A validated model to incorporate the effects of residual stresses in glass structures

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Oral presenter

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Background

Although glass offers great potential to be used in the built environment, design of glass structures is challenging for structural engineers due to its brittle material behaviour. In glass, high localised stresses cannot be redistributed (IStructE, 2014) and therefore conventional structural design approaches of steel and concrete are not appropriate for design of glass structures. Most of the design recommendations are based on rules of thumb (IStructE, 2014); the allowable stress design approaches focus on external loads only, neglecting the effect of residual stresses which inherently are present in glass. The misfit strains (i.e. eigenstrains) developed during the cooling process of glass in the manufacturing process, generate residual stresses and there is no method currently used in practical designs to incorporate these residual stresses.

Project objectives / outputs

- Development of an accurate analytical / numerical tool to characterise residual stress in glass.
- Establishment of a validated technique to incorporate the effect of residual stresses in designs.
- Prediction of the structural response of practical structural glass elements.

Description of method and results

A simple and convenient way of incorporating the effect of residual stress in designs is needed and the eigenstrain concept provides a good solution (Achintha and Nowell, 2011). The new hybrid contour method/eigenstrain method (Balan and Achintha, 2014) proposed here is able to construct residual stresses in glass using the knowledge of the misfit strains (i.e. eigenstrains). The results obtained based on the surface deformation (due to stress relaxation) in the contour method are used in an inverse analysis to determine the eigenstrain profile of glass elements. The step by step procedure of the proposed method is shown in Fig 1.

The residual stresses determined using the hybrid method were validated against experimental results of a scattered light polariscope. For the study glass samples of float and tempered glass with surface dimensions of 150 x 100 mm and varying in thickness from 4 mm to 10 mm were investigated. Due to space limitation only the results for 4 mm and 10 mm are presented here in Table 1. The table compares the residual stress values in the glass samples obtained using the hybrid method with those using the scattered light polariscope. The first two columns of the table show the results obtained from the hybrid model at surface and mid-depth, while the last two columns show the experimental results at the surface and respectively mid-depth.

The findings show that glass has a parabolic stress distribution, with surface compression on each side balanced by mid-thickness tension. The surface compression represent on average ~ 20 % of the thickness, while the middle tension zone represent on average ~ 60 %, irrespective of the type of glass (i.e. float or tempered). Moreover, the present results agree with the data available in the literature (IStructE, 2014). Fig 2 compares the stress depth profile (σ_{xx}) along a 10 mm thick float glass sample obtained using the hybrid method and experimental procedure. As can be seen there is a good agreement between the two profiles.

Potential for application of results

- *Correct prediction of failure*. Combined effects of residual stresses and applied stresses represent a cause of premature failure in structural elements, thus the knowledge of residual stresses play a significant role towards safe designs of glass structures. Investigations have shown that by failing to consider the correct amount of initial residual stress in analysis of glass elements can result in under-designing the element with ~ 50 %.
- *Determine high areas of stress concentrations*. The lack of yielding capacity suggests that areas of high localised stress concentrations should be avoided. By correctly incorporating residual stresses in glass analysis this can be accomplished. For example, results have shown that in order to avoid high localised stress concentrations around holes in glass plates, the hole's diameter should be higher or equal with the thickness of the glass plate.
- *Determine the safe distance of the connection away from elements edges*. The investigations of an in-plane loaded pinned joint connection has shown that even when the connection is not loaded the compressive surface stress is decreasing as the hole is closer to the free edge of the element. The results suggest that the hole should be at a distance of at least three times the thickness of the glass plate to ensure that it offers the requested reliability.

Benefits to structural engineering profession

- The proposed method offers a robust tool that allows incorporating residual stresses in structural design.
- The complex multi-physics problem behind residual stresses is simply and efficiently accounted so that engineers can determine residual stresses in new glass elements without experimental procedures or daunting FE procedures.
- Safe and sustainable designs can be achieved if residual stresses are correctly implemented.

Summary

The hybrid modelling approach works well to model residual stresses in glass, providing validated results. The current method enables modelling of residual stresses in new geometries (e.g. stress concentrations around hole) and or during subsequent loading. This allows correctly predicting the structural behaviour of glass elements and in terms a safe, reliable and sustainable design.

References

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Further information

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***Table 1**. Comparison of residual stress results (σ_{xx}) in different glass samples*

Glass type/ thickness	Hybrid Surface (MPa)	Hybrid Mid-depth (MPa)	Experimental Surface (MPa)	Experimental Mid-depth (MPa)
Float / 4 mm	- 3.0	1.5	- 4.0	1.8
Float / 10 mm	- 8.0	3.5	- 5.0	4.0
Tempered / 4 mm	- 96.0	48.0	- 96.0	51.0
Tempered / 10 mm	- 88.0	50.0	- 84.0	48.0

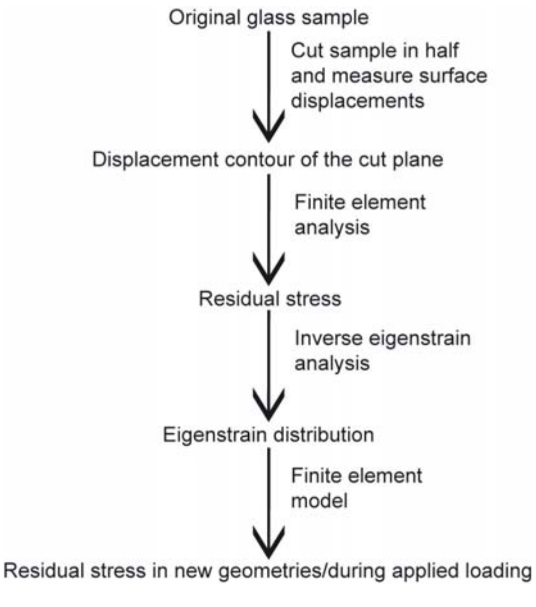

***Figure 1**. Step-by-step procedure of proposed method*

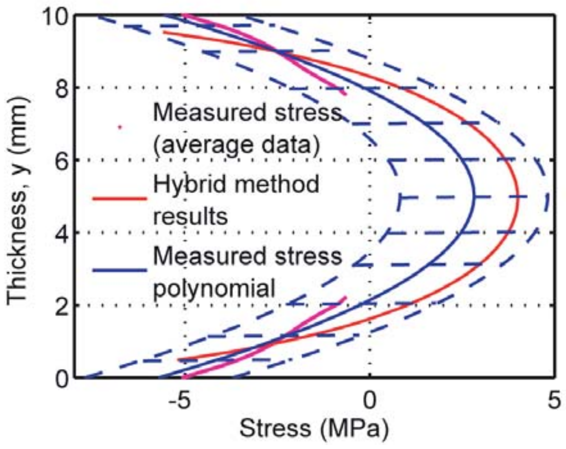

***Figure 2**. Comparison of stress profiles (σ_{xx}) for a 10 mm thick float glass sample*