Understanding Stress Distributions in Wet Glazed Glass Railing Systems

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Abstract

Glass railing systems have become increasingly popular due to their ability to provide unobstructed views and exceptional durability. While mechanical fixation methods are available, glass embedment is often preferred for its aesthetic and structural benefits. Wet glazed glass embedment systems for balustrades involve securing glass panels materials using a polymeric resin, sealant, or grout. These systems must comply with stringent standards and building codes to meet specific safety requirements, making it crucial to understand the performance of the materials involved. This study aimed to develop a comprehensive understanding of stress distribution in polymeric glass embedment materials as a part of a glass rail system. By combining finite element modelling and experimental testing, the research analysed how these materials behave under both wind loading and line loads. The goal was to develop dimensioning equations to optimize embedding design parameters, ensuring safety and performance. The findings are supported by a case study, which provides practical insights into the real-world application of the developed models and material. This case study highlights the importance of accurate stress distribution analysis in preventing failures and ensuring the performance of glass railing systems. The research contributes to the field by offering a framework for better understanding design factors that impact the stress state of glass balustrade systems. These learnings are valuable as they offer context for utilizing embedment materials in various applications beyond glass rail systems, including windscreens, dead load support, and panel stiffening.

Keywords

Glass embedment, Glass rail systems, Finite element modelling, Calculation tool, Case study

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1. Background

Glass railing systems are increasingly becoming mainstream due to their pure glass aesthetics and the invisible nature of their bonding methods. This seamless appearance is achieved by fixing glass panes at their base, which results in a clean and modern aesthetic. Compared to gasket, clamps, or cementitious mounting systems, polymeric embedment materials offer several advantages, including 1) concealed mounting components, 2) reduced glass stress states, 3) retention of glass in the event of failure, and 4) compatibility with laminated glass. These attributes render polymeric embedment an attractive option for glass railing systems.

The acceptance of polymeric embedment materials is contingent upon their capacity to sustain the imposed loads. This performance criterion is governed by local building codes and typically necessitates testing in accordance with established test methods and specifications, such as ASTM E2353 (ASTM 2021) and ASTM E2358 (ASTM 2024). Conducting full-scale mock-up testing, however, can be complex, expensive and time-consuming (Schauss 2019). Consequently, the adoption of finite element modelling emerges as a practical and efficient alternative. Employing this analytical tool can significantly enhance safety and provide a comprehensive understanding of system performance.

The versatility of polymeric embedment materials, when coupled with intricate modelling simulations, facilitates their utilization within diverse architectural contexts. These materials' capacity to accommodate varying load scenarios while sustaining structural integrity renders them highly suitable for high-rise structures and complex geometric designs. Furthermore, their advanced properties and adherence to stringent safety standards underscore their critical role in contemporary construction practices.

These systems not only enhance visual appeal but also contribute substantially to structural robustness, ensuring long-term durability and occupant safety. Ongoing research and development in this domain promise even more innovative applications, further harmonizing aesthetics with functionality in architectural designs.

The goal of the current study aimed to develop a comprehensive understanding of stress distribution in polymeric glass embedment materials as a part of a glass rail system. By combining finite element modelling and experimental testing, the research analysed how these materials behave under both wind loading and line loads. The goal was to develop dimensioning equations to optimize embedding design parameters, ensuring safety and performance.

2. Experimental Procedures

The embedment material properties were derived from testing of DOWSIL™ 375 Construction & Glass Embedding, a two-part polyurethane. Tensile testing in accordance with ASTM D638 (ASTM 2022) was conducted to define material modulus and ultimate tensile strength. Poisson's ratio and CTE values were determined using ASTM E132 (ASTM 2017) and ASTM E831 (ASTM 2024b), respectively. The modelling pass/fail criteria for the embedment material was based upon the tensile yielding stress, which was determined to be 11.2 MPa. The polymer exhibits typical elastic plastic material behavior, including elastic region, yielding point and hardening region (Figure 1). A nonlinear elastic plastic model is used for modeling purpose to perform overall design guidelines evaluation (Equation 1). Parameters of the model are provided in Table 1.

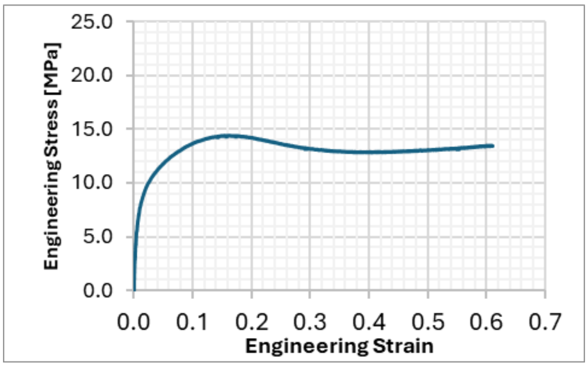

Figure 1: Averaged stress-strain curve for DOWSIL™ 375

$$\sigma(\varepsilon) = \begin{cases} E\varepsilon & for\ \varepsilon \leq 0.009 \\ \sigma_e(1+\varepsilon_e) & for\ 0.009 \leq \varepsilon \leq 0.162 \\ Kexp(M\varepsilon^{\beta}) & for\ 0.162 \leq \varepsilon \leq 0.610 \end{cases} \quad (1)$$

The commonly accepted elastic properties of aluminium were also used (Abaqus 2025). Typically, laminated glass is used for safety applications. The different existing interlayer and their mostly varying mechanical properties as function of temperature make testing and modelling exercises complex (Schauss 2019). To limit complexity, only 1 type of interlayer is considered in this study (PVB). PVB is modelled as elastic plastic material, based on property reported in literature (Zhang 2015), with an effective modulus of 52MPa, a Poisson's ratio of 0.485 and yielding stress of 2.725MPa. Only two thickness of glass (6mm or 12mm for a total laminate thickness of 12mm or 24mm) using this interlayer were considered. It was assumed that different laminate types could be reduced to an equivalent monolithic glass thickness, following methodologies such as those described in (Haydar 2023). The commonly accepted elastic properties of glass were selected from the finite element software database. A summary of the used modelling inputs is shown in Table 1.

Table 1: Defined elastic material inputs used for finite element modelling.

Parameter	Units	Embedment Values	Aluminium Values	Glass Values	PVB
Modulus	MPa	896	69000	70000	52
Poisson's Ratio		0.26	0.33	0.22	0.485
Yielding stress	MPa	11.2			2.725
K	MPa	11.595			
M		1.11			
β		1			
CTE	ppm/C	139.6			

Finite element analysis was completed using ABAQUS software. Two designs of experiment (DOE) were completed based on two different loading applications, wind load and line load. For wind loading a force was placed across the entire surface area of the glass. For line loading, the force was placed in a line horizontal to the aluminium rail length at a fixed height (at 1100 mm for glass heights greater than 1000 mm and at 1000mm for glass height equal to or less than 1000 mm). As the focus is on the polymeric material performance and durability, several simplifications were made. The first one relates to the use of PVB only as interlayer. The second simplification assumed a worst-case bonding scenario for the polymer with full adhesion between polymer and glass. The typical installation procedure recommends the use of a release agent to ensure there is no adhesion between polymer and glass, which allows for easy replacement is possible in case of breakage. The absence of adhesion ensures that stress imposed on the polymer is reduced to a minimum. A full adhesion between the embedment material, glass, and aluminium railing as boundary condition represents therefore the worst case for the polymer. The configuration of the material was modelled as shown in Figure 1.

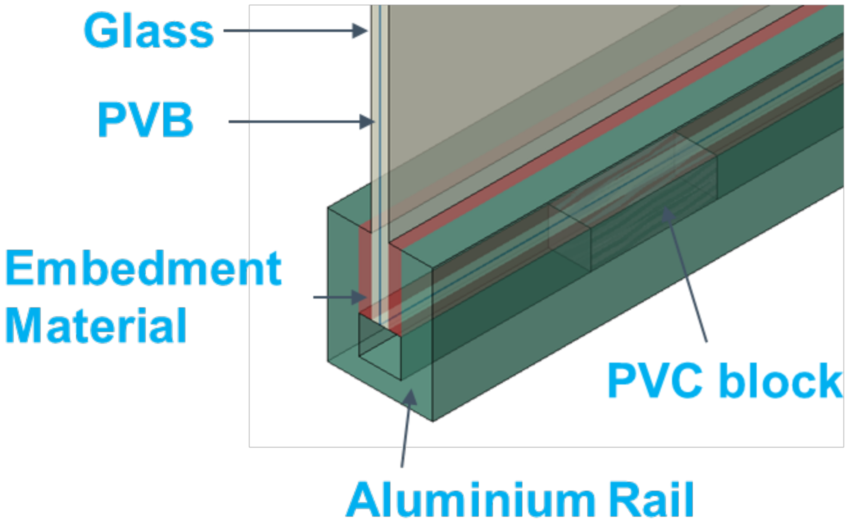

Figure 2: A schematic of the glass embedment system.

Design of experiment for each load type consisted of the different inputs as listed in Table 2 and schematically shown in Figure 2.

Table 2: Design of experiment parameters.

Parameter	Units	Values
Glass Thickness	mm	12, 24
Glass Height Above PU	mm	1000, 1600, 3000
PU Thickness Between Glass and Aluminium	mm	10, 20
Glass Embedment Depth	mm	60, 100, 140
Wind Load Level*	kPa	1, 2, 6
Line Load Level*	kN	1, 2, 3

*Note that only a single load condition was applied for either DOE

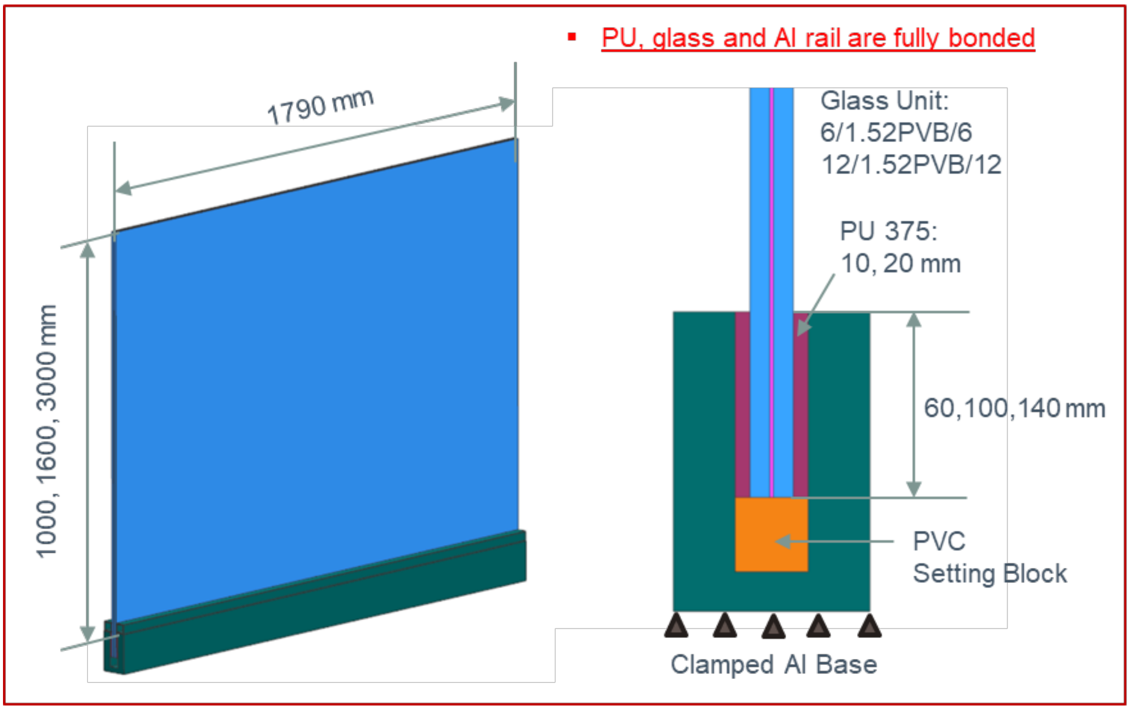

Figure 3:: A schematic of the modelling inputs utilized in the DOE.

3. Results & Discussion

A representation of how the stress distributes locally within the embedment material is displayed in Figure 4. As highlighted, stresses are concentrated at the top of the embedment material, where it first contacts the wind-loaded or line-loaded glass. It is noted that stress is dissipated quickly through the thickness and depth of the embedment material.

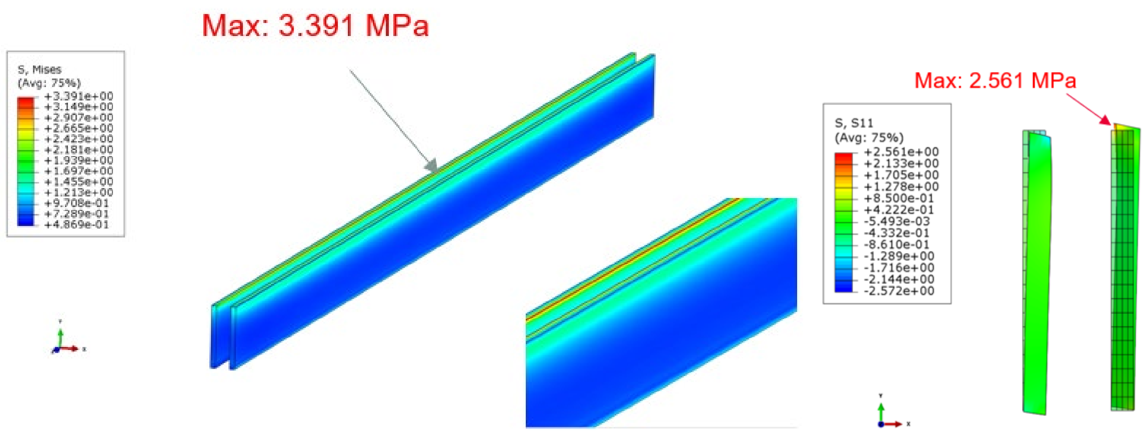

Figure 4: Stress output for a single condition highlighting the stress distribution through the embedment material.

While the magnitudes of the wind load DOE and the line load DOE differed, the trends of the stress maximum stress state of the embedment material versus each variable were similar. These trends can be observed in Figure 5 (showing only the wind-load data). The largest impact to the embedment material stress was the glass height, displaying a mostly linear trend, increasing with additional glass height. The amount of loading also had a significant impact on embedment stress, but it is noted that this trend was dampening with additional wind load. More moderate impacts were observed with the glass thickness and glass embedment depth, each resulting in lower stress with increasing glass thickness and increasing glass embedment depth. The thickness of the embedment material displayed the lowest impact to the stress, showing a nearly flat trend as the embedment thickness varied.

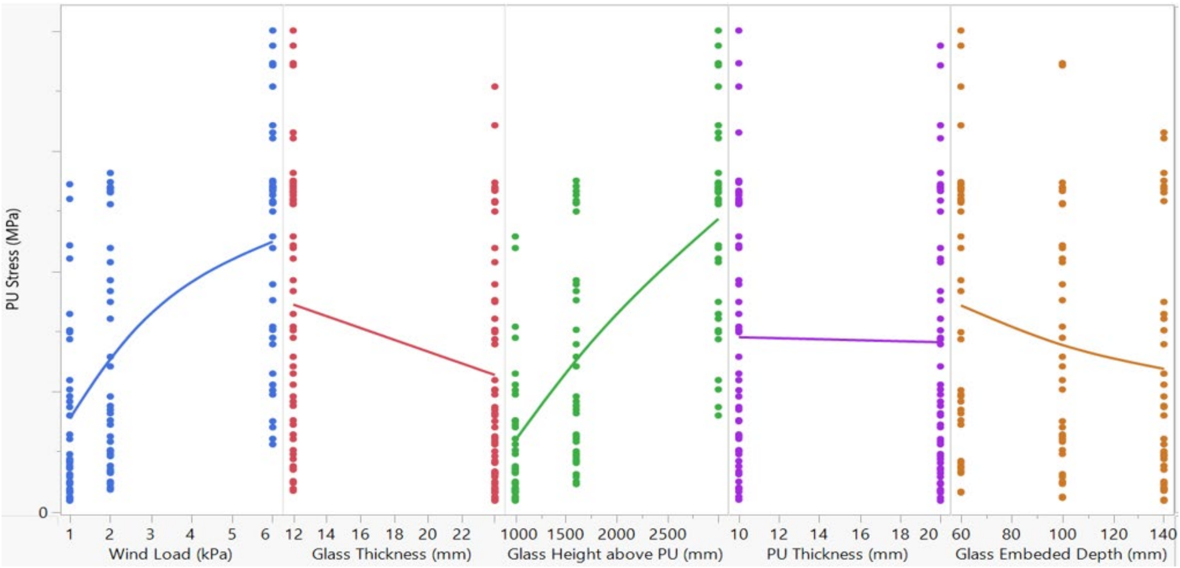

Figure 1: Embedment stress (PU Stress) as a function of each model input.

Reasoning for the smaller impact of embedment thickness and glass embedment depth can likely be rationalized by Figure 4, where the stress was shown to localize at the point where the embedment material and glass first make contact. Moving away from that point – either downward toward the base or the wall of the aluminium railing – resulted in a significant and almost immediate drop in stress within the embedment material. Therefore, any reasonable changes to these dimensions were unlikely to significantly impact the maximum stress state.

Conversely, the largest impact to embedment stress was observed to be the loading amount and the glass height. As the stress concentrated at that point, it logically follows that any factors that result in a higher force, such as load amount or glass height, are likely to have the greatest impact.

In comparison to alternative fixation methods, such as clamps, point-applied grout, or mounts, the stress state in the as-modelled polymeric embedment material is anticipated to be significantly lower since the force is dissipated uniformly through the length of the embedment material. A similar trend of lower stress state in the embedment material is likely when comparing the polymeric embedment material to that of a cementitious grout since the lower modulus of the polymer can better dissipate stress yet is still rigid enough to withstand significant loading events. The lower stress at the embedment/glass interface is likely to result in less glass breakage glass for polymeric embedded systems.

As a result of the modelling, multi-variable functions were created to predict the maximum embedment stress for either 1) wind load or 2) line load. To ensure good accuracy between the model and equation, up to third order equations were needed to fit equation factors. A generic form of the function is shown in Eq. 2.

$$\begin{aligned} &Maximum\ Predicted\ Embedment\ Stress \\ &\qquad = f(wind\ load\ or\ line\ load) + f(glass\ thickness) + f(glass\ height) \\ &\qquad + f(embedment\ thickness) + f(embedment\ depth) \end{aligned} \tag{2}$$

From this, the output could be compared against the maximum allowable tensile stress (11.2 MPa) to determine whether the specific conditions/inputs would result in a stress state beyond the mechanical limitations of the material, making it a practical tool in design and application.

Practical use of the glass embedment material can be supported in real-world application. One such use was in the design of the windshields of the Deos Mykonos Hotel, which were installed in 2023, and is highlighted in Figure 6. In this application the windshields were up to 2810 mm tall, 40 mm thick, and constructed of low-iron, tempered, heat-strengthened glass.

Figure 2: An image of the windshields at the Deos Mykonos Hotel.

4. Conclusions

This study has provided a comprehensive analysis of stress distribution in polymeric glass embedment materials within glass railing systems, employing both finite element modelling and experimental testing. The findings underscore the critical importance of accurate stress distribution analysis in preventing failures and ensuring the optimal performance of glass railing systems.

However, it is imperative to acknowledge the limitations inherent in the presented model. Firstly, the model's applicability is confined to conditions within the boundary limits defined by the design of experiments. This implies that the model may not be reliable beyond the specified parameters, thereby necessitating caution when extrapolating results to different scenarios.

Secondly, the model is intended solely as a preliminary design guide. While it provides valuable insights into the stress behaviour of embedment materials, it should not be considered a definitive solution for all design challenges. Engineers and designers are encouraged to supplement the model's findings with additional testing and validation to ensure comprehensive safety and performance.

Thirdly, the material inputs used in the model were derived from single data point testing. This approach, while informative, may not fully capture the variability and nuances of material properties in different conditions. Consequently, the results should be interpreted with an understanding of this limitation.

Furthermore, it should be noted that material properties can vary significantly depending on local ambient conditions, such as temperature, humidity, and exposure to environmental factors. These variations can impact the performance of the embedment materials, necessitating context-specific adjustments and considerations in the design process.

In conclusion, this study contributes valuable knowledge to the field of glass railing system design, offering a robust framework for understanding the stress distribution in polymeric embedment materials. While the model provides a solid foundation for preliminary design, it is essential to recognize its limitations and augment it with comprehensive testing and real-world validation. By doing so, the safety and performance of glass railing systems can be enhanced, ensuring their continued success in modern architectural applications.

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