

# The Effect of Glass Thickness on Stress in Vacuum Glazing

Farid Arya, Trevor Hyde, Andrea Trevisi, Paolo Basso, Danilo Bardaro

**Abstract**—Heat transfer through multiple pane windows can be reduced by creating a vacuum pressure less than 0.1 Pa between the glass panes, with low emittance coatings on one or more of the internal surfaces. Fabrication of vacuum glazing (VG) requires the formation of a hermetic seal around the periphery of the glass panes together with an array of support pillars between the panes to prevent them from touching under atmospheric pressure. Atmospheric pressure and temperature differentials induce stress which can affect the integrity of the glazing. Several parameters define the stresses in VG including the glass thickness, pillar specifications, glazing dimensions and edge seal configuration. Inherent stresses in VG can result in fractures in the glass panes and failure of the edge seal. In this study, stress in VG with different glass thicknesses is theoretically studied using Finite Element Modelling (FEM). Based on the finding in this study, suggestions are made to address problems resulting from the use of thinner glass panes in the fabrication of VG. This can lead to the development of high performance, light and thin VG.

**Keywords**—ABAQUS, glazing, stress, vacuum glazing, vacuum insulation.

## I. INTRODUCTION

WINDOWS play a critical role in energy efficient buildings by providing thermal insulation and solar control. However, they are in general less insulating in comparison with other building components as they must be transparent and have a limitation on the thickness. To fulfil these criteria, a common approach is to use multiple pane glazing with inert gas between the panes and low-emissivity coatings on the internal glass surfaces. However, in these systems, heat loss can still occur by gaseous convection and conduction. To minimize the heat loss by these mechanisms, the gas between the glass panes may be evacuated [1]. By creating a vacuum between the panes, atmospheric pressure will cause the panes to touch, consequently an array of support pillars is placed between the panes. A schematic diagram of VG is illustrated in Fig. 1. Despite the efforts of several researchers, the first functioning VG was fabricated by a research group at the University of Sydney [2]. This group has extensively studied several aspects of VG. They used glass frit

with a melting temperature of 450-500 °C to seal the glass panes around the edges [3], [4] and successfully fabricated VG of 1 m by 1 m with a center pane U-value of 0.80 Wm<sup>-2</sup>K<sup>-1</sup> [5].

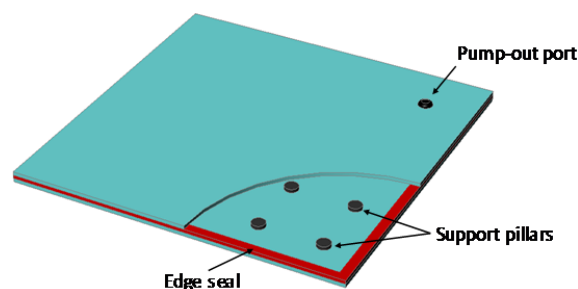


Fig. 1 A schematic diagram of VG

Atmospheric pressure and temperature differences between the two sides of VG induce large stresses across the glazing particularly in the edge seal region. The edge seal has a significant impact on the integrity and durability of VG [6]. The seal must be vacuum tight and mechanically strong to withstand these stresses. The diameter of the support pillars and the spacing between them can affect the stress level in the glazing thus consideration must be given to the design of the support pillar arrangement. In addition, the pillars should be mechanically strong to withstand the applied loads and have a low thermal conductance to minimize heat transfer. Various materials and designs have been proposed to fulfil these criteria [7], [8], [2]. In the previous studies, stress analysis has been undertaken on VG using an analytical approach to predict stress levels across VG [9], [10]. Experimental and theoretical investigations were undertaken to measure glazing deflection and strain under temperature differentials as well as atmospheric pressure [11]-[13]. It was reported that at some points in VG stress can be as high as 8.0MPa which is considered to be tolerable. In another study, using a FEM approach, a stress analysis was undertaken on VG utilising a low (indium) and high (solder glass) temperature edge seal. This study showed that the stress profile across the glazing in both instances was almost the same [6].

Research has shown that bending stress and glass deflection is smaller between the pillars in VG which is made with thicker glass panes. This reduces the possibility of glass fractures resulting in longer glazing life in service in comparison with VG made of thinner panes [2]. Conversely, thicker glass panes contribute to the increased heat flow through the edge seal resulting in a higher overall thermal transmittance U-value. To have a durable high performance VG system, a compromise must be made between these two

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conflicting parameters [5], [14]. In this paper, the stress profile of VG with different glass thicknesses is theoretically analysed using FEM. For comparison purposes, the simulation has been undertaken on four glass thicknesses, i.e. 3 mm, 4 mm, 5 mm, and 6 mm.

## II. METHODOLOGY

ABAQUS CAE (a FEM software) is used to simulate 0.5 m × 0.5 m VG with annealed glass panes of 3, 4, 5, and 6 mm thickness. Several assumptions have been made to simulate the glazing and study their stress profiles. It is realistically assumed that the support pillars are fixed to the glass panes and there is no relative movement between them. The pillars are 0.15 mm high, 0.4 mm diameter and made of stainless steel. The pillars are assumed to have flat contact surfaces; this may create some level of error as in reality they are not flat. The edge seal is assumed to be 10 mm wide and 0.15 mm thick and made of glass frit. In the modelling process, meshes are refined until the results are independent from mesh size. The glazing is assumed to be unconstrained and free to move in any direction. The results from the modelling are validated against theoretical and experimental works reported elsewhere [10]. Material specifications used in the modelling for glass, sealing material and support pillars are presented in Table I. The boundary conditions used in the simulation are illustrated in Fig. 2. As can be seen, glazing movement in both the X-direction and Y-direction is zero along lines A and B, respectively. The four corners of the glazing are assumed to be static in the Z-direction.

## III. GLAZING DEFLECTION DUE TO TEMPERATURE DIFFERENTIALS

VG must be mechanically strong to withstand stresses induced by temperature differentials between the two sides of the glazing. In extreme climates, the temperature difference could reach 70 °C (indoor temperature: +20 °C, outdoor temperature: -50 °C). In this paper, a realistic temperature

difference of 40 °C is assumed which would typically cover a wide range of climatic conditions and applications. Due to temperature differentials, the glazing assembly can bend imposing further stress on the glass panes [15], the edge seal and support pillars which will be investigated in this paper. In this section, the relationship between glass thickness and glazing deflection due to temperature differentials is investigated. In this analysis, the effect of atmospheric pressure on the glazing is also considered and as a result, both glass panes are in perfect contact with the support pillars resulting in both glass panes having the same deflection profile. Fig. 3 presents the deflection profile for VG with 3-mm thick glass panes, and Fig. 4 compares the maximum deflection for VG with varying glass thicknesses. Due to temperature differentials, the edge region is also deflected, and Fig. 5 summarises this deflection for different glass thicknesses.

TABLE I  
MATERIAL SPECIFICATIONS USED IN SIMULATION

|           | Thermal expansion coefficient | Young's Modulus | Poisson's Ratio |
|-----------|-------------------------------|-----------------|-----------------|
| Glass     | $8.3 \times 10^{-6}$ (K-1)    | 72 GPa          | 0.23            |
| Pillar    | $17.3 \times 10^{-6}$ (K-1)   | 180 GPa         | 0.3             |
| Edge seal | $8.3 \times 10^{-6}$ (K-1)    | 72 GPa          | 0.23            |

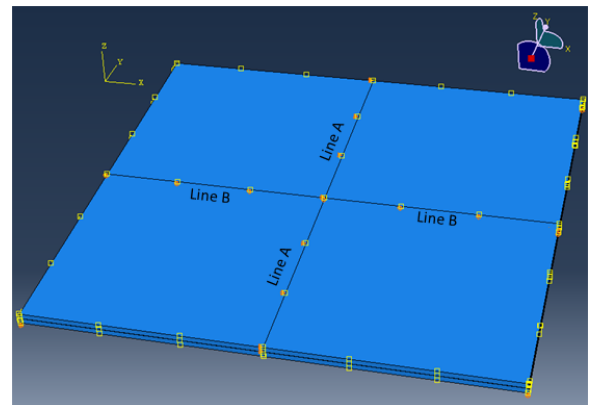


Fig. 2 Boundary conditions in the simulation

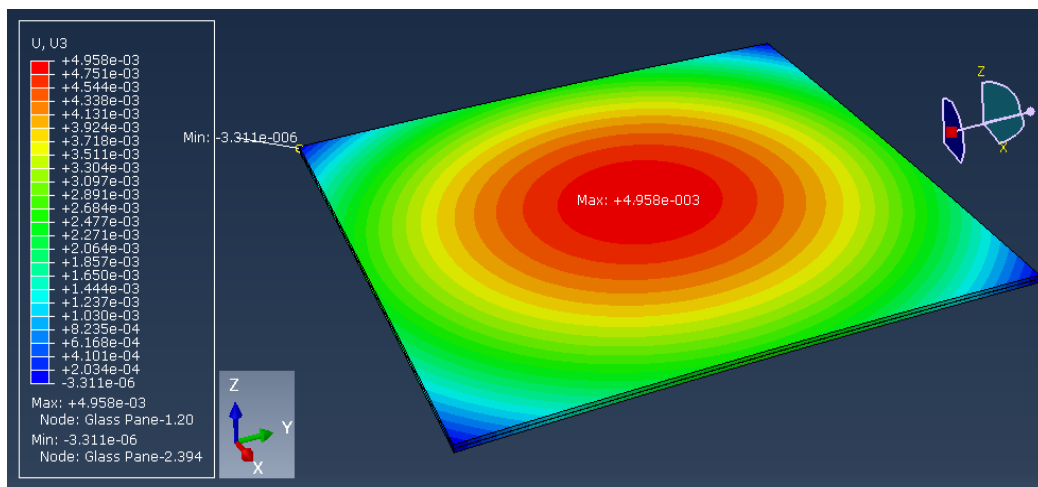


Fig. 3 Deflection of VG made of 3 mm thick glass

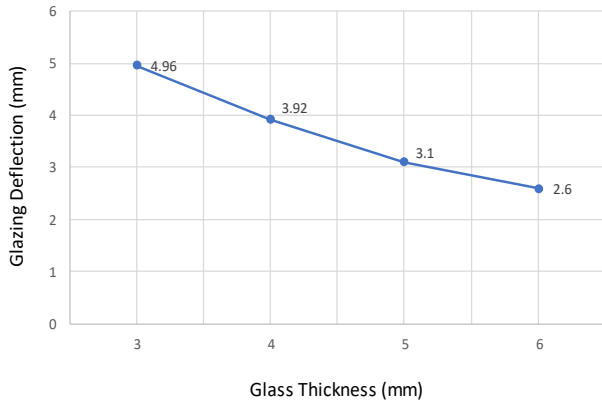


Fig. 4 VG deflection for different glass thicknesses

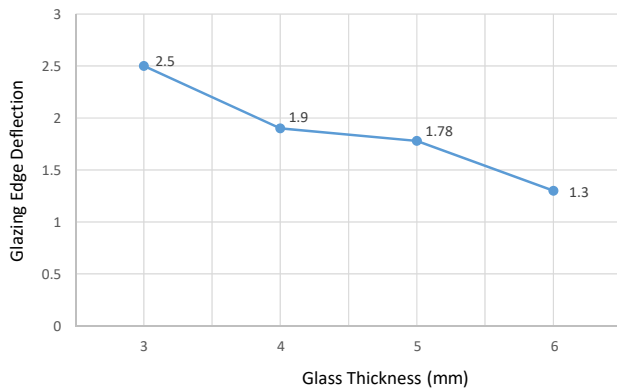


Fig. 5 Edge deflection of VG for different glass thicknesses

#### IV. STRESS IN GLASS OVER SUPPORT PILLAR

Due to atmospheric pressure the glass panes are bent over support pillars and between them as schematically illustrated in Fig. 6, resulting in tensile stresses on the external surface of the panes above the support pillars (point A) and on the internal surface of the panes between the pillars (Point B). The internal tensile stress (at point B) is negligible and does not induce glazing failure [4], therefore in this paper, this stress is not investigated.

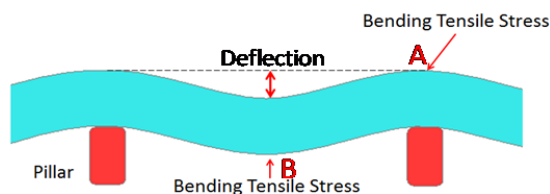


Fig. 6 Tensile stresses on glass surfaces (not to scale)

To determine the tensile stress on the external glass surface above the pillars, it is assumed that this stress is the same for all support pillars away from the edge seal. Therefore, the stress for a pillar in the centre of the glazing is determined using the FEM approach for a range of glass thicknesses. As both atmospheric pressure and temperature differentials impose stresses on VG, the external tensile stress (at point A) is determined with and without a temperature difference between the two sides of the glazing. Fig. 7 presents the

simulation results for the external stress above a support pillar in the centre of VG.

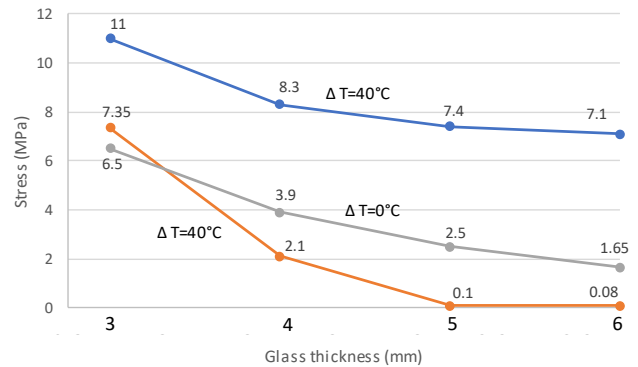


Fig. 7 Tensile stress above a support pillar in centre of VG

As can be seen, the external tensile stress above a support pillar is indirectly proportional to the glass thicknesses. The blue and orange lines in Fig. 7 present the tensile stress for the convex and concave sides of VG respectively with a temperature difference of 40 °C. On the convex side of the glazing, the tensile stress caused by the glazing deflection exacerbates that caused by atmospheric pressure, and as a result, stress is the highest on the convex side; however, the situation is reversed for the concave side resulting in a lower stress on this side. A higher temperature difference will induce larger stresses on the VG surfaces which might bring about limitations in the use of VG made of thinner glass panes in extreme climates.

#### V. STRESS IN EDGE SEAL

The edge seal plays a critical role in the durability and integrity of VG. Due to atmospheric pressure, the glass panes are bent between pillars imposing stress in the edge seal region [4]. Temperature differentials between the two sides of the glazing also results in glazing deflection as illustrated in Fig. 3. A number of parameters can affect the stress in the edge seal including glass thickness, edge seal width and pillar specifications [16], [4], [13]. In this section, the effect of glass thickness on the stress in the edge seal region is investigated using a FEM approach for VG with glass thicknesses ranging from 3 mm to 6 mm. For comparison purposes, two scenarios have been considered. In the first scenario, there is no temperature difference between the two sides of the VG, and as a result, atmospheric pressure is the only factor which imposes stress in the edge seal. In this case, it is found that the shear stress in the edge seal is negligible. In the second scenario, there is a temperature difference of 40 °C between the two sides. As discussed in Section III, temperature differentials cause bending of the VG which creates shear stress in the edge seal region; Fig. 8 presents the shear stress in the edge seal region for this scenario in which the effect of both atmospheric pressure and temperature differentials on edge seal is considered. As can be seen from Fig. 8, the shear stress is in direct proportion to the glass thickness having a maximum value of 4.9 MPa for VG made of 6-mm thick glass.

Sealing materials such as solder glass (frit) and metal based materials such as indium can withstand this level of stress [10], [17], [18].

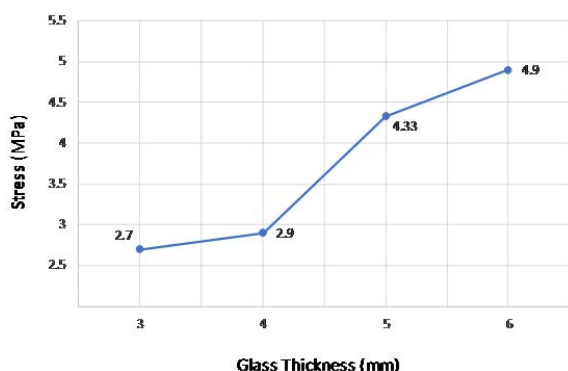


Fig. 8 Shear stress in the edge seal region of VG ( $\Delta T=40\text{ }^{\circ}\text{C}$ )

## VI. DISCUSSION

ABAQUS CAE was used to simulate  $0.5\text{ m} \times 0.5\text{ m}$  VG with annealed glass panes of thickness ranging from 3 – 6 mm. It was assumed that the support pillars were fixed to the glass panes and were 0.15 mm high, 0.4 mm in diameter, and made of stainless steel. The glazing was assumed to be unconstrained and free to move in any direction.

The relation between glass thickness and VG deflection due to temperature differential was investigated. A temperature difference of  $40\text{ }^{\circ}\text{C}$  between the two sides of the glazing was assumed. It was found that, due to temperature differentials, the edge region of the glazing was deflected and the relation between glass thickness and deflection was also calculated. It was shown that the glazing deflection was indirectly proportional with glass thickness, e.g. VG made with 3 mm and 6 mm thick panes exhibited 4.96 mm and 2.6 mm deflection in the centre of glazing, respectively. The glazing made of 3-mm panes also exhibited the largest edge deflection of 2.5 mm. This can be of concern when VG is constrained in a window frame; consequently, the frame would put pressure on the glazing edges unless a frame rebate is designed to accommodate the deflection.

As a result of atmospheric pressure, the glass panes tend to bend over the support pillars and between them resulting in tensile stresses on the external surface of the panes above the pillars. The external tensile stress was determined with and without a temperature differential effect. It was found that the tensile stress above a support pillar was indirectly proportional to the glass thicknesses. The tensile stress was calculated for both the convex and concave sides of the VG with a maximum of 11 MPa on the convex side of the glazing. This may be of concern when using VG in extreme climates where the temperature difference between the two sides of the glazing could be  $70\text{ }^{\circ}\text{C}$ . A potential solution to mitigate against this would be to add a third glass pane to VG to form hybrid VG, consequently reducing the temperature difference between the two sides of the VG [19].

The effect of glass thickness on the stress in the edge seal region was investigated for VG with and without a

temperature differential effect. It was found that the shear stress in the edge seal region is in direct proportion with glass thickness having a maximum of 4.9 MPa for VG with 6 mm thick glass panes. This level of shear stress would be insufficient to induce edge seal failure in VG sealed with solder glass (frit) or indium as sealing material.

## VII. CONCLUSION

VG can enhance energy efficient buildings by providing thermal insulation and solar control. In this glazing system, a high vacuum between the glass panes and low emittance coatings deposited on the panes minimize heat flow through the glazing. Atmospheric pressure and temperature differentials induce stress across the glazing and can result in fractures of the glass panes and failure of the edge seal. In this study, stress in VG with varying glass thicknesses is theoretically studied using FEM.

It was found that due to temperature differentials, the entire glazing is deflected including the edge region. It was also found that the glazing deflection was indirectly proportional to glass thickness having a maximum deflection of 4.96 mm and 2.5 mm in the centre and the edge regions respectively for VG made with 3 mm glass. Consequently, a window frame must be designed to accommodate the deflection, or the resulting stress could result in glazing failure.

It was found that the tensile stress on the external surface of glass panes above support pillars was indirectly proportional to the glass thicknesses. The tensile stress on the convex side of the glazing is higher than that on the concave side. This stress may be of concern if the temperature difference is higher than  $40\text{ }^{\circ}\text{C}$  which is the case in extreme climates. Using hybrid VG which incorporates a third glass pane and gas filled cavity may be a potential solution to reduce the temperature difference between the two sides of VG.

The effect of glass thickness on the stress in the edge seal region was investigated for VG with and without temperature differential effects. It was found that the shear stress in the edge seal region is in direct proportion with glass thickness having a maximum of 4.9 MPa for VG with 6-mm thick glass panes. This level of shear stress is insufficient to cause edge seal failure in VG sealed with solder glass (frit) or indium metal.

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## REFERENCES

- [1] A. Zoller, "Hohle Glasscheibe," German Patent Application, 1913, 387655.
- [2] R. E. Collins, A. C. Fischer-Cripps, "Design of support pillar arrays in flat evacuated windows," Australian Journal of Physics, 1991, 44, pp. 73-86.
- [3] R. E. Collins, G. M. Turner, A. C. Fischer-Cripps, J. Z. Tang, T. M., Simko, C. J. Dey, D. A. Clugston, Q. C. Zhang, J. D. Garrison, "Vacuum glazing - A new component for insulating windows," Building and Environment, 1995, 30(4), pp. 459-492.

- [4] A. C. Fischer-Cripps, R. E. Collins, G. M. Turner, E. Bezzel, "Stresses and Fracture Probability in Evacuated Glazing," *Building and Environment*, 1995, Vol. 30, No. 1, pp. 41-5.
- [5] R. E. Collins, T. M. Simko, "Current status of the science and technology of vacuum glazing," *Solar Energy*, 1998, 62(3), pp. 189-213.
- [6] J. Wang, P.C. Eames, J.F. Zhao, T. Hyde, Y. Fang, "Stresses in vacuum glazing fabricated at low temperature," *Solar Energy Materials & Solar Cells*, 2007, 91, 290 - 303.
- [7] J. Zhao, S. Luo, X. Zhang, W. Xu, "Preparation of a transparent supporting spacer array for vacuum glazing," *Vacuum*, 2013, 93, 60-64.
- [8] E. Cuce, S. B. Riffat, "Aerogel-Assisted Support Pillars for Thermal Performance Enhancement of Vacuum Glazing: A CFD Research for a Commercial Product," 2015, *Arab J Sci Eng* 40:2233 - 2238.
- [9] R. E. Collins, S. J. Robinson, "Evacuated windows," *Solar Energy*, 1991, Vol. 47, No. 1, pp. 27-38.
- [10] R. E. Collins, A. C. Fischer-Cripps, J. Z. Tang, "Transparent evacuated insulation," *Solar Energy*, 1992, 49(5), pp. 333-350.
- [11] T. M. Simko, A. C. Fischer-Cripps, R. E. Collins, "Temperature-induced stresses in vacuum glazing: Modeling and experimental validation," *Solar Energy*, 1998, 63(1), pp. 1-21.
- [12] A. C. Fischer-Cripps, R. E. Collins, G. M. Turner, E. Bezzel, "Stresses and fracture probability in evacuated glazing," *Building and Environment*, 1995, 30(1), pp. 41-59.
- [13] A. C. Fischer-Cripps, R. E. Collins, "Architectural glazings: Design standards and failure models" *Building and Environment*, 1995, 30(1), pp.29-40.
- [14] Y. Fang, P. C. Eames, B. Norton, "Effect of glass thickness on the thermal performance of evacuated glazing," *Solar Energy*, 2007, 81(3), pp. 395-404.
- [15] F. Arya, T. Hyde, "Theoretical Study of Flexible Edge Seals for Vacuum Glazing," *World Academy of Science, Engineering and Technology International Journal of Structural and Construction Engineering*, 2017, Vol:11, No:8, 2017.
- [16] P. Henshall, P. Eames, F. Arya, T. Hyde, R. Moss, S. Shire, "Constant Temperature Induced Stresses in Evacuated Enclosures for High Performance Flat Plate Solar Thermal Collectors," *Solar Energy*, 2016, Volume 127, 250–261.
- [17] Y. Fang, T. Hyde, F. Arya, N. Hewitt, P.C. Eames, B. Norton, S. Miller, "Indium alloy-sealed vacuum glazing development and context," *Renewable and Sustainable Energy Reviews*, 2014, 37, 480-501.
- [18] Y. Fang, T. Hyde, F. Arya, N. Hewitt, R. Wang, Y. Dai, "Enhancing the thermal performance of triple vacuum glazing with low emittance Coatings" *Energy and Buildings*, 2015, 97, 186–195.
- [19] Y. Fang, T. Hyde, F. Arya, N. Hewitt, "A novel building component hybrid vacuum glazing-a modeling and experimental validation," *ASHRAE*, 2013, Volume 119, Part 2.