Novel Connections for Steel-Glass and Glass-Glass Structures

James Watson [1], Mauro Overend [2]
[1] University of Cambridge, U.K.
[2] University of Cambridge, U.K.

Keywords

1 = Low temperature brazing 2 = Connections 3 = Ultrasonic Vibration.

Abstract

Since the invention of the float process in 1959 the use of glass in buildings has increased steadily. Architecturally it is a popular material due to its transparency, durability, low cost and high quality finish. Also, heat treatment processes increase the tensile strength of glass thereby allowing glass to be used as a structural material. Despite this there has been relatively little research in glass connections, and until recently the only option for joints in high stress applications was bolted connections and fully toughened glass. However the use of bolted connections in glass is somewhat surprising as they are inherently inefficient due to flaws induced during the drilling process, stress concentrations around the bolt holes and reduced glass strength in this area arising from incomplete thermal toughening. Adhesives have been identified as a potential alternative to bolted connections as they evenly distribute the load, reduce stress concentrations and require very little surface preparation except cleaning. However, there are uncertainties about the long-term performance of high strength adhesives [1], resulting in large safety factors. This paper introduces low temperature brazing or soldering as an alternative technology for creating structural glass bonds that combines the long-term reliability of metals with the strength characteristics of bonded connections.

Introduction

Brazing is a process that is widely used for creating bonds between two dissimilar materials - typically metals and ceramics. Traditionally brazing is carried out by placing the two substrates in their final position and then heating up a filler metal (placed near the joint) to just above its melting temperature at which point it is drawn into the bond by capillary action and then the joint is cooled. When this process is performed at lower temperatures (below 400°C) it is instead referred to as soldering. For this application only lower temperature bonding is of interest as higher temperatures would damage the toughening profile of the glass.

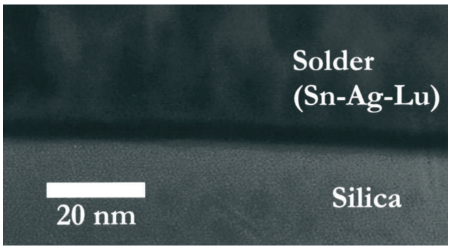


Figure 1 High-resolution TEM micrograph showing the nanometer-scale bonding layer (darker band at silica-solder interface) [2].

Figure 2 The "mirror-finish" of a soldered glass-steel joint aided by the use of ultrasonic vibrations

Usually when creating brazed joints the substrates must be clean and free from oxides. This is because most conventional filler metals cannot bond to oxide layers. This has historically made this process unsuitable for glass products. Furthermore, a flux is typically used to prevent oxides forming during the heating process which then has to be removed after the joint has been formed as it is corrosive. If a flux is used for large area bonds, removing the flux from central regions is problematic, which is another reason this technology has not been applied to structural glass before.

However, a recent development has allowed previously non-solderable materials such as glass and oxides to be bonded. By doping conventional tin based solders with rare-earth elements (such as lutetium, erbium or cerium) these materials can now be bonded [2-4]. These rare-earth elements have a strong chemical affinity for oxygen and migrate to the solder-substrate interface and a chemical reaction forms an interfacial layer of rare-earth oxides as shown in Figure 1 which creates the bond between the solder and the substrate.

To achieve the strongest possible bond it is important that the solder makes intimate molecular contact with the substrates and that no air bubbles are present at the interface. This would cause the solder to oxidise instead of bonding to the substrate and can be avoided by ultrasonic vibrations.

Ultrasonic vibrations generate alternating low-pressure and high-pressure waves in liquids, leading to the formation and violent collapse of small vacuum bubbles. This phenomenon is termed cavitation. When ultrasonic vibrations are applied to molten solder this cavitation removes the air bubbles at the solder-substrate interface and leaves a "mirror-finish" at the interface as can be seen in Figure 2.

The combination of these two technologies (soldering and ultrasonic vibrations) has to-date been limited to electronics/optics applications. This paper discusses and explores their potential for use in structural glass connections.

Experimental Work

Preliminary Experiments – Cube Pull-off Tests

Preliminary experiments were completed to prove that the combination of these technologies was indeed suitable for structural glass. In order to do this, bonds were created between samples of fully toughened glass with polished edges (50mm x 50mm x 6mm) and cubes of grade 304 stainless steel (19mm x 19mm x 19mm) as shown in Figure 3. The bonding area was 381mm^2 and the mean thickness of the bond was 0.08mm. Two solders were trialled, each from a different supplier. The solders chosen had the best mechanical performance (stiffest and strongest) from each manufacturer's range of solders. While one manufacturer provided mechanical properties these had to be determined experimentally (using simple tensile tests) for the other manufacturer's solders. These mechanical properties are given in Table 1.

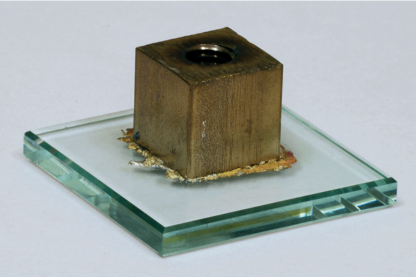


Figure 3 A typical sample from the cube pull-off tests.

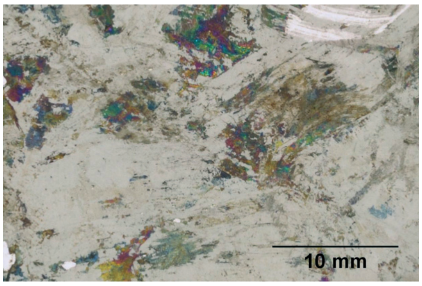


Figure 4 Solder wetting when no ultrasonic vibrations are used (darker regions indicate poor wetting)

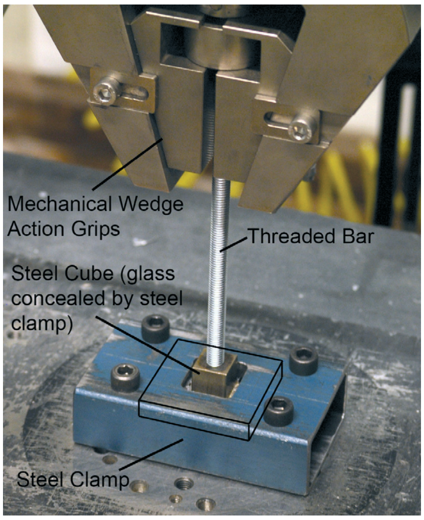


Figure 5 Test Rig

	Young's Modulus	Tensile Strength	Melting Point
Solder 1 [5]	26.2GPa	50.0MPa	221°C
Solder 2*	19.0GPa	45.0MPa	221-230°C

Table 1 The mechanical properties of the solders tested (experimentally determined by the authors)*

Both substrates were heated on a hot plate to 250°C and solder was melted onto both bonding faces. Once the solder was able to wet both substrates it was spread over the area to be bonded. Then the two "tinned" faces were brought into contact, with the steel positioned centrally with respect to the glass using a jig, and ultrasonic vibration was applied to the steel cube for approximately 30s and the specimen was left to cool.

Additional preliminary trials were performed to examine whether the ultrasonic vibration was necessary. The outcome of these tests was that while there was adhesion between the substrates and the solder the quality of the wetting was significantly poorer when ultrasonic vibrations were not applied as shown in Figure 4.

The tests were performed on a computer controlled Instron 5500R electromechanical testing machine fitted with a 150kN loadcell and mechanical wedge action grips. The samples were loaded in tension with a controlled displacement rate of 0.1mm/minute. The displacement was applied with a threaded bar attached to the centre of the stainless steel cubes. The glass was attached to the base of the testing machine and a 5mm rubber seal was placed between the glass and the steel clamp to ensure an even spreading of the load. This setup can be seen in Figure 5. The results of these tests are shown in Table 2.

The load vs. extension behaviour of the samples was highly linear for all the specimens (neglecting the compression of the rubber), indicating that the yield point of the solder was not reached for either solder. The extensions of the samples cannot be ascertained as the displacements recorded include compression of the rubber and extension of the threaded steel bar.

The failure mechanism of each of the samples was through fracture of the glass. However, there were two different types of fracture patterns. The "fully toughened" failure mode had an origin of failure in the vicinity of the edges of the steel cube as shown in Figures 6a & 6b. This failure mode appears similar to that of punching shear failure commonly seen in concrete slabs.

The second failure mode suggested that the glass was not fully toughened. This is because the fracture pattern generally consisted of a single crack (or branched crack) originating at the edge of the glass specimen, running across the width of glass producing a few large fragments. This can be seen in Figure 7.

This implies that some of the glass used was not effectively toughened. This is possibly because the samples are very small and so edge effects during the toughening process will cause significant distortions to the surface pre-stresses. It is also possible that the preheating stage has affected the toughening profile of the glass, although it seems unlikely as some samples were unaffected. This argument is strengthened by the fact that the temperature of the hotplate did not exceed 250°C which is significantly lower than the strain point/annealing point of glass (520°C/540°C). However, this will be investigated at a later date.

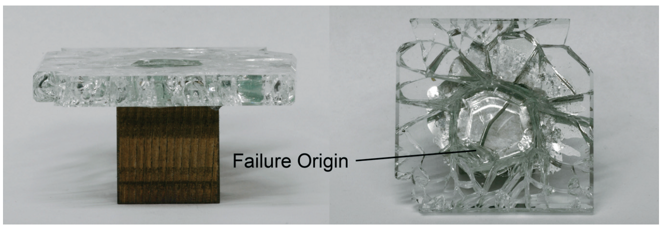
The crack patterns of both of these failure modes seem to suggest that the solder has some ability to divert crack propagation away from the joint itself. This can be seen in Figure 6b as there is only 1 crack across the width of the solder joint itself and in Figure 7 the crack appears to deflect around the joint.

A preliminary linear elastic finite element model was constructed in LUSAS v.14.3 for solder 1. A linear elastic material model was used as this provides a good approximation of the largely linear load vs. displacement behaviour observed in the experiments. The peak stresses in the glass element were predicted for the mean failure loads for the two failure mechanisms (i.e. annealed and fully toughened). In both cases the peak stresses occurred at the corners of the steel cube and are shown in Table 3.

Both the peak stresses are of an appropriate magnitude to cause failure in the glass specimens. However, the true level of surface precompression in the glass specimens is complex and is expected to vary from the edge of the glass specimen to the centre of the specimen. Perhaps failure begins at the edge of the glass where the toughening is least effective and it then propagates through the thickness of the glass in regions where there is little or no compressive prestress. Furthermore a

	Solder 1	Solder 2
Specimen 1	8.92MPa	3.62MPa
Specimen 2	7.76MPa	3.59MPa
Specimen 3	3.88MPa	3.49MPa
Specimen 4	4.16MPa	4.86MPa
Specimen 5	3.86MPa	4.38MPa
Mean Failure Stress (MPa)	**5.72MPa**	**3.99MPa**

Table 2 The failure stresses of the cube pull-off tests (stress = load/bonding area, i.e. mean stress in joint)



Figures 6a and 6b "Fully toughened" failure mechanism for the cube pull-off tests

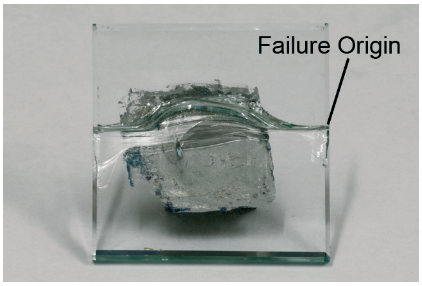


Figure 7 "Annealed glass" failure mechanism for the cube pull-off tests

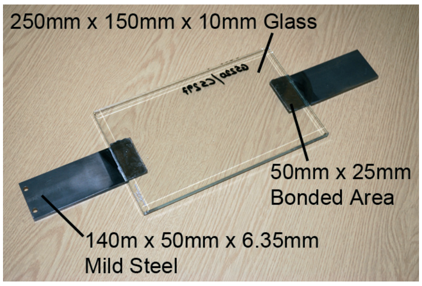


Figure 8 The single lap shear specimen

	Mean Failure Load	Peak Stress
"Fully Toughened"	3.178kN	72.07MPa
"Annealed"	1.511kN	34.27MPa

Table 3 Finite element results for peak glass stresses for both failure modes

small amount of plastic deformation is expected to occur within the solder in the highly stressed corner regions. A more detailed non-liner finite element analysis and a characterisation of the variations in surface prestress across the glass specimens should provide a more realistic representation of the soldered joint.

Single Lap Shear Test

In addition, a single lap shear (SLS) specimen (Figure 8) was prepared using an ultrasonic soldering iron. This is a conventional soldering iron which is vibrated ultrasonically simultaneously and creates a better surface finish - as the wetting is completed in one stage not two as in for the cube pull-off tests. For the SLS procedure both the mild steel and glass were preheated to 200°C using a hotplate and then pre-tinned with the ultrasonic soldering iron. The parts need were then placed in the final position and heated with a hotplate to 300°C so that the solder layers fuse together. The glass (250mm x 150mm x 10mm) was fully toughened and the steel used was HR 275 black mild steel (140mm x 50mm x 6.35mm) and each bond was 50mm x 25mm and 0.075mm thick. The steel was ground for a high quality finish on the areas that were bonded.

This sample was tested using a computer controlled Instron 5500R electromechanical testing machine fitted with a 150kN loadcell and mechanical wedge action grips at a controlled displacement rate of 0.1mm/minute. In-plane and lateral displacements were measured by means of linear variable differential transformers (LVDTs) and recorded on a Solartron SI 3535D Scorpio datalogging system. The results of this test are plotted below in Figure 9.

Failure in this sample was again in the glass component with the failure originating near the corner of the bond (see Figure 10). This mode of failure was consistent with some previous testing carried out with stiff adhesives [1]. However, the failure load was 4.121kN for this sample compared to an average 13.482kN for samples of similar geometries made with a UV-Cured acrylic adhesive reported in Watson et al. [1]. This is because the solder is considerably stiffer (E = 19.0GPa) than the adhesive (E = 1.0GPa) and consequently the stress peaks in the joint which cause failure will be much larger. It is possible to estimate the shear stress peaks by using Bigwood and Crocombe's SLS model [6]. This shows that the peak glass stresses in the soldered joint would be approximately four times larger than for the adhesive joint for the same load.

Conclusions and Summary

These studies demonstrate that rare-earth solders provide a new solution for connections in structural glass. The benefit of ultrasonic vibrations to surface wetting has been shown qualitatively – future work will aim to quantify the effect this has on the strength of the bond. It is not possible to make any comparisons between the two solders trialled as failure always occurred in the glass. Moreover as the strength of the glass elements appears highly variable any comparisons are not representative of the actual joint strengths.

In the instances where the glass was fully toughened, the failure of soldered steel-glass joints is governed by the stiffness of the bond. This is too high at the moment and as a result causes premature failure of the glass element. If the stiffness of the joint could be reduced without adversely affecting its

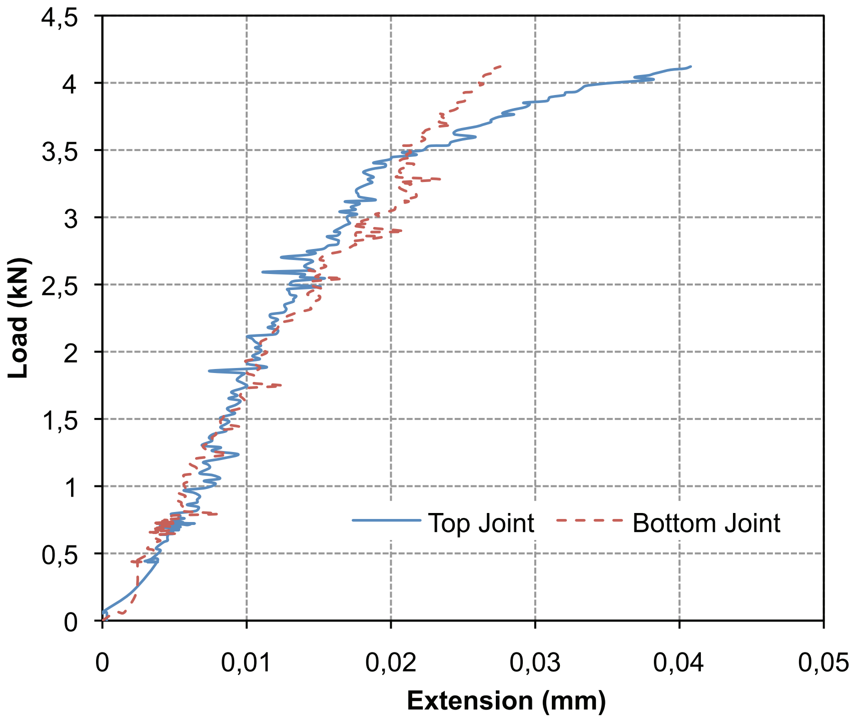


Figure 9 Experimental results from the single lap shear test

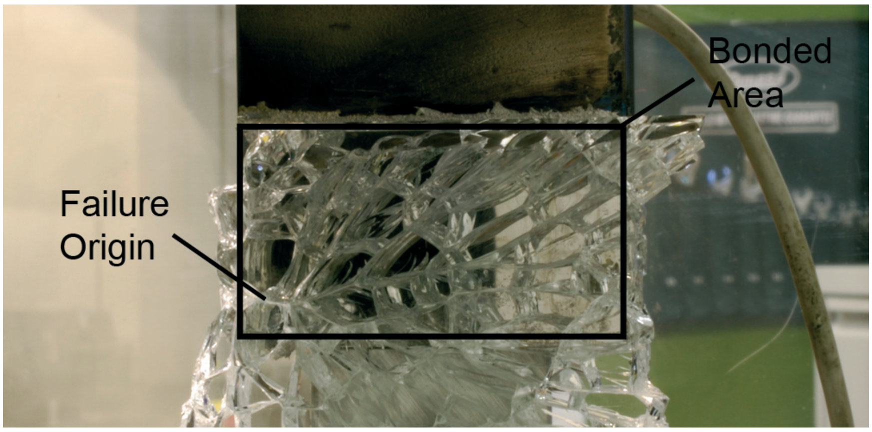


Figure 10 Origin of failure of single lap shear sample

strength then its load carrying capacity would be increased. This forms part of ongoing research by The Glass and Façade Technology Research Group at The University of Cambridge.

Overall the combination of rare-earth doped solders and ultrasonic vibrations produces a strong and stiff bond which could be applicable for structural glass joints. However, further development is required to reduce stress peaks in the bond. Furthermore, other factors that affect bond strength need to be examined such as long-term loading, fatigue, ageing and crucially the ability to absorb differential thermal expansion before this technology can be used. Future research will also be carried out to determine whether there is any strength reduction in the strength of fully toughened glass when it is heated to 250°C.

Acknowledgements

The authors would like to thank Dr. Amir Shirzadi for his input and advice as well as Prof. Ian Hutchings for the use of his ultrasonic probe and generator. We would also like to thank Hourglass and the EPSRC for funding this research and MBR Electronics GmbH for providing samples and technical advice.

References

[1] J. Watson, M. Overend, Q. Jin, and W. Lai, "Premature Failure in UV-Cured Adhesive Joints," International Symposium on the Architectural Application of Glass, Munich: 2010, pp. 179-186.

[2] A.G. Ramirez, H. Mavoori, and S. Jin, "Bonding nature of rare-earth-containing lead-free solders," Applied Physics Letters, vol. 80, 2002, pp. 398-400.

[3] H. Mavoori, A.G. Ramirez, and S. Jin, "Lead-free universal solders for optical and electronic devices," Journal of Electronic Materials, vol. 31, Nov. 2002, pp. 1160-1165.

[4] H. Mavoori, A.G. Ramirez, and S. Jin, "Universal solders for direct and powerful bonding on semiconductors, diamond, and optical materials," Applied Physics Letters, vol. 78, 2001, p. 2976.

[5] Fiber Optic Centre Inc., "AngstromBond Technical Datasheet."

[6] D.A. Bigwood and A.D. Crocombe, "Elastic analysis and engineering design formulae for bonded joints," International Journal of Adhesion and Adhesives, vol. 9, 1989, pp. 229-242.