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TKTS – Tilted Glass Bearing Walls and Glass Roof

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The TKTS booth in Times Square, New York, is a 250m^2 all glass public amphitheater, with seating for 500 people. Its all glass load path includes treads, rafters and the 4.9m tall SentryGlas laminated walls. The 9.1m long beams were spliced using the overlap method with pins. The glass walls hold the full weight of the structure above, and in the real world environment of Times Square there are many possible causes of sudden failure including vehicle impact. A redundancy system was developed that accounts for the complete loss of one or two panels. In order to eliminate the need for metal lateral bracing, the treads were structurally siliconed to the rafters. A number of tests were conducted to confirm the validity of design concepts. This paper reviews the structural concepts behind the design, the fabrication methods, and the testing that was completed.

Keywords: Structural Glass, SentryGlas, Buckling, Load bearing wall, Glass Beam

1. General

The TKTS booth at Times Square in New York was initially the object of an design competition, attracting over 600 entries from around the world. The winners were the Australian architectural partnership Choi and Ropiha, who presented a concept for red glowing steps, allowing the public to sit on top, as well as to buy half price theater tickets through the front window. In collaboration with the executive architects, Perkins Eastman, the design became all glass, and therefore load bearing glass.

Precedents for the project include the Klein house in Santa Fe, New Mexico, with its load bearing glass walls which support the roof, and the Yurakucho canopy in Tokyo, with its 9.1m long overlap spliced beams.

2. Walls

All of the dead, live, and lateral load of the roof is transferred to the all glass load bearing walls.

The walls are four ply laminated with SentryGlas, with a maximum structural span of 4.8m. A grouted moment resisting shoe is provided at the base connection to improve the lateral stability of the wall, especially to improve its buckling resistance.

The SentryGlas provides good composite action amongst the four plies, leading to a slenderness ratio of approximately 230. This is more than that classical 200 traditionally adopted as a maximum by steel column designers, though is still more than adequate in respect to buckling capacity because of the large area of glass engaged.

Glass walls made from float glass are relatively thin and wide normal structural standards, so have inherently large slenderness ratios. As such it is important to include a consideration of initial out of straightness and lateral loads in their vertical load capacity calculations. Tempered and laminated glass also has an intrinsic tendency to be bowed during fabrication, especially with large panel sizes. The US standard for laminated glass (ASTM C1172) requires that fabricators be limited to 22.2mm of bow. This is a conservative figure that most fabricators can better, including the glass for TKTS. In the redundancy condition of one of the outer plies being broken, additional bow is introduced into the glass because the tempered glass tends to expand when broken.

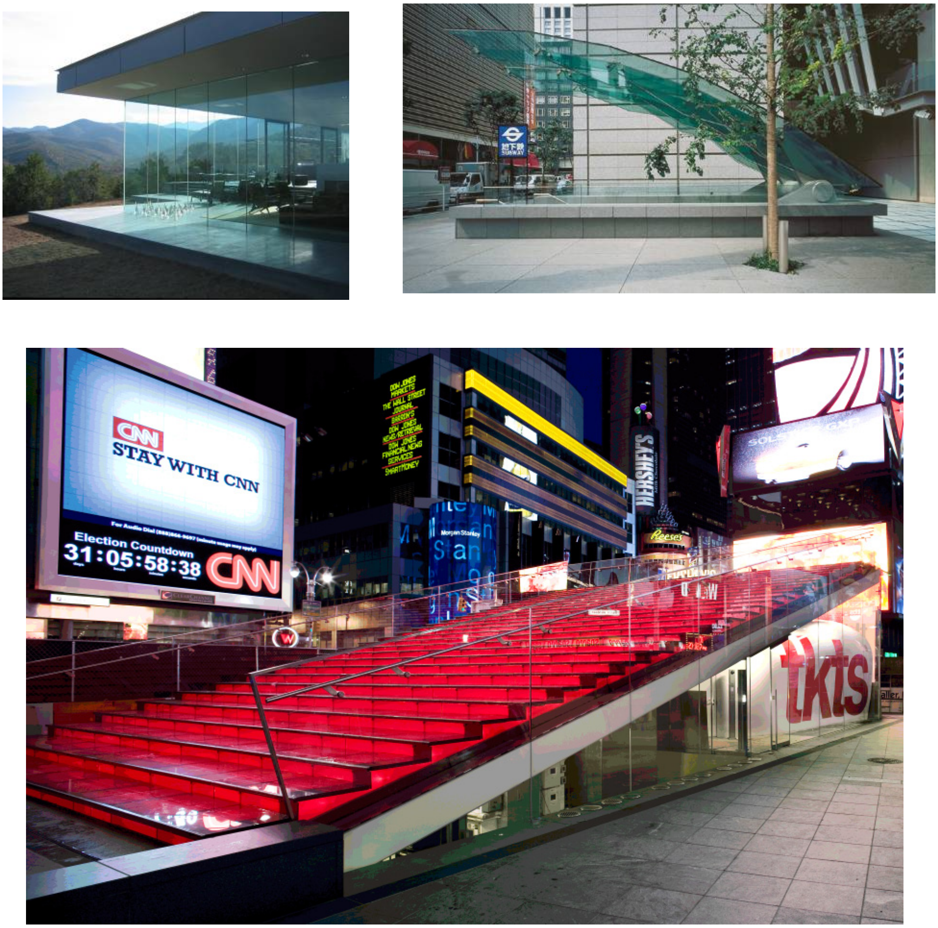

Figure 1: Top left – Klein house with load bearing glass walls. Top Right – Yurakucho Canopy with overlap splced beams. Bottom: TKTS Booth.

Notwithstanding the high slenderness ratio and required reductions for the lateral bow, the buckling capacity of the wall in the undamaged condition is more than 10 times greater than the applied load.

2.1. Tilted Wall

A significant architectural feature of the booth is that the North wall is tilted from vertical by 6.5^0. The load is however directed almost exactly along the centerline of the wall because a moment-free rotule connection is used to transfer load into the wall. The top of the wall is restrained from lateral movement by its connection to the beams. Under gravity load, the beams are in tension because of the wall's tendency to fall forward.

The tilt and the self weight of the wall glass leads to an effective gravity lateral load. Whilst the tilt is a striking visual feature, the engineering implications of the tilt are relatively modest. The lateral bow from the self weight is an order of magnitude smaller than the bow from tempering distortion and the flexural bending incurred from wind loads.

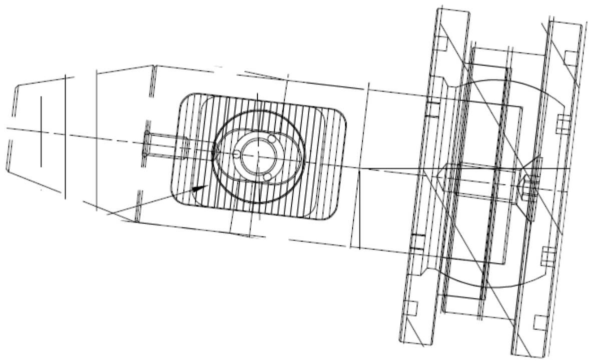

Figure 2: Rotule at North Wall detail.

2.2. Glass-Timber Comparison as Compression Element

Glass is in some respects a rational engineering choice for a material in compression applications. Its allowable stress in compression is high, and its Young's modulus substantially more than timber. If compared with timber, its stiffness is approximately five times more, and its allowable stress more than 10 times as much. Timber has a history of thousands of years as a compression element, whereas glass is just beginning.

If vertical glass elements are a visual or daylighting requirement for other reasons, there will be already built in a substantial cross section of glass that can be taken advantage of with relatively modest supplementation to form a high strength vertical load system.

Timber suffers from a degree of brittleness, though the clear disadvantage of glass is of course its extreme brittleness. The design focus was to engineer around this limitation with a redundant structural system that minimizes the scope for structural breakage, and allows for alternate load paths should breakage occur.

Table 1: An Timber vs Glass as a compression element.

Material	Young's Modulus (MPa)	Allowable compressive Strength (MPa)
Glass (fully tempered)	70,000	200
Timber (e.g. Southern Pine)	14,000	10
Glass/Timber Ratio	5.0	20

2.3. Redundancy System

The walls are the sole load bearing elements for the roof load. There is human occupancy both on top of the roof and underneath it, so structural performance of the walls is important. Accordingly, the design criterion was that structural integrity must be maintained in the event of failure of any one ply of glass, or any one complete panel. The ability to withstand the failure of a panel also allows for replacement of a damaged panel.

The primary mode of redundant structural behavior is simply laminated glass. Four plies are used, and are designed to carry full live load with for any one to be broken. There is significant loss of buckling capacity (more than 50%) in this redundancy condition.

In event of a whole panel failing, a beam was installed that is designed to transfer load to adjacent panels. The critical condition is when the end panel is broken, and the beam must cantilever beyond from the second panel. High forces are exerted on the end fitting in this condition, which drove much of this detailing. The vertical forces on the panel are also asymmetrical because of this cantilever. The load asymmetry did not significantly reduce the buckling capacity of the panels.

The demands of the end condition drove the design, and as such, the redundancy system is capable of withstanding the loss of two interior panels.

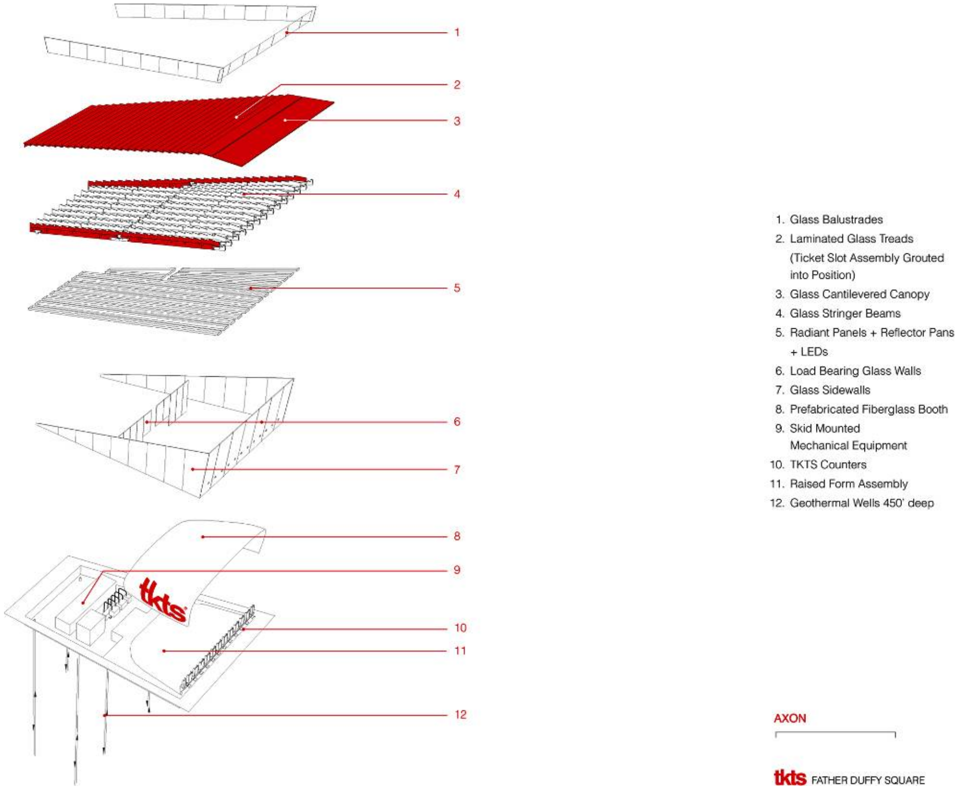

Figure 3: Exploded view of components.

3. Beams

Glass beams span from the ground to the mid wall, and from the mid wall to the North wall. The beams span a maximum of 9.1m, and have water jet cut stepped middle plies that attach to the glass treads. The treads are attached to the treads using a high modulus structural silicone (Dow Corning 993 European Spec), and the treads become the lateral restraint for the beams.

3.1. Splice

The maximum length of tempered laminated glass at the time of design was 6.0m, which is less than the required beam span of 9.1m. As such, a beam splice was required. The classic metal splice plate used in typical vertical façade applications was considered to be too visually bulky, and would have increase the required beam depth considerably. The adopted splice solution was the overlap splice.

The principle of the splice is that two pieces of glass are overlapped, and connected with two bolts separated along the length of the element to form moment continuity between the elements. This principal is extended to include four pieces of glass per beam. Refer to figure 4.

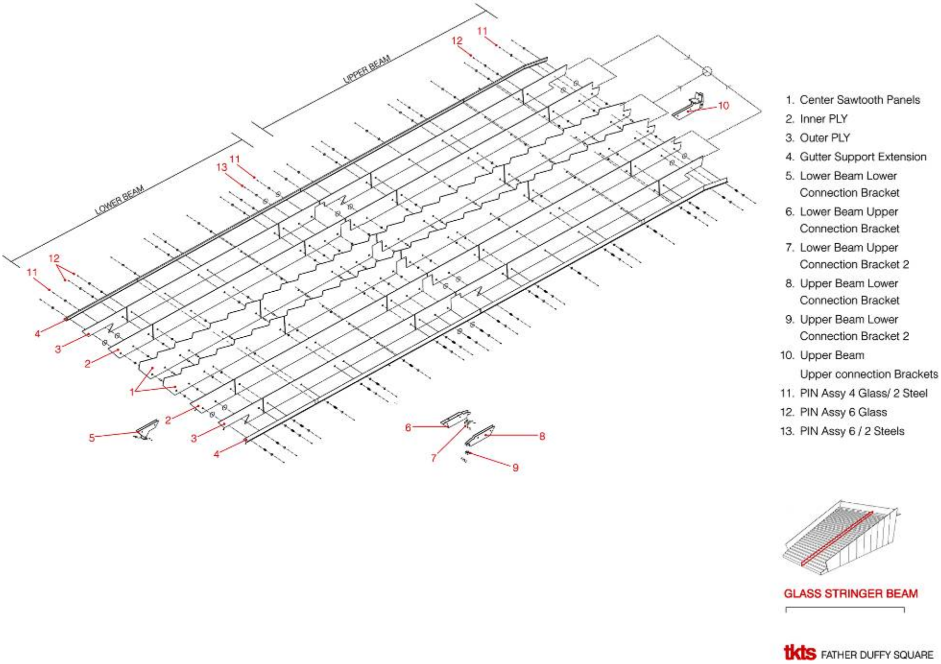

Figure 4: Exploded view of beam showing overlap splice.

The bolted connections are formed with nylatron disks that were epoxied into each ply of glass using 3M Scotchweld. The elements are then aligned with each other, drilled through, and a stainless steel pin is inserted through the assembly. This system was chosen for its high degree of uniformity of load application between glass plies. One of the problems of pinning multiple plies of glass is that one ply inevitably picks up more load than others, and thus limits the strength of the assembly.

3.2. Buckling + Lateral Strength

The treads are structurally siliconed to the rafters through a small aluminum shoe. This connection forms the lateral bracing for the beams to restrain them from flexural torsional buckling. The treads are connected back to a steel beam running along the length of the structure.

Testing was undertaken to determine the medium term shear modulus of the structural silicone, and of the assembled stiffness of the connection taking into account the contribution of the setting block and vertical load. The restraint of the beams was accordingly flexible. The test was conducted by adhering two aluminum plates together with the structural silicone, and hanging weights equal to the 0.138 N/mm^2 (20psi) shear load for 6 hours. Six repetitions were performed.

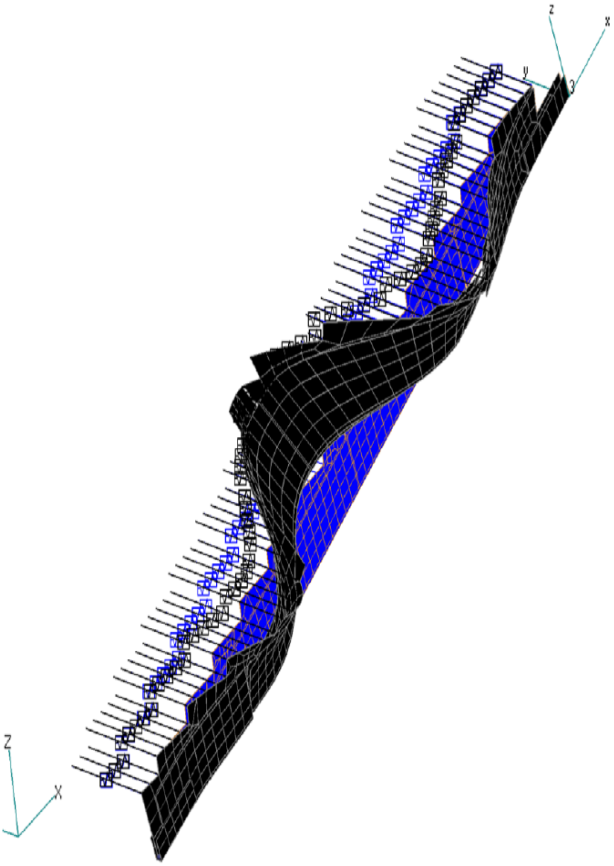

Figure 5: Finite element analysis of buckled shape (NASTRAN).

4. Conclusions

TKTS has is one of relatively few all glass buildings in the world, and the biggest such structure to be accessible by the public on its roof.

5. Acknowledgements

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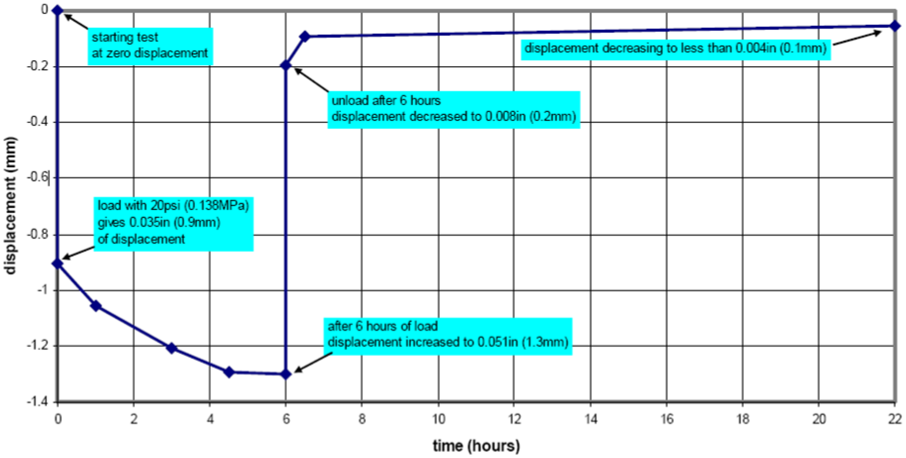

Figure 6: Medium term structural silicone test data. Displacement under 20psi shear stress over 6 hours.