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The Ledge
Structural Glass Observation Boxes at the Willis (Sears) Tower

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Abstract

The owners of the Willis Tower (formerly the Sears Tower) were looking for a new attraction to help stimulate interest in the observation deck level at the 103rd floor. The concept was to create a glass box outside the existing façade that would allow patrons to walk outside beyond the face of the curtain wall and look straight down 1350 feet (411.5m) to the sidewalk below (See Figure 1). They wanted it to feel like you were walking on air and offer new unobstructed panoramic views of the city of Chicago. Naturally, there would be some challenges. First and foremost, the observation boxes had to be designed to retract into the building in order to allow for the window washing equipment to travel along the façade and to facilitate a maintenance program for the units. Secondly, it had to withstand very high wind loads. Thirdly, it had to be void of any continuous steel or aluminum members along the vertical walls and horizontal floor so that any connection would not distract from the view, or obstruct the view. Finally, the assembly had to be comprised of parts that would fit in the freight elevator and allow for installation to take place on the floor until fully assembled and then get pushed out through the new opening in the existing façade. This paper will look at the solutions for these design challenges and offer insight to the design and construction of this landmark attraction.

Figure 1: Observation Boxes at the 103rd Floor

Keywords: Structural Glass, Laminated, Tempered

1. Introduction

The four glass observation boxes (now referred to as "The Ledge") have a footprint approximately 1.3 m x 3.2 m in plan and are close to 3.6 m high. The walls, roof, and floor are all fabricated from laminated tempered glass. Our goal was to create this glass structure with as little structural steel or aluminum elements as possible, and to ensure that any support structure required was above the viewing lines of the patrons. As the lead engineer for the project, this challenge was met with excitement, but most of all, with a sheer determination to create something spectacular for an iconic landmark building. Despite the high wind loads, the lateral drift of the building, the requirement for moving the boxes in and out, the thermal stresses they would be exposed to, there was no way that we would accept a steel frame at the floor level and corners of the walls to support the glass and its patrons. Maximizing the "fear factor" effect of the attraction while engineering a safe structure that could obtain a building permit from a conservative city made for a very interesting project that had budgets and schedules to adhere to like any other project.

2. The Concept

It was decided early in the design phase to create a stiff steel braced structure that would be hung from the ceiling structure of the 103rd floor observation deck level. The only portion of the steel frame that would be exposed and project beyond the existing façade would be a perimeter cantilevered tube section as shown in Figures 2 and 3. The perimeter tube would provide a structure that the glass box could be hung off of, and allow for forced air to be pumped through the section and blow onto the glass to help control condensation. The stiff frame itself allowed for the assembly to be hung off a rail system in the ceiling and be pushed or pulled into position by the linear beam oscillating motor. This ensured that the boxes could be retracted flush to the building face during window washing and also be retracted 1.3 meters into the building for any maintenance on the boxes themselves. This solution meant we could assemble the boxes on the floor with minor hoisting devices and eliminate the need for any external cranes during construction or any other time during the life of the attraction and also ensured we did not have to modify the automated window washing systems already in place on the tower.

The top rails were used to support the weight of the glass boxes. The bottom rails were used to provide added lateral stability. Both rails would be used to lock the glass boxes into predetermined positions along the tracks so that the oscillating motor would not have to withstand high wind force pressures while not in operation. These observation boxes are left extended in the "viewing position" at all times of the year despite any threat of high wind storms. They are only retracted when the west face of the tower is having its windows washed, or if there is any maintenance required to the boxes themselves.

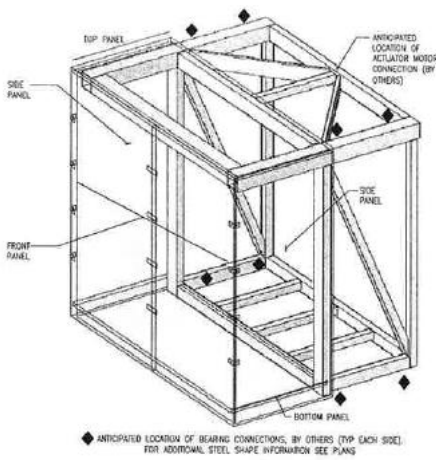

Figure 2: Isometric view of Steel Frame and Glass

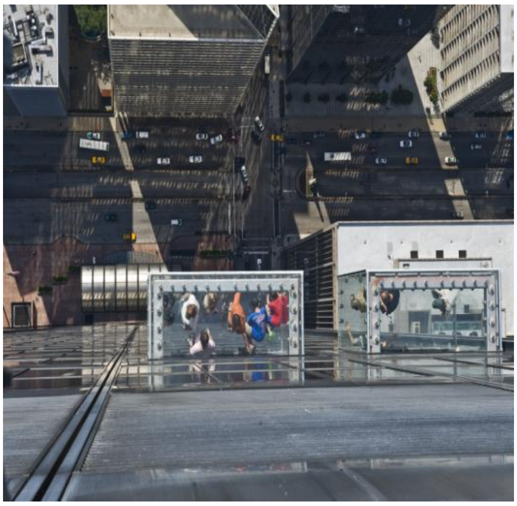

Figure 3: View from Above

3. Forces of Nature

As previously mentioned, the observation boxes are designed to withstand significant wind loads. Apart from the obvious requirement to design the floor glass to support a live load of 4.8 kPa due to its intended occupancy, the faces of the glass box were designed to resist a wind force of ±4.6 kPa and the roof and floor to resist a wind force of 6.0 kPa. As an assembly, the glass box had to be stable on its own and stiff enough to resist large movements due to the wind loads. This was necessary because the boxes had to be able to move in and out of the building, and therefore, could not rely on any mechanical connection to the tower structure or curtain wall.

4. The Details

In order to minimize the opaque structural elements at the floor and walls, the wall panels were hung off the cantilevered steel frame at the ceiling level of the glass boxes with threaded pins (See Figure 4). The corners and intermediate joints where the different wall panels came into contact with each other were simply stitched together with stainless steel angles and through bolts. The floor, similarly, was stitched to the glass walls creating small local opaque connections that would allow for the transfer of external loads into the hanging glass panels and subsequently, into the steel cantilevered frame (See Figures 5 and 6).

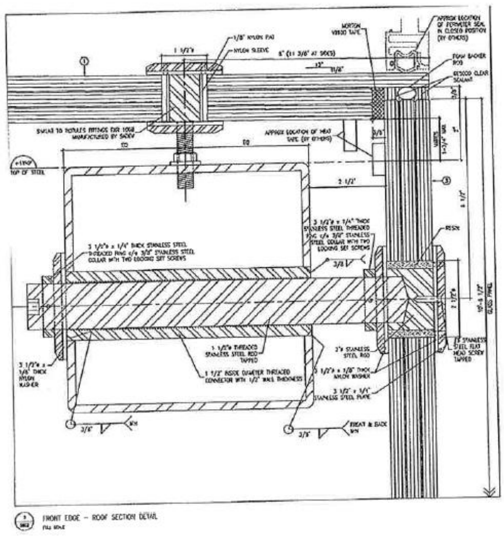

Figure 4: Glass Panel Hanging Detail

Figure 5: View from Below

Figure 6: Interior View of Observation Box

All the holes in the glass were oversized to allow for tolerances in fabrication and erection. This also allowed for different support conditions at each hole to ensure thermal movements were incorporated into the design elements and did not create high stress points due to locking the overall system into place. This was achieved by specifying three different types of bolt connection details. Firstly, there was the fixed point connection which required the oversized hole to be filled entirely with a Hilti HY-70 resin ensuring that the through bolt was in full bearing in all directions. The second utilized an oval bushing within the oversized hole so that the resin infill would only lock the bushing into place and still allow movement within the hole in either a horizontal or vertical direction. The third required locking the through bolt into position under very light loads only, but could allow movement in all directions at the same time when subjected to higher wind loads or thermal loads. This was accomplished by filling the oversized hole with silicone (See Figures 7 and 8).

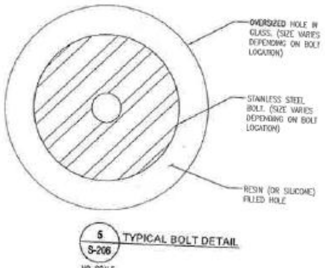

Figure 7: Tyipical Bolt Detail

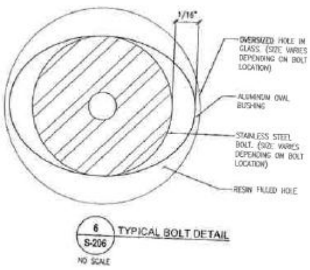

Figure 8: Typical Bolt / Oval Bushing Detail

The combination of these fastening types placed in the appropriate locations allowed the completed assembly to live and breathe with the elements of wind and temperature without overstressing any connections in the glass.

Allowing the glass observation boxes to retract into the building required more than just a linear beam oscillating motor. There were two other issues that needed resolution. Firstly, the seal between the existing curtain wall and the glass boxes had to allow for the movement of the boxes without tearing out the weather seals each time it moved. This was achieved using a pneumatic vulcanized seal that would deflate when the box was in motion, and inflate when the box was in position. Secondly, the boxes had to be able to retract within the floor of the observation level with minimal effort. The observation level has a raised floor which accommodated the guide rails; however, the raised floor elevation was in line with the glass floor of the observation boxes and would be in the way during the retracting exercise. To eliminate this issue, the floor directly behind the glass boxes was attached to a small custom made pneumatic lift that would allow the floor panels to drop below the glass box and effectively remove themselves as an impedance to the operation.

5. Life Safety

As with any structural design, human comfort and safety are a necessity. Several issues required our attention. First and foremost, the glass had to be designed with enough redundancy to ensure that any accidental breakage would not result in a total collapse of the system. For this reason, three layers of glass were selected for all the elements. The structure was designed so that only two layers of glass were required to resist the design loads, and only one layer of glass would be able to support the self weight of the structure. In addition to this design decision, the glass floor was constructed using an ionoplastic interlayer (Sentry Glass) captured by the through bolts in the floor which would ensure the stiffness of the tempered floor panel would remain in-tact in the remote possibility that all three structural glass lites failed (See Figures 9, 10 and 11 for post-breakage behaviour). In the end, the glass box elements are all created with three layers of 12 mm tempered low iron, heat-soaked glass. The latter requirement of heat-soaking, naturally helped eliminate the potential for spontaneous breakage due to nickel-sulphide inclusions.

Figure 9: Mock up of Wall and Floor Panel

Figure 10: Loaded Mock up

Figure 11: All Floor Panels Broken Retain Stiffness

To assist in protecting the glass surfaces from scratches that could cause the inner lite to fail, a safety film was applied to all the walls. This 3M product will protect the glass surface from scratches and any attempt at graffiti. It is easily replaced and maintains a level of security against accidents or vandalism. The floor glass on the other hand, has a floating sacrificial layer on top with a 3M film between it and the structural glass. Again, a necessity to ensure that the structural glass is protected at all times, especially since there is no restriction against foot attire permitted on the glass floor. It is better to replace the 6 mm sacrificial lite than to replace the entire laminated floor assembly!

Lastly, the effects of Mother Nature can cause dangerous conditions to occur to the public at ground level as well. Ice formation on the face of the glass boxes or along the edges of the underside could create undesirable conditions. In order to alleviate this situation, heat tracing cables were introduced in strategic locations to maintain a minimum temperature along critical areas of the glass box.

6. Conclusions

The Ledge attraction at the Willis Tower has accomplished everything everyone was hoping for. It is a successful structural glass element that achieved maximum transparency while accommodating several design requirements and city approvals. Since it opened in July 2009, attendance to the observation level has essentially doubled. Structural glass is being utilized in far more complex projects today, and this is proof that we, as designers, are only limited by our imaginations.

7. Acknowledgements

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