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Theoretical Study of Flexible Edge Seals for Vacuum Glazing

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***Abstract*—**The development of vacuum glazing represents a significant advancement in the area of low heat loss glazing systems with the potential to substantially reduce building heating and cooling loads. Vacuum glazing consists of two or more glass panes hermetically sealed together around the edge with a vacuum gap between the panes. To avoid the glass panes from collapsing and touching each other under the influence of atmospheric pressure an array of support pillars is provided between the glass panes. A high level of thermal insulation is achieved by evacuating the spaces between the glass panes to a very low pressure which greatly reduces conduction and convection within the space; therefore heat transfer through this kind of glazing is significantly lower when compared with conventional insulating glazing. However, vacuum glazing is subject to inherent stresses due to atmospheric pressure and temperature differentials which can lead to fracture of the glass panes and failure of the edge seal. A flexible edge seal has been proposed to minimise the impact of these issues. In this paper, vacuum glazing system with rigid and flexible edge seals is theoretically studied and their advantages and disadvantages are discussed.

***Keywords*—**Flexible edge seal, stress, support pillar, vacuum glazing.

I. INTRODUCTION

THE window is a critical component in the design of energy efficient buildings since windows are generally less insulating than other components of the surrounding building structure and consequently they have a major influence on energy consumption. To improve the thermal performance of window systems a common practice is to use double or multiple pane glazing filled with an inert gas such as Argon or Krypton. For further improvement, low-emissivity coatings on the internal glass surfaces are also employed which minimize radiative heat losses. In gas filled double glazing, gaseous conduction and convection still exists. To minimize these forms of heat transfer the concept of vacuum glazing with an evacuated gap was firstly presented by [1]. Fig. 1 shows a schematic diagram of vacuum glazing. In spite of the efforts made by a number of researchers, the first published report on the successful fabrication of a double vacuum glazing using rigid solder glass as the edge seal with a melting point in the region of 500ºC was from the University of Sydney [2]. A heat transmittance of 0.8 $Wm^{-2}K^{-1}$ was achieved in the central region of a vacuum glazing sample, sized 1m×1m, fabricated by this group [3].

The edge seal plays a crucial role in the integrity and durability of vacuum glazing. Due to temperature differentials and atmospheric pressure there are large stresses in the edge seal region [4]. The edge seal must remain hermetic and be mechanically strong to withstand these stresses. Work by Benson in 1985 used a laser welding process to create a hermetic seal in vacuum glazing. Although the sealing process was successful, the level of vacuum was not low enough (below 0.1 Pa) to suppress gaseous conduction; thus, the thermal performance achieved was poor [5].

Rigid edge seal is widely used in the fabrication of vacuum glazing [3], [6], [7]. However, in recent years there has been a growing interest in using flexible edge seals in the construction of vacuum glazing. An extensive study of vacuum glazing was undertaken by [8], as reported in his patent application. He concluded that it is necessary to use a flexible edge seal in the construction of vacuum glazing to overcome the stresses in the edge seal region. A number of patents have been filed [9]-[11] on flexible edge sealing, however, there is little literature on functioning flexible edge sealed vacuum glazing in scientific publications. Consequently, there is a need for research regarding the challenges in the fabrication process, durability, ageing and in-service functionality related to flexible edge sealing of vacuum glazing.

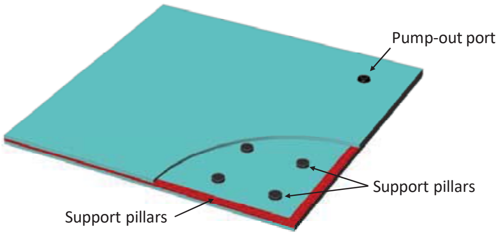

Fig. 1 Schematic diagram of vacuum glazing

The rational for using flexible edge seals for vacuum glazing is to minimise existing stresses across the glazing especially in the region of the edge seal, however, flexible seals can result in other issues such as sliding of the glass panes over the support pillars which could damage the low emissivity coatings. Additionally, the support pillars and glass panes would be in constant movement and over time this could result in damage to the support pillars or the glass surfaces which could compromise glazing integrity. Moreover, the window frame design must accommodate glass movement resulting from glass thermal expansion/contraction, to avoid any mechanical constraints which could impose mechanical

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stresses on the glazing. In this paper the issues relating to flexible edge sealing of vacuum glazing are discussed.

II. FLEXIBLE EDGE SEALING

Edge sealing is one of the most critical components of vacuum glazing which must be hermetic and mechanically strong to accommodate stresses caused by thermal gradients, atmospheric pressure, wind loads, etc. Flexible edge seals have been proposed to overcome the stresses in the edge seal area. Within the last 10 years, a number of companies including Guardian, EverSealed Window Inc., and a German group Grenzebach GmbH have reported using either a strip of metal or very thin stainless steel foil as flexible edge seals bonded to the glass using ultrasonic soldering techniques. The stress in the region of the edge seal is considered to be lower than that when using a rigid edge seal as demonstrated in Fig. 2. Using flexible edge seals in the construction of vacuum glazing may overcome some problems but it may result in other problems. Since the level of stresses in vacuum glazing varies with glazing size [12], [13] these problems might be more pronounced in bigger glazing. This issue has been briefly discussed here but would be investigated in the future work.

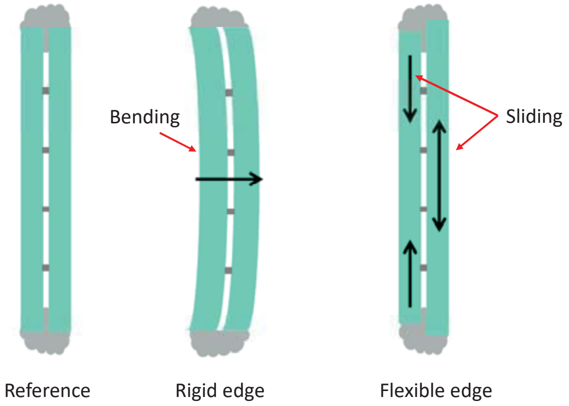

Fig. 2 Movement of glass panes with rigid and flexible edge seals

Using Abaqus CAE (a finite element modelling software), a vacuum glazing sample (0.5m×0.5m) with a flexible edge seal has been simulated and the level of stress in the edge seal region and over the support pillars has been analysed. The simulation was carried out under two conditions: firstly, the support pillars were pinned to both glass panes without any degree of freedom of sliding (as shown in Fig. 3 (a)), and secondly, the support pillars are pinned to one glass pane, and allowed to have a finite amount of sliding relative to the other glass pane (as shown in Fig. 3 (b)).

For comparison purpose the simulation is undertaken for a rigid and a flexible edge seal. The rigid seal is assumed to have the specifications of solder glass such as frit (thermal conductivity: $1 Wm^{-1}K^{-1}$, thermal expansion coefficient: $8.3\times10^{-6}K^{-1}$, Young's Modulus: 72GPa, Poisson Ratio: 0.23). The flexible edge seal is assumed to have the characteristics of silicon rubber (thermal conductivity: $0.2Wm^{-1}K^{-1}$, thermal expansion coefficient: $250\times10^{-6}K^{-1}$, Young's Modulus: 9.16MPa, Poisson Ratio: 0.47).

The vacuum glazing is assumed to be made of two 4 mm glass panes. The glazing has an edge seal of 0.15 mm thick and 10 mm wide. The support pillars are assumed to be stainless steel (304 grade), 0.4mm in diameter and 0.15mm high spaced on a regular Cartesian grid at 25mm centres. The temperature difference between the two glass panes of the vacuum glazing is assumed to be 25°C.

Fig. 3 Simulation conditions for support pillars: (a) top-bottom pinned pillars, and (b) bottom pinned-top sliding pillar

As atmospheric pressure and temperature differentials impose significant stresses on the support pillars in vacuum glazing, the design of the pillars in terms of the size, spacing and material is crucial. In this work, the thermal specification of the pillars is not discussed. The size and the spacing of the pillars are those of vacuum glazing fabricated in Ulster University.

The deformation of the pillars will occur in all directions, however in order to simplify the visualization of deformation pattern, only one direction (Y-direction) is discussed in this work. However, due to the symmetry of vacuum glazing, the pillar deformation pattern (in X-drection) will be the same as that presented here for Y-direction.

III. VACUUM GLAZING WITH A FLEXIBLE EDGE SEAL AND UN-PINNED SUPPORT PILLARS

In this section vacuum glazing with a flexible edge seal is simulated while there is 25°C temperature difference between the two sides of the glazing. Atmospheric pressure acting on the two glass panes results in significant frictional resistance at the pillar-glass interface. Due to the small size of the pillars and the large compressive forces acting on the glazing it would be realistic to assume that the pillars are pinned to the glass panes without any relative movement as discussed in the next section. However, for this analysis the panes are permitted to have a finite amount of sliding over the pillars. For simplicity, the pillars are pinned to one glass pane, with a finite amount of sliding between the opposing pane and pillar as demonstrated in Fig. 3 (b). The friction coefficient between the pillars and the sliding glass pane is assumed to be $\mu=0.7$ which is a typical value for friction between glass and metals.

Temperature differentials between the two panes bend the entire glazing as schematically demonstrated in Fig. 4. The green line in Fig. 7 represents the bending profile of this glazing with a maximum deflection of 2.30mm. Due to temperature differentials the glass panes impose an average shear stress of 2 KPa on the edge seal having a maximum of 8 KPa at the corner region. Due to the shear stress the edge seal is deflected as schematically illustrated in Fig. 5. The deflection of the edge seal can be as high as 12.15μm.

Sliding of the glass panes imposes a shear stress on the support pillars in the range of 100 Pa - 20 MPa depending on the location of the pillar; having the largest influence on the pillars near the edge seal. The shear stress results in a pillar deflection of up to 1.9 μm as illustrated in Fig. 5.

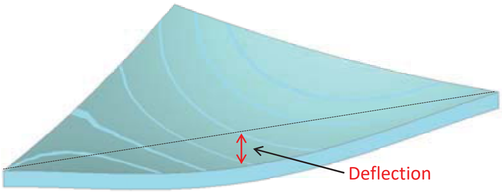

Fig. 4 Schematic diagram illustrating bending of vacuum glazing due to temperature differentials

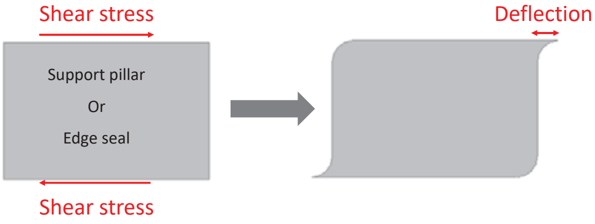

Fig. 5 Schematic diagram of deformation of support pillar/edge seal due to shear stress

IV. VACUUM GLAZING WITH A FLEXIBLE EDGE SEAL AND PINNED SUPPORT PILLARS

In this section vacuum glazing with a flexible edge seal and pinned support pillars is simulated. The temperature difference between the glass panes is 25°C. This temperature differential would result in bending of the entire glazing, imposing a large stress in the region of the edge seal and support pillars. The blue line in Fig. 7 shows the bending pattern of this glazing. The glazing would have a maximum deflection of 2.36 mm which is 0.06 mm larger than that of vacuum glazing with a flexible edge seal and un-pinned support pillars. This is a result of the two glass panes being fixed to each other via pinned pillars.

The glass panes impose an average shear stress of 0.5 KPa in the region of the edge seal having a maximum of 1.4 KPa at the corners. The edge seal has a maximum deflection of 10.30 μm, which is smaller than that of vacuum glazing with a flexible edge seal and un-pinned support pillars.

The glass panes impose a shear stress on the support pillars in the range of 10 Pa - 70 MPa depending on the location of the pillars, having the largest impact on the pillars near the edge seal. The shear stress results in pillar deflection of up to 2.47 μm. The shear stress on the pillars and their deflections are both larger than those of vacuum glazing with a flexible edge seal and un-pinned support pillars.

V. VACUUM GLAZING WITH A RIGID EDGE SEAL AND PINNED SUPPORT PILLARS

In vacuum glazing with a rigid edge seal it is realistic to assume that the support pillars are pinned to both glass panes as the rigid seal does not allow any relative movement between the pillars and glass panes. In this section vacuum glazing with a rigid edge seal and pinned support pillars is simulated. The temperature difference between the two sides of the glazing is 25°C. In this case the shear stress would be distributed between the pinned pillars and the rigid edge seal.

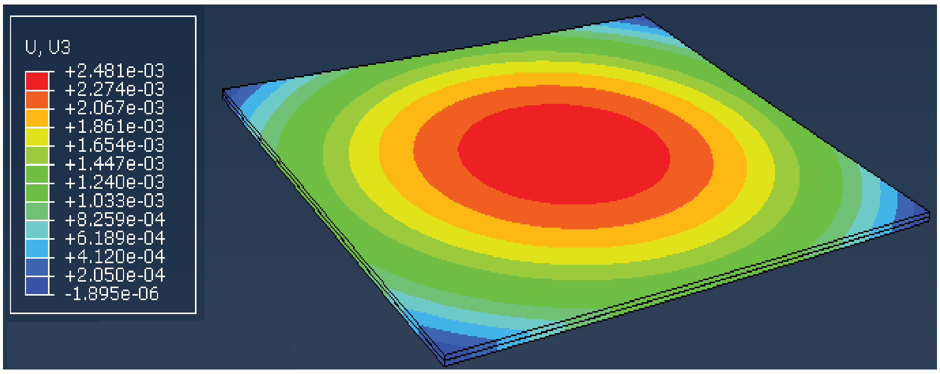

Fig. 6 Deflection of vacuum glazing with a rigid edge seal

TABLE I
SIMULATION RESULTS FOR THREE EDGE SEAL SCENARIOS FOR VACUUM GLAZING

	Flexible Edge Seal & Un-Pinned Pillars	Flexible Edge Seal & Pinned Pillars	Rigid Edge Seal & Pinned Pillars
Shear stress on pillar	100 Pa - 20 MPa	10 Pa - 70 MPa	10 Pa - 0.9 KPa
Pillar deflection	Max: 1.9 μm	Max: 2.47 μm	Max: 1.36 μm
Shear stress on edge seal	2 KPa	0.5 KPa	Average: 13 KPa
Edge seal deflection	Max: 12.15 μm	Max: 10.3 μm	Max: 1.55 μm
Glazing deflection	2.3 mm	2.36 mm	2.4 mm

In Fig. 7 the red line shows the bending pattern of this glazing where the glazing has a larger deflection (2.4mm) than those of the flexible cases. This is a result of the edge seal preventing any relative movement between the panes causing the glazing to bend further. The simulation result for this particular case is presented in Fig. 6.

The mean shear stress across the edge seal is 13 KPa resulting in a mean deflection of 1.55 µm. The shear stress at the glazing corners can be as high as 1.4 MPa.

In this scenario, the shear stress imposed on the pillars and their deflection can be up to of 0.9 KPa and 1.36 µm, respectively. These values are smaller than those of the flexible sealed glazing as the rigid edge seal accommodated a larger proportion of the shear stress.

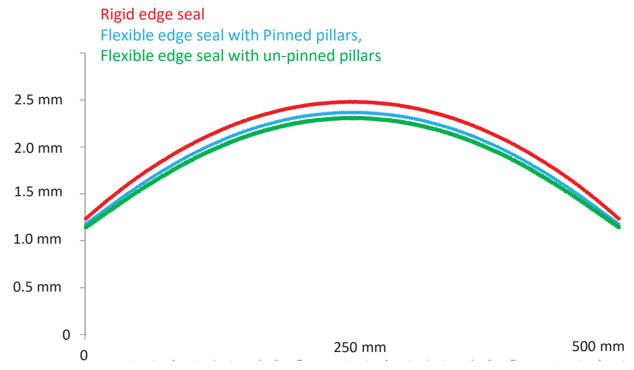

Fig. 7 Deflection due to temperature differentials

VI. DISCUSSION

To compare the three-vacuum glazing edge seal scenarios, the simulation results are summarised in Table I. Bending occurs in each glazing due to temperature differentials, however the difference between the bending is small (0.1 mm). The reason for bending in vacuum glazing with a flexible edge seal and un-pinned pillars is that the thickness of the edge seal is very small (0.15 mm) and as a result the seal cannot accommodate the movement of the panes relative to one another. In addition, the friction between the pillars and the glass panes is large enough to prevent the glass panes from moving independently. Therefore there may be limited benefit in using flexible edge seal materials to reduce the bending of vacuum glazing due to temperature differentials.

Flexible edge seals have smaller shear stresses in comparison with rigid edge seals. This indicates that flexible edge seals may be more durable than rigid edge seals which would result in vacuum glazing with a longer life-span. Conversely, flexible edge seals result in larger deflections of the panes which may require a purposely designed window frame to accommodate the deflection.

In any vacuum glazing made with either a rigid or flexible edge seal, the support pillars are effectively fixed to both panes. This is because atmospheric pressure imposes significant forces on both pillars and panes. This results in large frictional resistance between them, preventing any relative movement.

In this scenario, the edge seal accommodates the least shear stress (0.5 KPa) which improves durability of the edge seal; however the support pillars accommodate the largest shear stress. In the long term, this stress may damage the pillars and the glass panes. It is therefore necessary to design support pillars to withstand these stresses.

VII. CONCLUSION

The concept of flexible edge sealed vacuum glazing has been proposed to address stress related issues including bending of the entire glazing and to reduce the possibility of edge seal failure due to temperature differentials. However, using finite element modelling it has been found that flexible edge seals may have little effect on vacuum glazing bending profile, but may have a significant impact on reducing shear stress in the edge seal. This would help improve the durability of the edge seal over its life-span.

It has also been found that flexible edge seals have larger deflections due to temperature differentials in comparison with rigid edge seals; as a result a purposely designed window frame is required to accommodate the deflections.

In all three scenarios the pillars furthest away from the glazing centre had the largest deformations. In vacuum glazing with flexible edge seals and pinned pillars this was the most pronounced (2.47 µm). This may indicate that using a flexible edge seal imposes a restriction on the size of vacuum glazing achievable.

Using flexible edge seals in the construction of vacuum glazing might potentially address some issues but may result in other problems. Further research is required to investigate the impact of larger scale vacuum glazing under a range of environmental conditions.

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REFERENCES

[1] A. Zoller, "Hohle Glasscheibe," *German Patent Application.* 1913; 387655.
[2] R. E. Collins, S. J. Robinson, "Evacuated windows," Solar Energy Vol. 47, No. 1, pp. 27-38, 1991.
[3] R. E. Collins, T. M. Simko, "Current status of the science and technology of vacuum glazing," *Solar Energy*. 1998; 62:189–213.
[4] 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 91 (2007) 290–303.
[5] D. K. Benson, C. E. Tracey, J. G. Jorgenson, SPIE symposium on optics and electro optics. San Diego; 1985.
[6] T. J. Hyde, P. W. Griffiths, P.C. Eames, B. Norton, "Development of a novel low temperature edge seal for evacuated glazing," *Proceedings of the world renewable energy congress VI (WREC2000).* 2000; 271–74.
[7] 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. 37 (2014) 480–501.
[8] E. Bachli, "Heat-Insulating construction and/or lighting element," International Patent Element Number: PCT/CH 86/00166 (1987).
[9] K. Bettger and D.H. Stark, "Flexible edge seal for vacuum insulating glazing units," US patent 20100178439; 2010.

[10] T. P. Kerr, S. B. Lin, P. P. Harmon, W. R. Siskos, J. L. Oravitz, Jr., P. E. Shaffer, “Vacuum insulating unit,” US5124185 A; 1992.

[11] D. J. Cooper, “Vacuum IG window unit with metal member in hermetic edge seal,” US7919157 B2; 2011

[12] T. M. Simko, A. C. Fischer-Cripps, R. E. Collins, “Temperature-induced stresses in vacuum glazing: Modelling and experimental validation,” *Solar Energy.* 1998; Vol. 63, No. 1, pp. 1–21.

[13] A. C. Fischer-Cripps, R. E. Collins, G. M. Turner, E. Bezzel, “Stresses and Fracture Probability in Evacuated Glazing,” *Building and Enoironmenf.* 1995*; Vol. 30, No. I, pp. 41-5.*

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