMENTAL WORK

2.1 *Prototyping*

The development of reinforced glass components involves the selection of different metal-glass combinations, with similar thermal expansion coefficients (Table 1). More specifically, two borosilicate glass types (Alkali Borosilicate: 68% SiO_2, 18% B_2O_3, 11% alkali oxides, and Soda Borosilicate: 80% SiO_2, 13% B_2O_3, 3.5% Na_2O) are combined with F15 Kovar (54% Fe, 29% Ni, 17% Co) bars of ø4-6mm. Moreover, a soda lime silica glass (Float: 75% SiO_2, 12% Na_2O, 8% CaO) is combined with Titanium Grade 2 (99.3% Ti) bars of ø4mm. The material pairs are introduced in 50mm cubic silica plaster investment moulds (Crystalcast M248) according to the desired configurations (Figure 1) and kiln-cast in a ROHDE ELS 200S kiln employing different firing schedules (Table 1), with the aim to achieve adhesion between the two materials. The resulting specimens are examined for cracks by naked eye and a Keyence VHX-7000 Digital Microscope, and the presence of internal stresses is checked using cross-polarized light. Upon evaluation of the results, 30*30*240mm beam specimens are kiln-cast in a similar fashion, to be tested in flexure.

Table 1. Material combinations (a-c), thermal expansion coefficient (α) and firing schedule data.

	Glass		Metal		Temperature** (°C)	
Mix	Type	α*	Type	α*	Form	Anneal
a	Alkali Borosilicate	5.15	F15 Kovar	5.2	970 900 870	512
b	Soda Borosilicate	3.3	F15 Kovar	5.2	1070 1120	560
c	Soda lime silica (float)	8.7	Gr2 Titanium	9.2	1120	560

* Thermal expansion coefficient in 10^{-6} K^{-1}, reported in the literature for a 20-300°C range.

** Dwell time, both at forming and annealing temperature, is 10hrs.

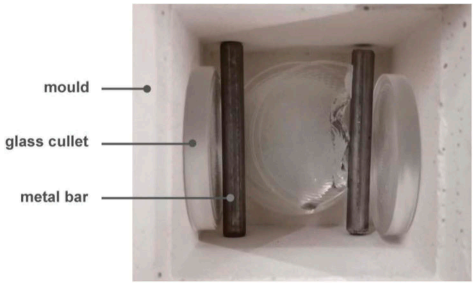

Figure 1. (top, bottom). Glass cullet and metal rod assembly within an investment mould, prior to kiln-casting. The rod is secured in position by glass cullet pieces that are laterally placed.

2.2 *Four-point bending experimental set-up*

As a proof of concept, a one-off flexural test is conducted using a Schenck 100kN displacement controlled hydraulic universal testing machine. An alkali borosilicate beam of 30*30*240mm size, reinforced with a 240mm long ø6mm F15 Kovar bar at the middle of its bottom surface, is tested in 4-point bending until failure. Rollers of ø20mm are used in a span of 100mm (loading) to 200mm (support). A displacement rate of 0.3mm/min is used. The specimen's displacement is measured using Digital Image Correlation (DIC) with the support of GOM correlate software, as well as with a Linear Variable Differential Transformer (LVDT) displacement sensor placed under the middle part of the bottom surface. The flexural strength of the hybrid specimen is calculated from the maximum bending moment and area moment of inertia, and compared to previously tested mono-material cast glass components of similar composition (Bristogianni et al. 2020).

3 RESULTS

3.1 *Evaluation of compatibility*

The kiln-casting experiments (Table 2) show compatibility for material combinations a and c, and partial or total incompatibility for combination b (Figure 2 bottom right), where a difference in thermal expansion coefficient of almost $2*10^{-6}$ K^{-1} occurs between the chosen metal and glass composition. More specifically, the titanium reinforced soda lime specimen presents the best collaboration between the two materials, and only minimum colour streaks are observed (Figure 2 left). These streaks result from the partial diffusion of the metal's surface into the surrounding glass and are mainly concentrated around the bar in a "halo" form (Figure 2, top right). The Kovar reinforced alkali borosilicate specimens show compatibility, yet the forming temperature alters the amount of metal diffusion and bubbles in the glass (Figure 2 middle row and bottom left). The least colour streaks and bubble formation are observed at the lowest forming temperature, namely 870°C (Figure 2 middle, left). Microscope images of the glass-metal interface capture this interfacial diffusion and how particles from the metal surface transport to the surrounding glass with the aid of emerging bubbles (Figure 3).

Table 2. Compatibility assessment for material combinations (a-c) and corresponding forming temperatures.

Mix	Temp.(°C)	Compatible	Comments
a	970	Yes	Intense colour streaks
	900	Yes	Medium streaks, bubbles
	870	Yes	Minor coloration
b	1070	Questionable	Large bubbles at interface
	1120	No	Cracks
c	1120	Yes	Minimum streaks

The kiln-casting experiments also show that the horizontal placement of the reinforcement, preferably at the bottom of the mould, is advantageous over a vertical orientation, in achieving the desired reinforcement location within the glass component. The vertical placement of the rod within the mould in fact requires the introduction of the metal bar during the preparation of the investment mould, to later on prevent the sliding of the bar as the surrounding glass becomes viscous. This leads to a hybrid component with a metal protrusion. The protruded bar can be cut off or used as a connective element between components.

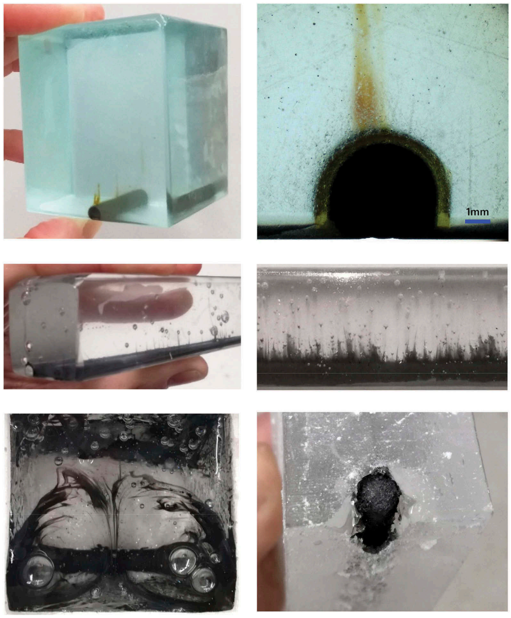

Figure 2. Hybrid kiln-cast specimens. Top row: titanium reinforced soda-lime glass cube (left) and microscope image of the titanium bar and matrix glass, depicting the surrounding diffusion zone and an emerging colour streak (right). Middle row: Kovar reinforced alkali borosilicate beams with double rod reinforcement formed at 870°C (left) and single rod reinforcement formed at 900°C (right). A 30°C reduction of the forming temperature significantly decreases the amount of colour streaks. Bottom row: alkali borosilicate cube with double Kovar reinforcement formed at 970°C (left) and Kovar reinforced soda borosilicate beam formed at 1120°C (right).

3.2 *Failure mode investigation*

A sample specimen of c-900°C category with a ø6mm reinforcement bar is tested in 4-point bending until failure, with the aim to investigate the fracture pattern of the hybrid component. The specimen fails in a progressive manner, initially presenting a series of perpendicular to the tensile stress flexural cracks at the bottom surface, within the maximum tensile zone (Figure 4-5). Thereafter, angular shear cracks appear at the zones between the support and the loading rollers. The processed DIC images (Figure 5) reveal the arrest of the created cracks as they propagate upwards towards the compression zone of the beam, and their slow growth as the force increases. The first crack is observed at a 16.6MPa stress, while complete glass failure occurs at 40.8MPa. More specifically, this failure refers to the appearance of a transverse crack through the cross section of the glass beam (bottom to top), while the metal bar still remains intact. The bottom part of the beam is shuttered in several small pieces, yet the majority of the glass mass still remains connected to the metal bar, and as such the component remains in place. The experiment is stopped at this point, and no permanent deformation is detected in the bar. The overall failure mode observed is similar to that of a reinforced concrete beam.

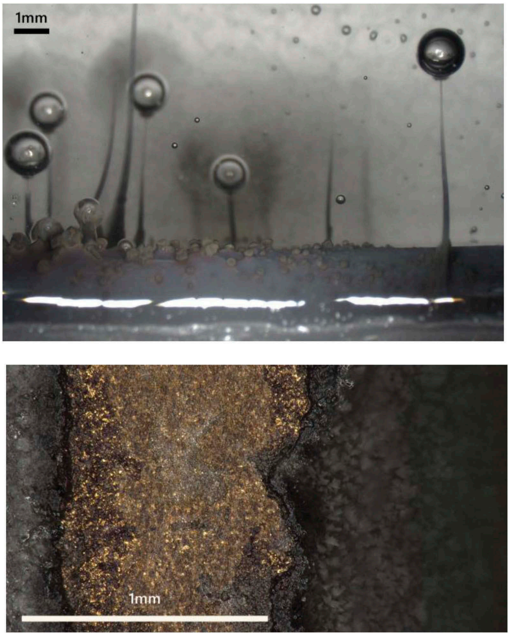

Figure 3. Microscope images of the glass-metal interface. Top: Kovar reinforced alkali borosilicate formed at 870°C. The image shows the partial melting of the external surface of the rod. Entrapped bubbles at the bottom of the mould pick up on the molten substance and carry it up as they volatize. Bottom: titanium reinforced soda-lime-silica formed at 1120°C. The image shows part of the unexposed titanium bar in the middle, and the surrounding glass. Particles of detached metal can be observed at the glass-metal interface, similarly to the Kovar hybrid sample.

Figure 4. Side view of the Kovar reinforced specimen during 4-point bending. The zone of maximum tensile stress (bottom surface, between the loading rollers) is characterized by -perpendicular to the stress field- cracks that get arrested as they move upwards to the compression zone. The areas between the support and load rollers exhibit angular shear cracks.

4 DISCUSSION

The flexural behaviour of the reinforced beam is compared to the performance of mono-material Borosilicate specimens, previously tested by Bristogianni

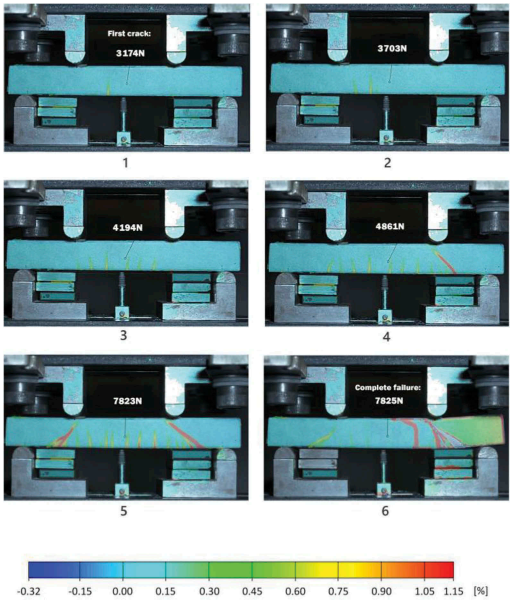

Figure 5. Major strain in the reinforced beam during loading, as obtained by the DIC analysis. The appearance of different cracks is associated with the corresponding load (in Newton). The first crack appears close to the center at 3.17kN (step 1), and then several flexural cracks appear at the maximum tensile stress zone. The first shear crack appears at 4.8kN. The cracks increase in size as the load increases, and complete glass failure occurs at 7.8kN.

et al. (2020), using the same experimental settings. It should be specified that, although minor chemical variations exist between the borosilicate composition of the unreinforced and the reinforced beams, these are not considered determining for the comparison of the flexural behaviour of the different specimens.

The mono-material beams (eight Soda Borosilicate specimens kiln-cast at 1120°C) fail at a range of 30-50.6MPa, exhibiting an average flexural strength of 43.3MPa. The specimens show an elastic behaviour followed by sudden catastrophic fracture (Figure 6-7). One high-velocity propagating crack starts from the maximum tensile zone at the bottom of the beams, splits in 2 or more branches according to the stored energy and reaches the top surface with a characteristic compressive curl. Thus, upon failure, the beam separates in two or more distinct pieces without any post-fracture load-bearing capacity.

The reinforced beam, on the other hand, fails progressively. Nielsen and Olesen (2007) report a three-stage mechanism for laminated, steel reinforced glass beams: the elastic, cracked and yield stage. Between each stage, a change in the stiffness of the system is observed. As seen in Figure 7, the tested reinforced beam, prior to cracking, presents an elastic behaviour of almost identical stiffness to the unreinforced beam. Once the first crack appears (at

3.17kN), the system enters the cracked stage and presents a decrease in stiffness. The yield stage is not reached in this experiment, given that the test is discontinued upon complete glass failure, and at that point the metal bar exhibits only elastic deformation. The reinforced beam exhibits the first crack at approximately one third of the strength (16.6MPa) when compared to the 43.4MPa average strength of pure beams. The emerging cracks at an early loading stage are speculated to be linked to peak shear stresses developing at the metal-glass interface, due to their distinct reaction to the imposed deformation. This can be anticipated, given the significant difference in stiffness of the two materials, with the employed glass exhibiting a 64GPa Young's modulus, while the Kovar bar 138GPa. Nonetheless, the reinforced beam continues to perform upon the first crack, sustaining up to 1.44 times more load prior to failure. Failure occurs at a similar stress (40.8MPa) to the pure beams' average value (43.4MPa). Yet, the progressive failure offers a valuable warning mechanism, and allows the use of a lower safety factor, provided that the design strength used corresponds to the elastic stage of the reinforced beam.

In terms of material separation and retrieval after the end of life of the hybrid component, it seems that the glass can be easily separated by mechanical crushing (Figure 8) and recycled as pure cullet -if not contaminated by colour streaks- while the metal can be reused or recycled. This separation mechanism is advantageous in comparison to the case of laminated or adhesively bonded metallic reinforcements, where the glass interface is contaminated by the bonding medium.

Overall, the described experiment successfully exhibits the behaviour of the hybrid cast beam, encouraging the further development and testing of the concept. Both a and c material combinations need to be systematically tested in 4-point bending, taking several aspects into account, such as the size and quantity of the reinforcement, but also the

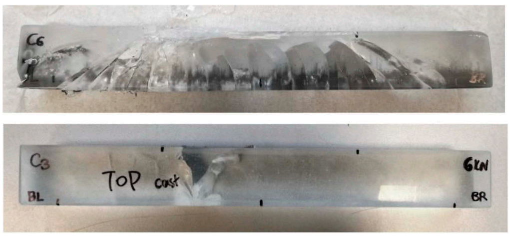

Figure 6. Side view of the Kovar-reinforced alkali borosilicate beam (top) and a soda borosilicate beam (bottom). The reinforced beam shows progressive failure and multiple cracks, yet although heavily damaged, still exhibits post-failure load-bearing capacity. The unreinforced beam (bottom) fails in a sudden manner (in this case at 6kN), with a transverse, branching crack that splits the beam into 3 separate components of no post-fracture loading capacity.

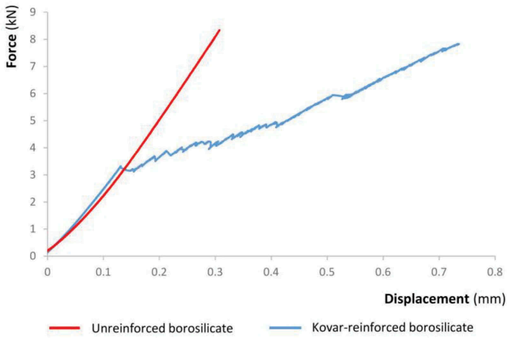

Figure 7. Force-displacement graph of an unreinforced soda borosilicate beam and the Kovar reinforced alkali borosilicate beam. Both beams exhibit an elastic behaviour, only in the case of the unreinforced beam, this is followed by a brittle response and sudden failure. The reinforced beam enters the cracked stage at a much lower load, yet endures the increasing load for 1.4 times more, before complete failure. The displacement in this graph is measured by the LVDT sensor.

Figure 8. Upon glass failure, the separation of the two materials can be mechanically achieved.

stiffness difference of the two materials. Metal alloys of not only similar thermal expansion to the glass, but also stiffness, may need to be sought. Larger hybrid specimens should be tested to account for the size factor, considering both short-term and long-term loading conditions. The proposed research steps are required to allow the design and manufacturing of safe cast glass components for structural applications. Considering the superior compressive strength of glass in comparison to concrete, and the shaping freedom of casting, great potential can arise in construction from the success of this concept.

5 CONCLUSION

Kiln-cast experiments conclude to the possibility of embedding a metal reinforcement in a glass component during the casting process, provided that the thermal expansion coefficient of the two parts is (almost) identical. Samples with a metal-glass combination of

$\approx 2*10^{-6}$ K^{-1} difference lead to immediate cracking during cooling. In this study, the combinations of soda-lime-silica with titanium, and alkali borosilicate with Kovar, are proven successful, yet the forming temperature requires adjustment to prevent the occurrence of colour streaks and large bubbles. The proof of concept flexural testing of a Kovar reinforced alkali borosilicate beam shows that the hybrid glass component fails progressively, in a similar manner to reinforced concrete. Although the failure strength of the component is comparable to the strength of a non-reinforced beam, a warning mechanism in the form of small arrested cracks appears well before failure, at 1/3 of the ultimate strength. During cracking and upon glass failure, the reinforced beam remains connected through the metal bar and exhibits post-fracture load-bearing capacity. The experiment suggests that further development of the concept is meaningful, and can lead to safer cast glass components for structural applications.

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