Design of a Single Span Nine Metre Long Glass Bridge

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Halcrow Yolles was retained to conceptualize ideas for a glass bridge designed to span across the main lobby of a new hotel. Its defining feature, laminated glass balustrades, span continuously over the entire nine metre opening. Design work for the bridge was completed using a finite element model of the entire bridge allowing for a detailed analysis of stress concentrations in the glass at bearing bolt connections. Special attention was paid to the transportation and erection of the bridge to ensure that the large panels remained intact. This project demonstrates how state of the art glass production techniques in combination with leading edge design methodology can lead to architecturally interesting structures.

Keywords: Glass, Bridge, Laminated, Polyvinyl Butyral Interlayer, Finite Element Analsysis

1. Introduction

The owners of a new hotel in downtown Toronto, Canada were looking for a unique focal point to complete the look of the building's lobby. Several glass structures were considered and, with Halcrow Yolles' assistance, it was decided that a glass bridge spanning across the lobby on the mezzanine level would be the best option. The design of the bridge evolved though several iterations, with less steel incorporated each time. Finite element analysis was carried out after each major design change to ensure that the bridge remained structurally feasible. The final design, while simple, elegant and economical, presented unique challenges that arose from working with large pieces of glass. Aside from the difficulties of transporting and erecting the large panels, special consideration had to be given to the bridge's overall stability should accidental breakage occur. Through coordination between the building's owner, architect, engineer and the bridge contractor, this unique structure was designed, transported and assembled successfully.

2. Concept

2.1. Original idea

The initial idea, which involved hanging a glass walkway from the lobby's ceiling by means of stainless steel tension rods, was quickly replaced with a free spanning glass bridge. A design that utilized the balustrades as the main structural members was deemed capable of bridging the ten metre opening. While the span was achievable without the need for intermediate supports, it was too long to be constructed with continuous sheets of glass. Consequently, splice joints were used to splice together three separate panels to create a continuous glass beam long enough to span the distance. The

joints consisted of stainless steel brackets located at the top and bottom of each pane, connected by a pre-tensioned, stainless steel rod (figure 1). At either end of the bridge, the balustrades are supported by steel shoes, as illustrated in figure 2. Nylon shims were used in the bottom and at the sides of the steel shoes to ensure proper contact was made between the glass and steel. These were crucial in accounting for any inconsistencies in the alignment of glass edges. At one end of each balustrade, a through bolt was used within the shoe to create a pinned connection. The other end was left free to move in order to accommodate any movements. To support the glass floor panels that make up the bridge deck, laminated glass cross beams were spaced at 2100 mm on centre. The floor panels were secured to the tops of the cross beams using structural silicone and resin, thus allowing the floor to act as a continuous diaphragm (figure 3). The beams were connected to the balustrade using two custom stainless steel brackets located at the top and bottom of the cross beam (figure 4). By designing this particular connection using a detailed finite element analysis, the amount of steel required to properly restrain each beam was minimized, thus maintaining the transparency of the structure. A hand rail was added along the top of each balustrade to satisfy the requirements of local building codes. In addition to their intended purpose, the hand rails were found to provide additional lateral support at the top of each balustrade even though the analysis proved that the bridge was stable without them.

Figure 1: Balustrade splice connection (initial concept).

Figure 2: Steel shoe with through bolt.

Figure 3: Cross beam to floor panel connection.

Figure 4: Cross beam to balustrade connection.

2.2. Redesign

After consultation with the bridge contractor, Gartner Steel and Glass GmbH, it was determined that, by reducing the length of the bridge by half a metre on either side, the previously spliced glass balustrades could be fabricated from one piece. This proved to be very desirable to all parties involved as it made for a cleaner, simpler structure at a decreased construction cost. While advantages in many ways, the large panels of glass that the redesigned structure relied on made handling the various components more difficult, particularly during transport and erection. The remaining structural glass components and all other connections remained unchanged. However, steel platforms were used at both ends of the bridge to fill in the half metre gap left from the shortening the structure.

2.3. Connections

During the design of the glass bridge, both bearing and friction bolts were considered as possible means to connect the various elements together. By drawing on past experience in the design and assembly of glass structures, it was decided that for several reasons, bearing bolts would be the preferred connection mechanism [1]. While friction bolts are capable of carrying higher loads, the realities of onsite assembly render them difficult to use or impractical. This is because of the need for different interlay materials surrounding the connection to make them work and the very small tolerance afforded by this method of construction. The final bearing bolt assembly consisted of a stainless steel bolt in an oversized hole surrounded with resin injected through the head of the fixing. The resin was injected after the various elements were aligned to ensure consistent contact between the bolt and glass.

2.4. Interlayer and glass selection

To ensure that the most efficient and safe system was designed, varying glass compositions were used for the different glass elements. The glass floor panels consist of three lites of glass laminated with a polyvinyl butyral (PVB) interlayer. The top lite is fully tempered in order to increase the impact resistance of the assembly. The bottom two lites are heat-strengthened glass to ensure adequate post breakage rigidity. The cross beams and balustrades were both made up of three lites of glass laminated with a PVB interlayer. The outer lites were fully tempered glass, while the middle lite was made of heat strengthened glass. This composition was chosen to maximize the overall strength of the assembly while ensuring adequate post breakage rigidity. Using an ionoplast interlayer was considered for both the beams and floors; however, it was determined that any benefit from using the material would not warrant the additional cost.

3. Design

Analysis and design of the glass bridge was conducted with the aid of a finite element model constructed in RFEM 4 [2]. The geometry of the model, shown in figure 5, incorporates all significant components of the bridge, including the resined bearing bolt connections, which allows for accurate evaluation of glass stresses at bolt holes. In addition, it was used to obtain input data for design of the balustrade to floor beam connections and supports.

3.1. Structural glass members

The decision to design the bridge utilizing a finite element analysis program was driven by the need to accurately evaluate stress concentrations in the glass members. Although the relatively simple structural configuration of the bridge yields itself to straightforward determination of bending stresses in the cross beams and balustrades, the use of bearing bolt connections to connect these two members creates amplification of tensile stresses at bolt holes which has the potential to govern the design [3].

All three types of glass members were modelled using shell elements with the thickness being equal to the total thickness of glass in the respective elements. In the case of the balustrades and cross beams, the decision to neglect the effect of the interlayer was considered justified as a majority of the force in these elements acts in the plane of the glass. This is not the case for the floor panels which undergo out-of-plane loading from live load and their own self weight. Consequently, these were sized based on an analysis completed in SJ Mepla, a finite element program capable of properly simulating the behaviour of laminated glass loaded out of plane [4]. Nevertheless, in the global model, the floor was assumed to be made up of monolithic glass. The use of solid elements was considered because it would have permitted stress gradients across the thickness of the glass to be captured. This would have been especially beneficial in the case of the balustrade which is loaded eccentrically by the connections to the cross beam. Practically, however, it was believed that the use of resin in bearing bolt connections would evenly distribute the force from the through bolt across the entire thickness of the glass panel. Use of solid elements would also result in a prohibitively long analysis. Allowable stresses used in the design were obtained from ASTM E1300-04 and were adjusted for load duration according to the type of loading [5].

3.2. Connections

The stainless steel connections between the beams and balustrade were incorporated into the finite element model using frame elements, as illustrated in figure 6. Since each arm is composed of welded steel plates, each was assumed to be a rigidly constructed element with no releases. Both through bolts were taken to allow rotation at their intersections with glass elements as well as about their own longitudinal axes. Moreover, in order to obtain the desired behaviour at the bearing bolt connections, the resin was simulated using the masonry shell type in RFEM which transfers only compressive stresses, thus allowing for an accurate determination of the level of stress concentration at the bolt holes. The same type of shell element was employed to model the structural silicone bead between the floor panels and cross beams.

3.3. Supports

As stated earlier, the structure is principally held in place by steel shoes onto which the ends of the balustrades bear through a nylon padding. For the purpose of the analysis, these supports were modeled as compression-only shell elements with dimensions equal to those of the proposed nylon padding sitting on vertical line supports. Effectively, this assumes that the shoes and elements supporting them are perfectly rigid. Longitudinal support was provided by means of a bearing bolt connection through the balustrades at one end of the bridge while leaving the other side unsupported thus achieving a simply supported system. This connection was modelled in the same manner as that between the cross beam to balustrade. Finally, both handrails were pinned at both ends as, at the time of design, it was unclear what structure these would be tying into. However, it

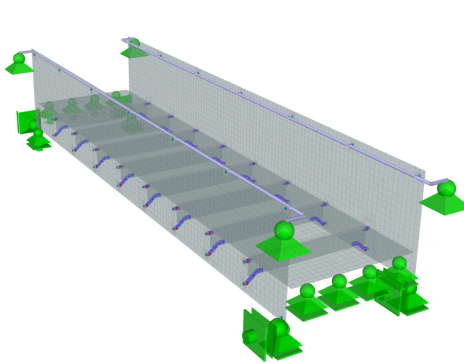must be said that the bridge was designed to safely carry all loads without the contribution of the handrails.

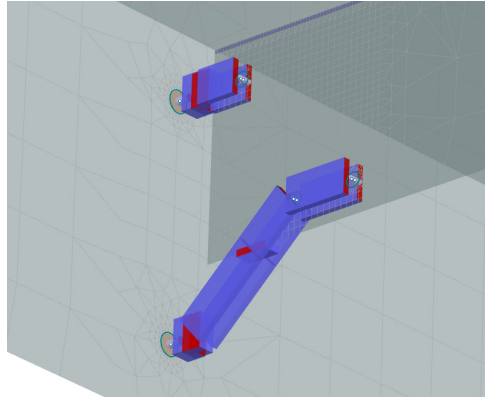Figure 5: Finite element model of glass bridge.

Figure 6: Connection between cross beam and balustrade

3.4. Loading

The loads imposed on the bridge and the combinations analyzed were governed by the National Building Code of Canada [6]. In addition to dead, live and guard loads, asymmetrical loading were considered. Live load was applied to the model as a uniformly distributed surface pressure while, guard loads were assumed to act at the top of the balustrades.

3.5. Analysis

In order to achieve accurate results around bolt holes and in other critical locations, mesh refinement was employed. This technique permits steep stress gradients, which often occur at the areas in question, to be captured in the analysis. Since a particular connection detail is used multiple times, it was necessary to use the denser mesh only in the location where the highest stress is known to exist, thus saving analysis time. Furthermore, a non linear analysis was performed in order to capture any second order effects. This is particularly useful when considering the stability of the structure which is supported by beams with laterally unsupported compression flanges. A separate analysis was conducted assuming the case when one of the lites in the balustrade was broken. This was carried out to ensure that the bridge would not fail catastrophically in the event of accidental breakage. In addition to ensuring that the bridge is capable of withstanding all possible load combinations, a modal analysis was conducted in order to make certain that vibration of the structure would not be an issue. Furthermore, an elastic buckling analysis was conducted to guarantee that the balustrades are in no danger of buckling under the worst case load combination. This was also back checked with a separate hand calculation employing a procedure used to estimate the buckling factor of U-trusses.

3.6. Results

Results from the finite element analysis were used in sizing the glass and steel elements which make up the bridge. The model's ability to determine the stress concentration around bearing bolt connections, as shown in figure 7, allowed for more accurate

determination of the required bolt and hole diameters, as well as the thickness of the glass and type of heat treatment for the glass. In order to keep a reasonable margin of safety and maintain flexibility, the first three elements were selected so that the maximum principal stresses at the connections did not exceed the allowable stresses for heat strengthened glass, thus allowing for its use along with that of the fully tempered variety. As predicted, these stresses, determined to be 23 MPa in both cases, were significantly higher than those arising from bending of the cross beams and balustrades. Furthermore, the relatively high stiffness of the balustrades resulted in vertical live load deflections of less than 5 mm over the 9 m span. However, as expected, a significant inward lateral deflection was noticed at the top of the balustrades under gravity loading (figure 8). This behaviour, common in U trusses, is exacerbated by the uniformly distributed guard load which must be applied to the top of the balustrade. Nevertheless, the maximum deflection of 13 mm predicted by the model was still well under that allowed for guards by the building code. The output of the modal analysis showed the period of the structure to be over 10 Hz, thus making it unlikely that the bridge can be excited at its resonant frequency by occupants [7]. Finally, both stability analyses conducted revealed that the equivalent buckling factor for the balustrades is at least ten relative to the maximum live load.
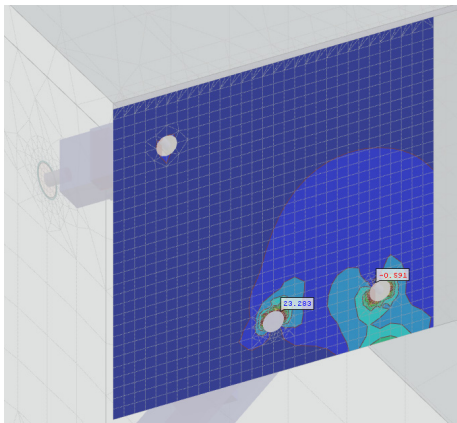

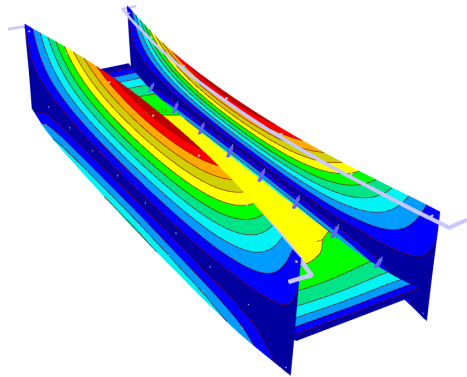Figure 7: Maximum principal stresses in cross beam at connection.

Figure 8: Deflected shape.

4. Fabrication and erection

One challenge to the construction of the bridge was the transportation and erection of the structure. The components of the bridge, including the nine metre long laminated balustrades were manufactured entirely in Europe and had to be transported to Canada. This was facilitated by securing the balustrades into custom made steel frames at the source of production (figure 9). These were then shipped by sea along with all of the other components to site for assembly. Scaffolding was first erected to support the balustrades which were still mounted in the steel framing while the shoes and infill pieces were mounted to the base building (figure 10). The glass cross beams were then aligned to the balustrades and held in place while the floor was installed and the steel connections were assembled. The last step prior to the removal of the temporary supports was injecting resin in of all bearing bolt connections. As the bridge was

completed prior to the rest of the lobby, protective measures had to be taken to avoid damaging the glass. The steel frame used for erection was left on site for the owner in the event that either of the balustrade panels were accidently broken. This was critical as the nature of the design meant that the entire bridge had to be shored in order to replace a balustrade.

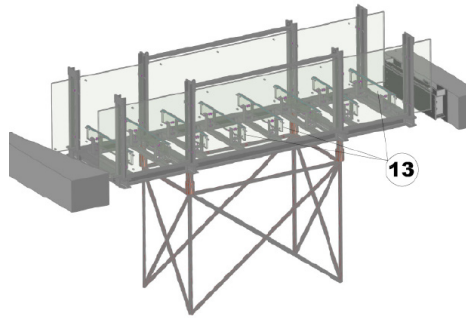Figure 9: Glass balustrade supported in temporary steel frame.

Figure 10: Erection sequencing as provided by Gartner Steel and Glass GmbH.

5. Conclusion

This project underwent considerable changes from time of conception to completion. As understanding of the availability of unique glass products grew, the design was adapted to incorporate the latest advances in structural glass design. This resulted in a structure with maximum transparency and little steel needed to span the relatively large distance. Furthermore, modeling the bridge using the latest advancements in finite element analysis led to a simple but effective design which was flexible enough to easily accommodate various changes that occurred during the history of the project. Through a close working relationship with all parties involved the most innovative solution was realized.
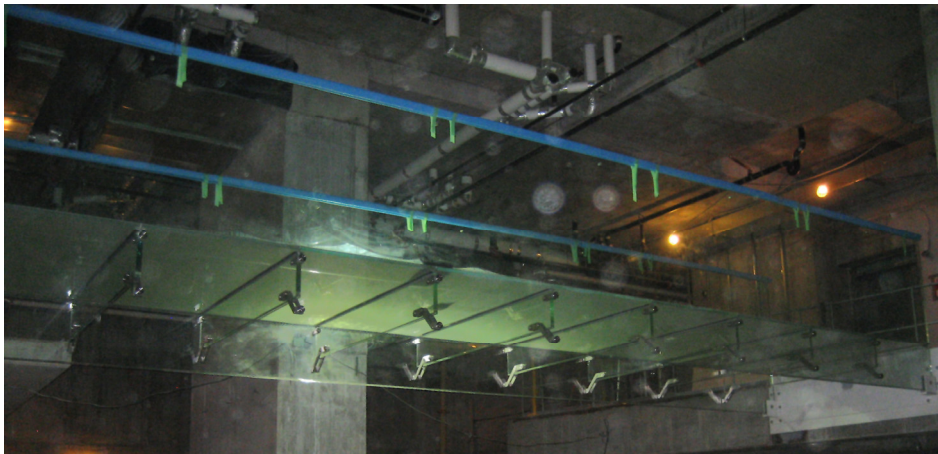

Figure 11: Completed glass bridge.

6. Acknowledgements

7. References

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