

Where Glass Meets Machine: Sarah Oppenheimer's N-05001 at MIT

David Bott ^{a,b}, Sarah Oppenheimer ^c

- a Heintges Consulting Architects & Engineers P.C., USA, dbott@heintges.com
- b Ventus Architecture & Engineering PLLC, USA, dbott@ventusae.com
- c Folding Enterprises, The Netherlands, sarah@foldingenterprises.com

Abstract

The artist Sarah Oppenheimer has designed a dynamic glass sculpture titled “N-05001” to inhabit the newly renovated Metropolitan Warehouse at the Massachusetts Institute of Technology. This immense warehouse facility, the Met, was originally constructed in stages between 1894 and 1916, and has been repurposed into the new home for MIT’s School of Architecture, with Diller Scofidio + Renfro as the design Architect. The renovation includes four new atriums running from ground to roof levels that cut directly through the core of the existing building, exposing century-old structural layers and enabling natural light to flow into the surrounding academic spaces. “N-05001” will roam about one of the most populated atriums at a nearly imperceptible pace, challenging occupants’ perception of static architectural space. The sculpture consists of a 0,5 m diameter glass cylinder, 3,8 m tall, which travels up and down the end of a 6,0 m long cantilevered horizontal glass beam suspended from a trolley traversing the flange of a structural steel girder. A stainless steel counterweight on the opposite end of the glass beam balances the asymmetric configuration. This paper will focus on the initial problem of engineering a moving large-scale glass cylinder, and the increasingly complex stages of analysis, design, and coordination culminating in the creation of a glass machine whose intentionally exposed operation is transparent yet undetectable.

Keywords

Structural Glass, Glass Cylinder, Glass Beam, Kinetics, Kinematics

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1. Introduction

The recently renovated Metropolitan Warehouse at the Massachusetts Institute of Technology (the Met) will become home to the university's School of Architecture and Planning. Originally built in stages between 1894 and 1916, the old warehouse building has been given new life by the design architect Diller Scofidio + Renfro (MIT Metropolitan Warehouse, n.d.) (Fig. 1). Among numerous interventions to the original fortress-like structure are four new atriums carved out of the old warehouse spaces, exposing multiple layers of the existing structure to natural light from new skylights and adjacent exterior wall openings, and creating attractive gathering places for the occupants within (Fig. 2).



Fig. 1: Metropolitan Warehouse during renovation, viewed from the southeast corner of the building.

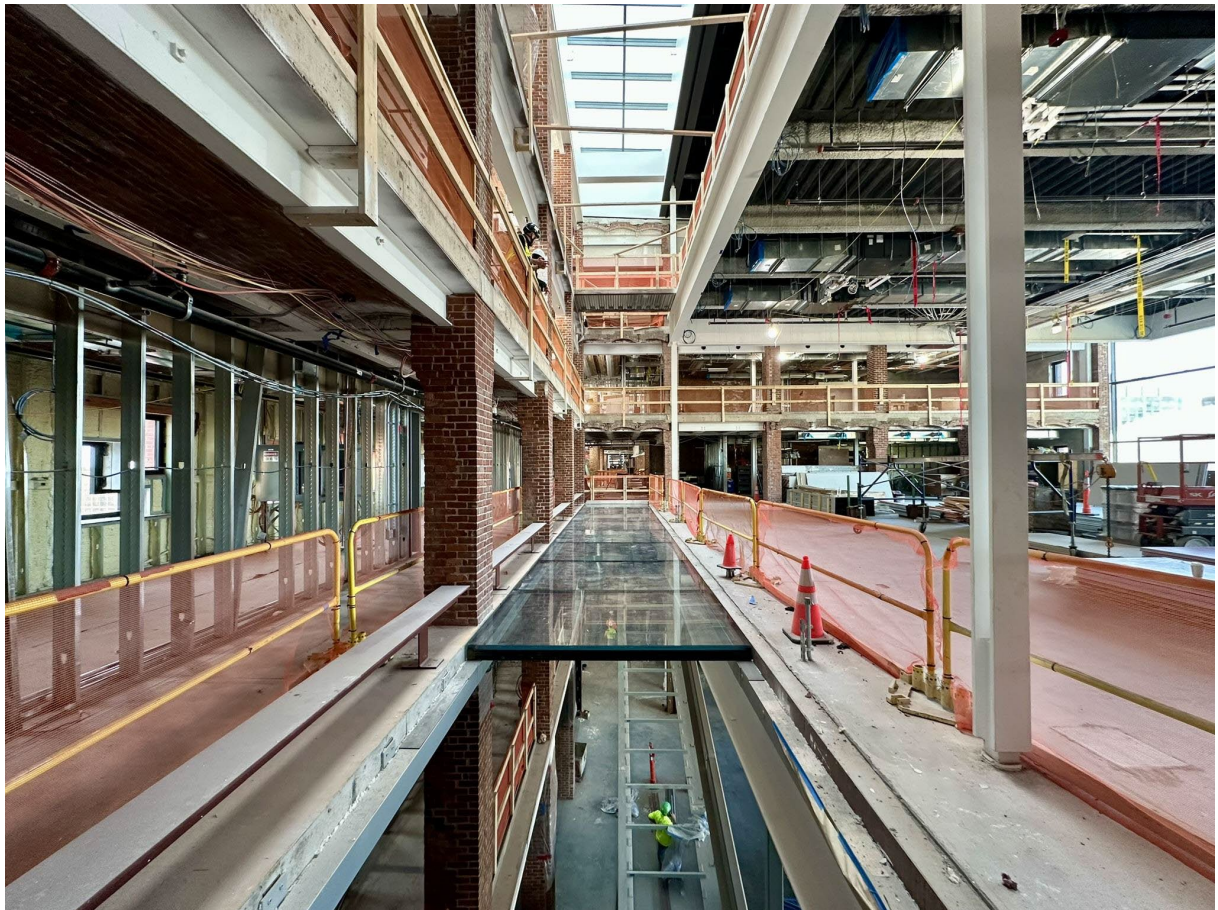


Fig. 2: New atrium space under construction within the Metropolitan Warehouse.

Within one such atrium and hovering high above a monumental stair, a new glass sculpture titled “N-05001”, designed by the artist Sarah Oppenheimer, will silently roam about at a barely perceptible pace. The installation may appear fixed to occupants transiting through the atrium, but for occupants lingering in the area, or perhaps leaving and re-entering the area after attending a lecture in the adjacent auditorium, the sculpture will be in obviously different positions at different points in time, challenging perceived notions of static architectural space.

Like the newly renovated building itself, with its existing structure purposely exposed to view within each atrium, the glass sculpture will deliberately expose its structure and operation to view. The sculpture features a 3,8 m tall, 0,5 m diameter vertical glass cylinder, which moves up and down its full length along guides mounted to the end of a 6,0 m long, 0,5 m deep horizontal glass beam. The glass beam is cantilevered from the underside of a steel trolley to which it is mounted, with the trolley riding back and forth horizontally along an existing steel girder parallel to the long dimension of the atrium. The back span of the cantilevered glass beam carries a stainless steel counterweight to balance the system and ensure smooth trolley operation. A pair of exposed cables thread their way along sheaves throughout the sculpture, silently raising and lowering the glass cylinder as the piece slowly traverses the atrium space (Figs. 3 and 4).

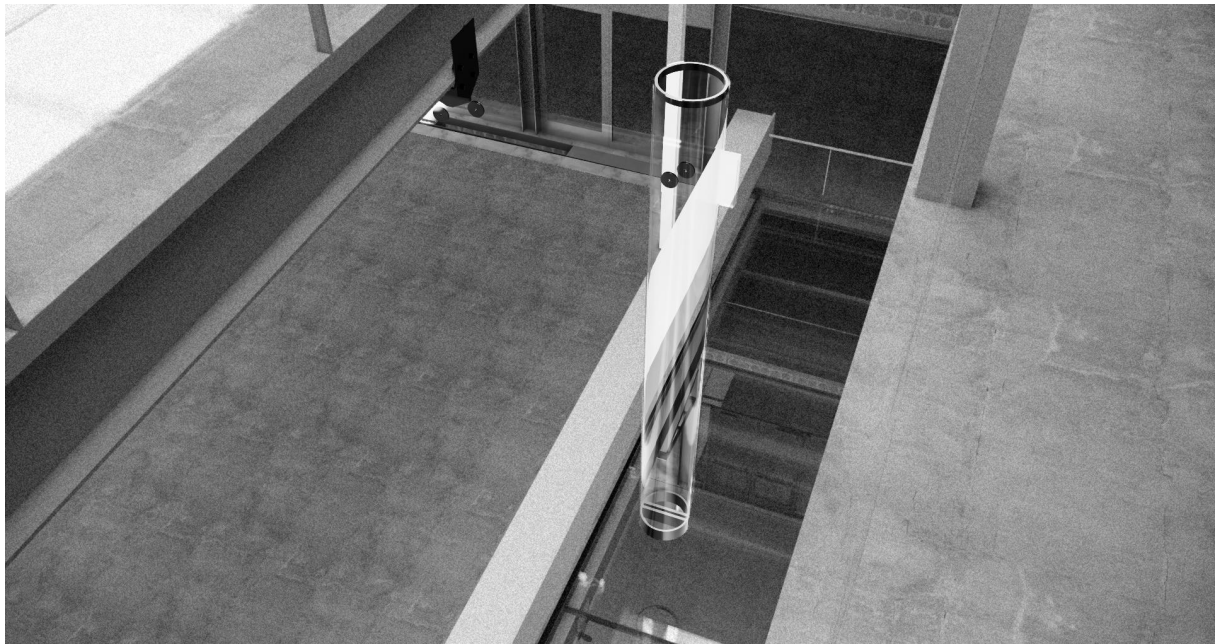


Fig. 3: Schematic study of N-05001 with glass cylinder at lower position. Courtesy of the artist. © 2025 Sarah Oppenheimer.

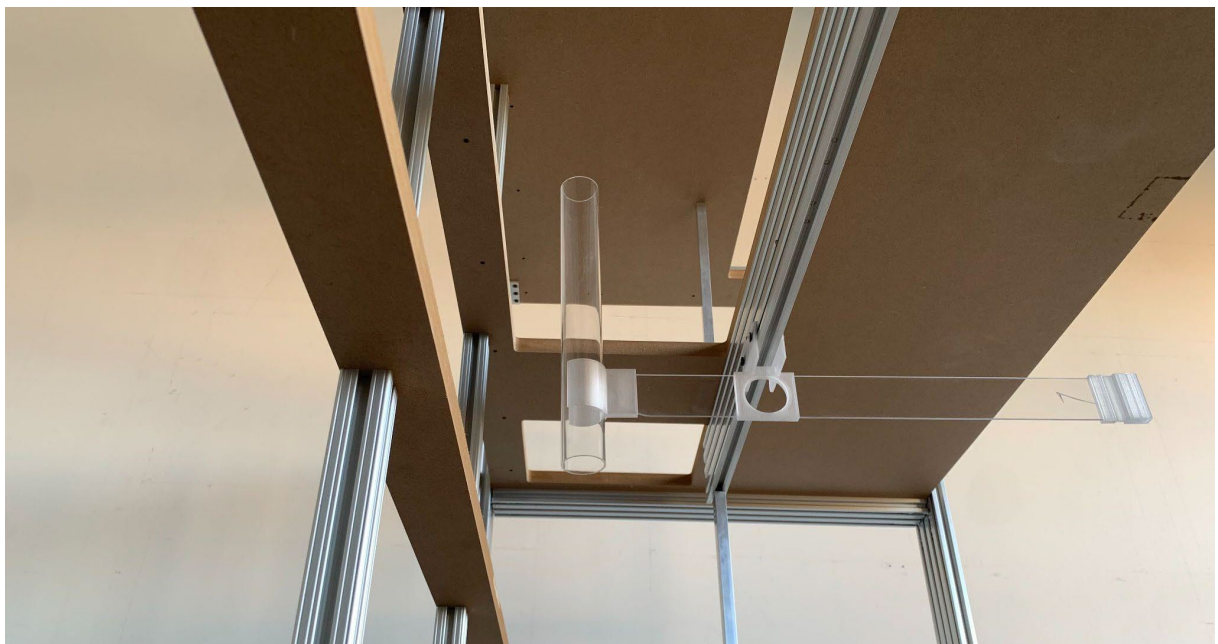


Fig. 4: Studio model of N-05001 with glass cylinder at upper position. Courtesy of the artist. © 2025 Sarah Oppenheimer.

2. Structural Analysis

The structural analysis for the sculpture occurred in stages of increasing complexity, in conjunction with development of the design, and in close coordination with the following organizations:

- sedak GmbH & Co. KG; specialty glass fabricator
- TriPyramid Structures Inc.; manufacturer of the stainless steel framing, plus design and engineering support for connection details
- Creative Connors Inc.; mechanical engineering and automation specialist for the piece

Additional coordination continues with Diller Scofidio + Renfro (DS+R) and MIT, regarding structural and architectural implications of the trolley interface with the existing steel girder on which it rides, associated fireproofing code requirements, and access to the sculpture for cleaning and maintenance.

We began by modelling and analyzing the glass cylinder, followed by incorporating the glass beam that would carry it, and finally calibrating the counterweight that would balance the entire system. Interlaced throughout this process were multiple iterations of hand calculations and sketches of possible glass make-ups and connections details, testing out numerous ideas as the analysis model evolved to best represent the ultimate configuration of the sculpture (Fig. 5).

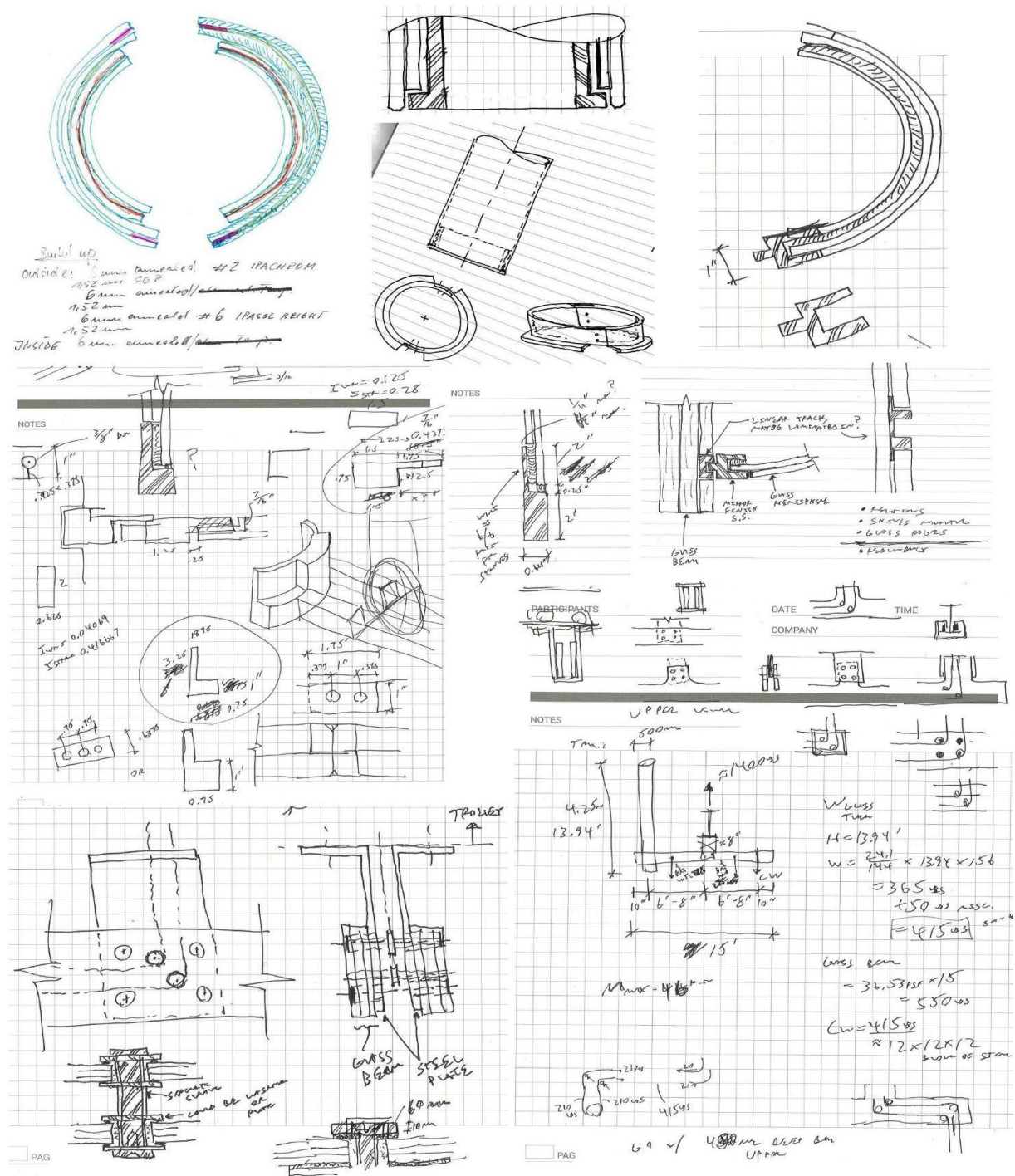


Fig. 5: A collection of preliminary sketches and hand calculations made throughout development of the FEA model.

2.1. The Glass Cylinder

Central to the work, the 3,8 m tall glass cylinder requires two half cylinders of bent glass, each with a 0,25 m radius and limited or no distortion. From early on, the goal was to achieve a cylindrical shape using annealed glass to limit the effects of distortion and anisotropy so common in heat treated bent glass. In preliminary conversations with sedak, chemical strengthening was also explored to achieve the undistorted quality of annealed bent glass combined with the strength of fully tempered glass, but the possible use of glass coatings precluded chemical strengthening, not to mention the high cost.

To start, a finite element analysis (FEA) model of the glass cylinder was developed in *Strand7 Release 3* (2019), envisioning the cylinder in its highest position of travel, restrained laterally at its base by guide tracks mounted to a glass beam that had yet to be designed. Vertical restraint was achieved by suspending the cylindrical framework at its base from a conceptualized central cable (Fig. 6).

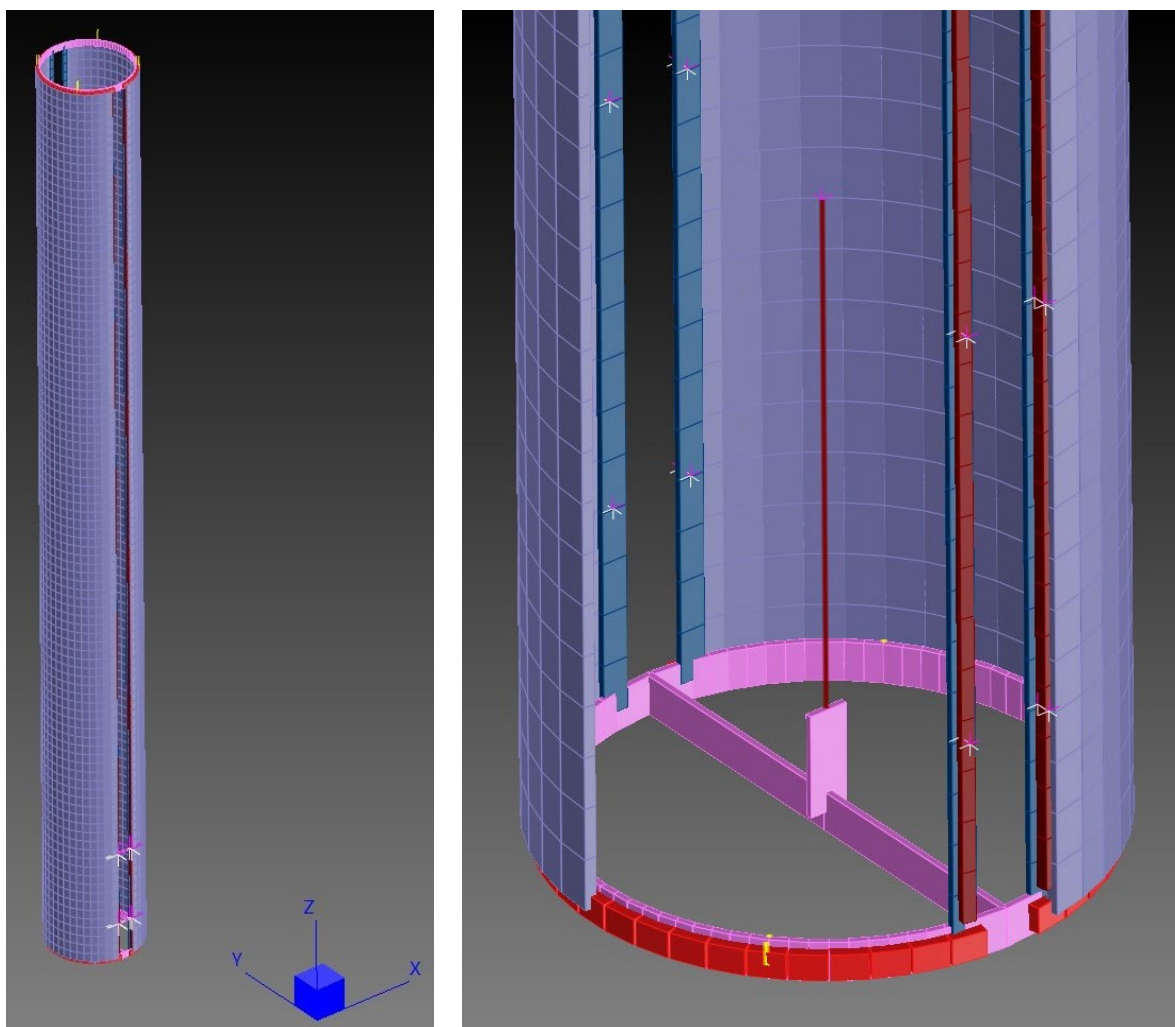


Fig. 6: Overall view of initial glass cylinder model (left). Base detail (right) with portion of glass hidden to expose central cable for vertical support, plus eight pinned restraints at the glass edges to simulate guide tracks providing lateral support.

As the piece is being installed within a public atrium at MIT, where students are notorious for creative “hacks” involving daring temporary installations at seemingly unreachable campus locations (IHTEP Hack Gallery, n.d.), several “abuse” load cases were envisioned to anticipate the structural behavior of the glass sculpture under unusual loading conditions. The primary load combinations consisted of dead load only, and dead load plus a conservative indoor wind pressure of 0,24 kPa from a possible four

different directions. The abuse load combinations consisted of dead load plus a conservatively high 890 N point load applied either laterally in various directions, or else vertically off-center, at the very top of the glass cylinder, far away from its lateral supports below. The effect of the abuse combinations was to induce human impact forces, conventionally specified for guardrail design, onto the sculpture to generate bending and twisting of the system in its most unbalanced condition. These combinations governed over interior wind pressure and were far worse than the system’s normal operating condition under gravity loading only. They also represent rare situations, as the piece will never be positioned such that building occupants can reach out and touch it.

The curved shapes of the half cylinders of glass greatly stiffen them, lending them moments of inertia suitable for resisting unusual bending loads and sufficient to keep strong axis bending stresses relatively low even for thin glass make-ups. The stainless steel framework, designed to protect the vertical edges of the cylindrical glass as they glide through support tracks, is intended to be minimized to the greatest extent possible so that the glass itself remains the primary visual focus of the piece. As such, it is the rigid cylindrical glass that ends up stiffening the more flexible metal framework, working compositely with it through the use of structural silicone that glues the two materials together. The modeling, analysis, and sizing of the silicone bite was paramount to capturing this behavior.

Although silicone is a hyperelastic material, a linear approximation for its average elastic modulus was assumed for the analysis model based on engineering guidance provided by The Dow Chemical Company (2018) (Fig. 7). The silicone was modeled using beam elements to primarily capture axial forces and 2D plate elements to capture both shear and axial forces, using properties of Dowsil 995 structural silicone under extreme events where up to 50% strain may occur (Figs. 8 and 9). The assumption was that abuse load combinations, when the silicone would likely see the most stress, could be considered extreme.

Linear Approximation Model Data

Strain Range	Linear Elastic Constants
$\epsilon = 0$ to 10%	$E = 1.380$ MPa $\nu = 0.5$
$\epsilon = 0$ to 25%	$E = 1.038$ MPa $\nu = 0.5$
$\epsilon = 0$ to 50%	$E = 0.816$ MPa $\nu = 0.5$

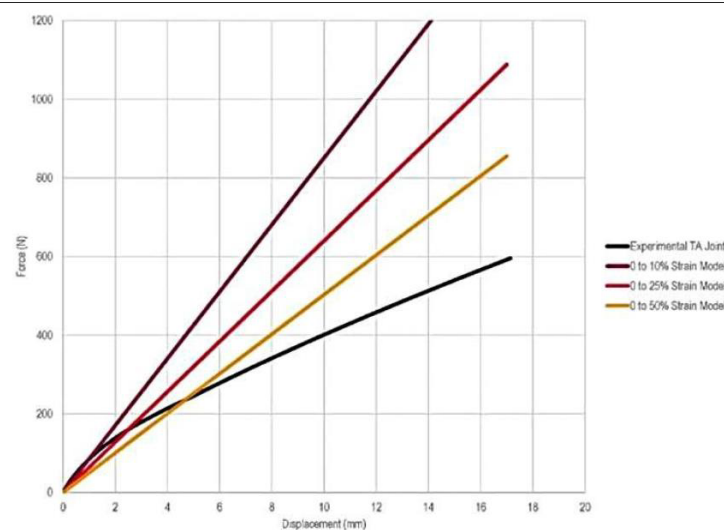


Fig. 7: Average modulus of Dowsil 995 silicone at various strain ranges. 0 to 50% strain was used for extreme loading events.

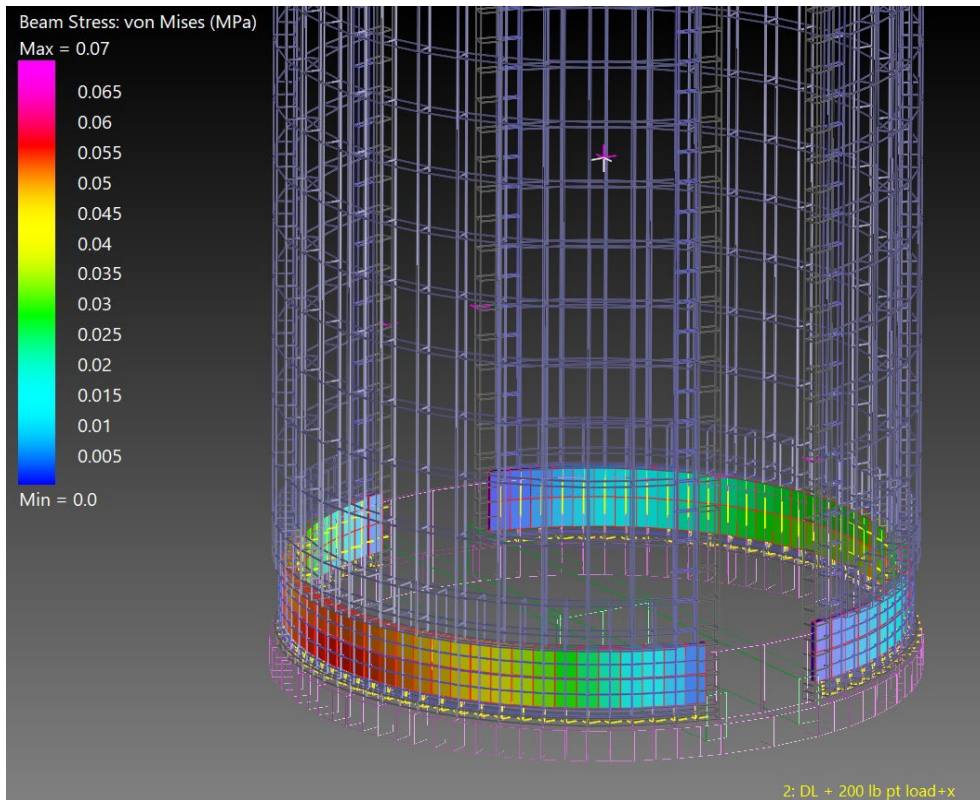


Fig. 8: Preliminary von Mises stress at silicone interface between glass cylinder base and stainless steel ring beam under potential “abuse” case; silicone modeled using beam elements.

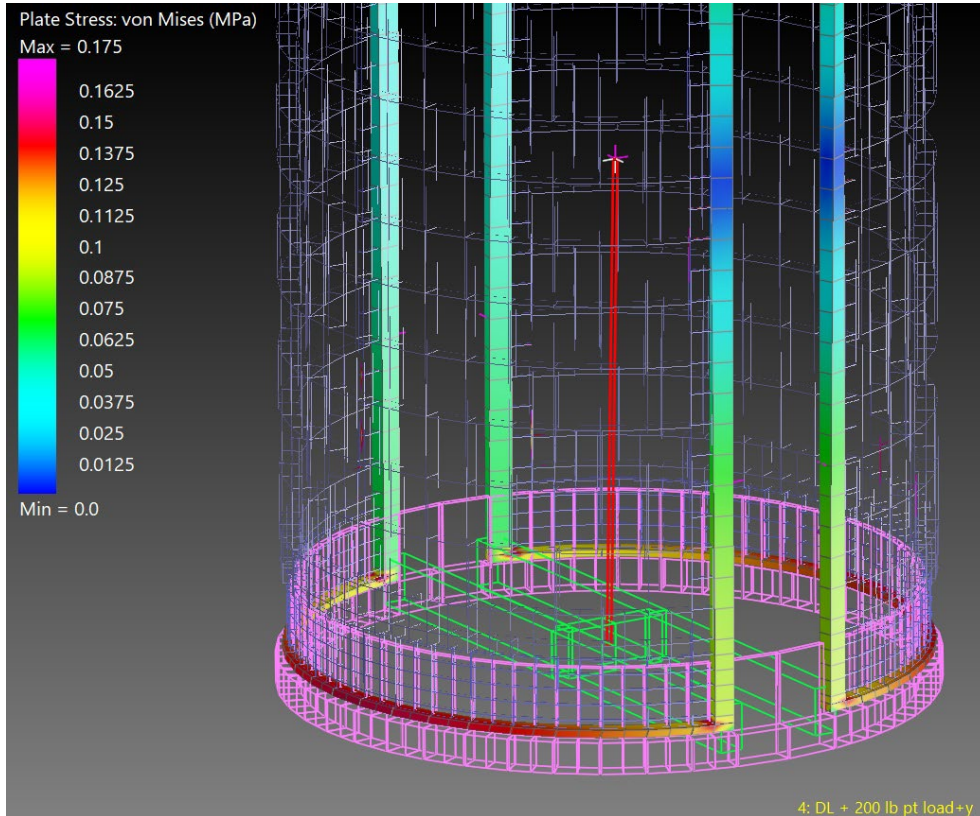


Fig. 9: Preliminary von Mises stress at silicone along glass cylinder edges under potential “abuse” case; silicone modeled using 2D plate elements.

In order to minimize the visual impact of the framing and structural silicone bond required at the glass cylinder edges, integration of glass edge offsets and a mirror-like glass coating are utilized.

An additional, important safety constraint on the cylindrical glass was its need to meet code requirements for overhead glazing. As the glass is intended to be annealed, it must be laminated for safety. In the case of a break, the glass must also remain safely in place until such time as it can be replaced. An ionoplast interlayer (SentryGlas) was chosen for its superior performance in a post-breakage situation.

The need for laminated glass, offsets at the edges, structural silicone bond lines, and a mirror-like coating used in part to conceal the silicone, necessitated a 4-ply laminated glass make-up consisting of three inner plies of 4 mm bent glass and one outer ply of 6 mm bent glass (Fig. 10).

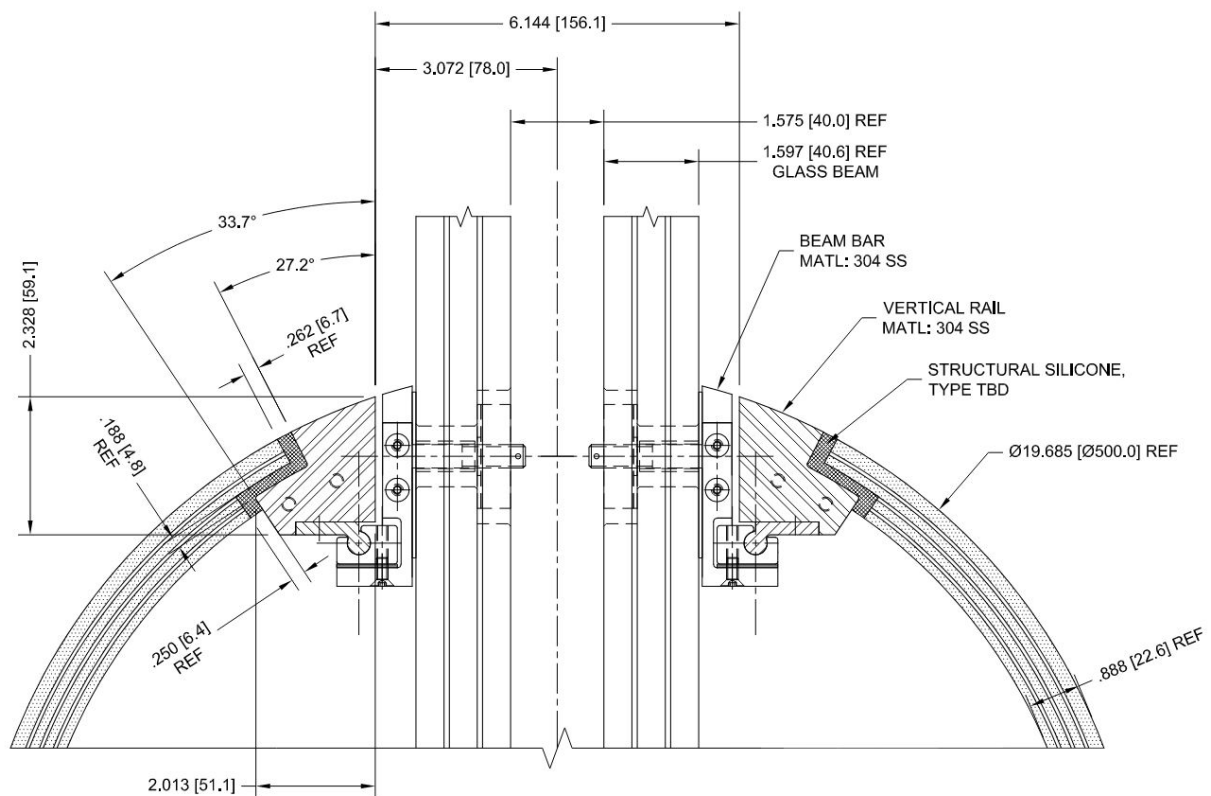


Fig. 10: Horizontal section through interface of glass cylinder and glass beam, indicating 4-ply bent laminated glass structural silicone glazed to vertical stainless steel guide rails. Image courtesy of TriPyramid.

Glass thicknesses and the laminated make-up were designed and engineered to keep stresses below the limits for annealed glass, especially at the more vulnerable and higher stressed edges (Fig. 11). To further limit the potential for glass breakage, the edges of the annealed bent glass will be highly polished and visually inspected to ensure as clean an edge as possible with no visual defects.

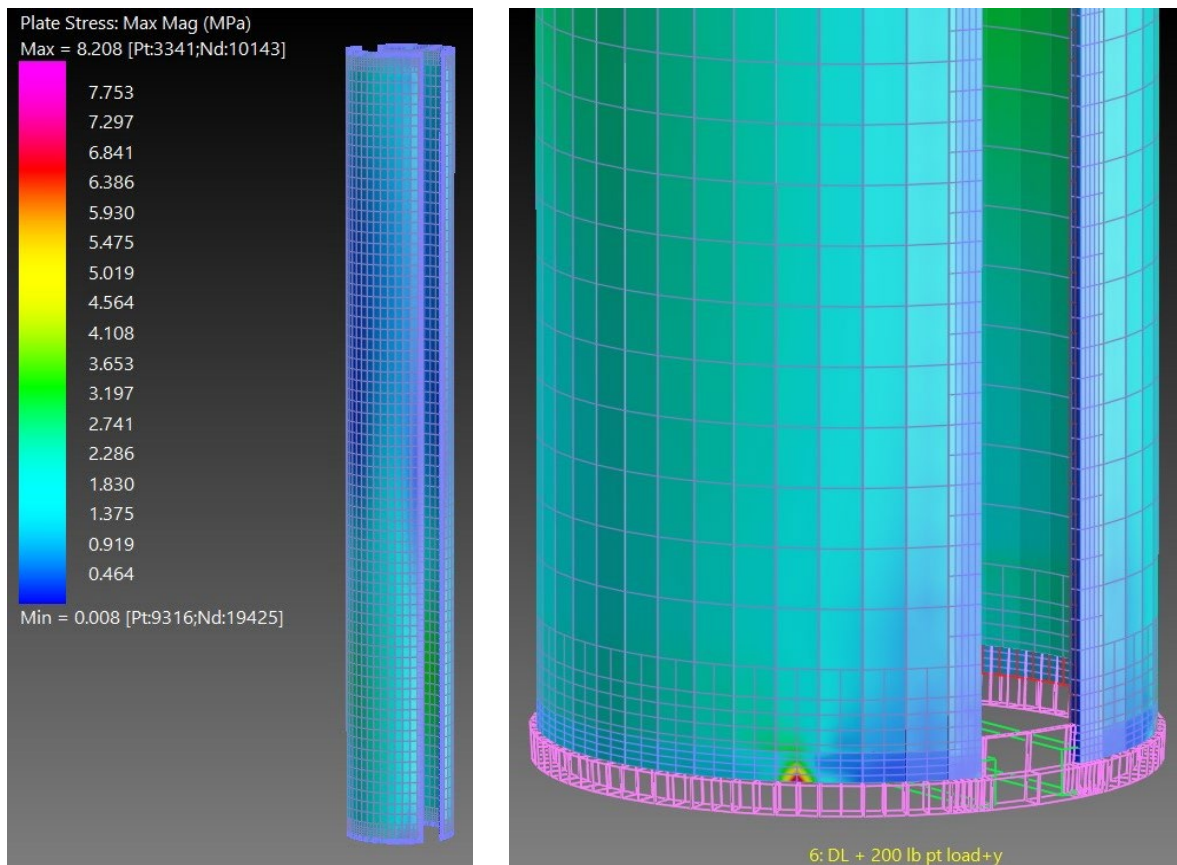


Fig. 11: Overall view of glass cylinder model (left) indicating range of principal stresses in the glass under an “abuse” load combination. Detail at base (right) shows expected area of peak stress concentration above glass setting block location.

2.2. The Glass Beam

As development and analysis of the glass cylinder continued, the glass beam to which the cylinder would be attached was incorporated into the FEA model. The beam is composed of two triple-laminated glass plates, each 500 mm tall and 6 m long, running parallel to one other with a 40 mm gap between them. The glass plates are bolted together at eight locations, with four bolts carrying sheaves for cables to control the up and down motion of the cylinder, and four bolts mounting the beam assembly to the trolley above via a T-shaped stainless steel plate modeled with brick elements. As the glass beam is cantilevered from its trolley support, a stainless steel weight is incorporated into the backspan of the beam, opposite the end carrying the glass cylinder, to balance the entire system. The counterweight is represented in the model using non-structural masses (Figs. 12 and 13).

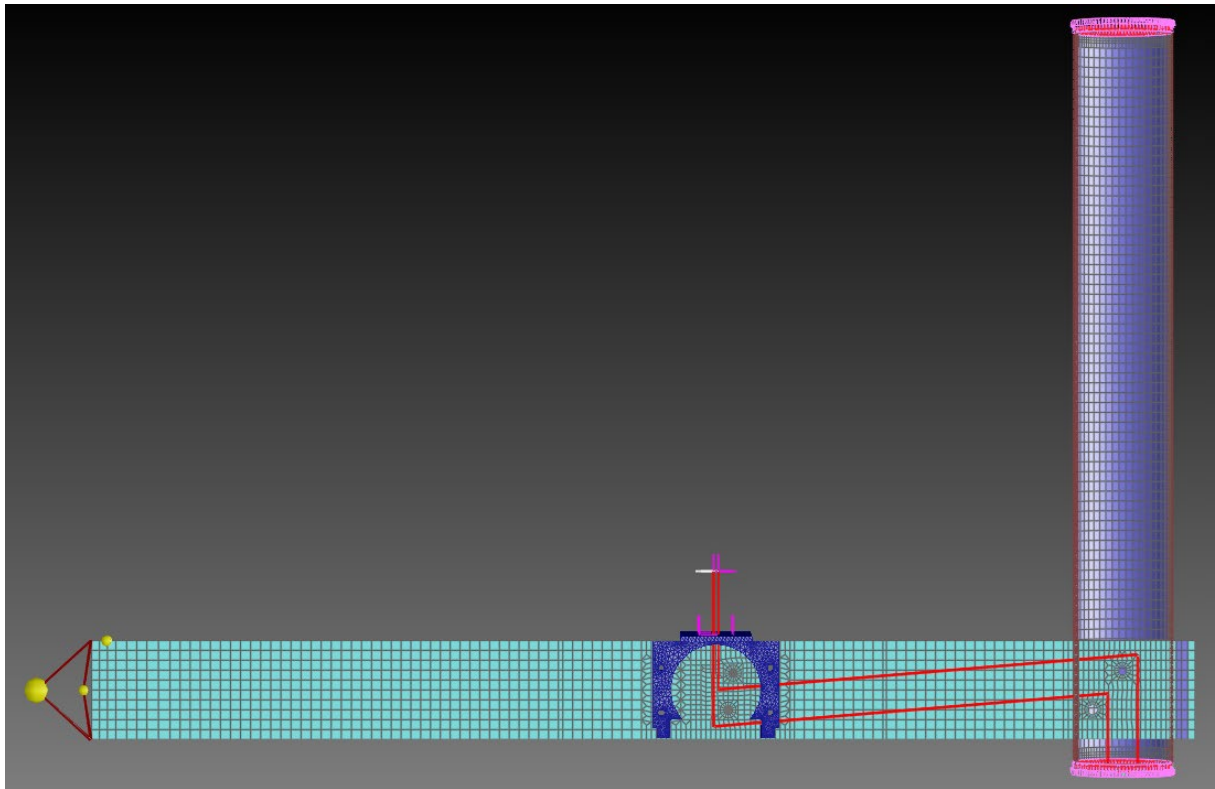


Fig. 12: FEA model with horizontal glass beam and cylinder held in its upmost position at the right end. Near beam center is the trolley plate. At far left end is a representative counterweight of non-structural masses. Cable elements run from just above the trolley plate, between both sides of the glass beam assembly, and down to support the base of the glass cylinder.

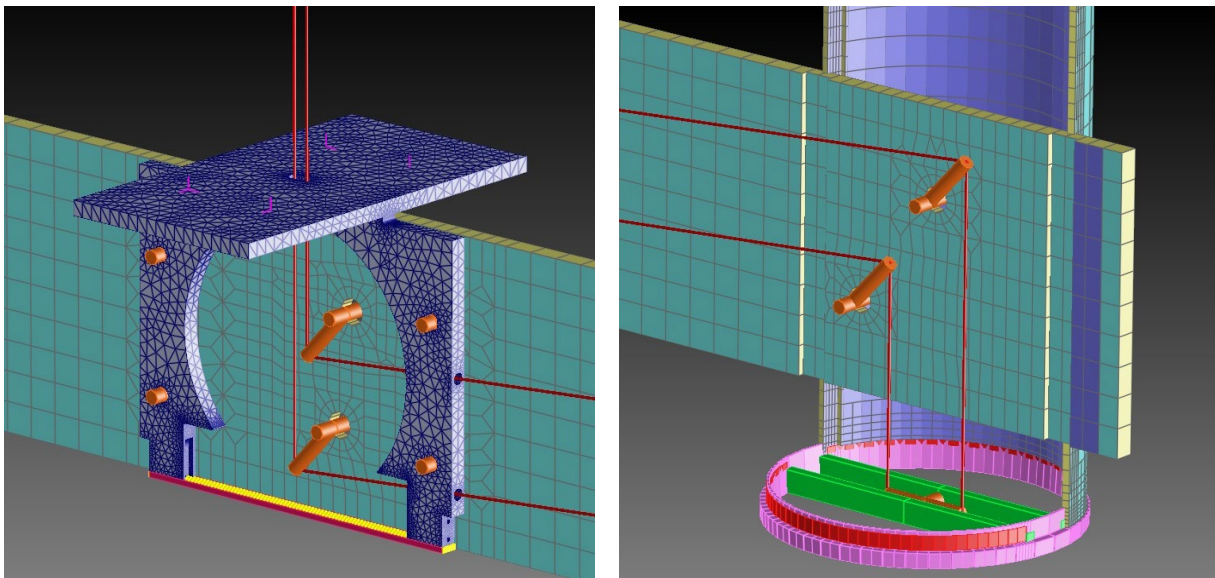


Fig. 13: Detail of trolley plate solid FEA model (left). Detail at beam end supporting glass cylinder (right). Note: One side of the glass beam has been hidden to expose the trolley plate and cables within the gap.

The glass beam is the primary support element for the sculpture, not only supporting multiple sheaves, but also a moving glass cylinder on one end with a counterweight on the opposite end. As such, the structural approach included fully tempered glass to provide as much strength as possible, and multiple plies of glass with redundancy built in so that if any one ply breaks the beam can safely remain in place.

Like the glass cylinder, stiff SentryGlas interlayers were used, bonding the 12 mm plies of glass to one another.

A requirement of the piece is to countersink all of the bolts and pins for the sheaves within the outer ply of the glass beam. The FEA model accounts for this with reduced thickness glass at the bolt locations, combined with beam elements to represent the bolts, plus an interpolated multi-point link assembly to couple all of the perimeter bolt hole nodes to the bolt without rigidly linking them to each other; effectively distributing bolt forces around the bolt hole (Fig. 14).

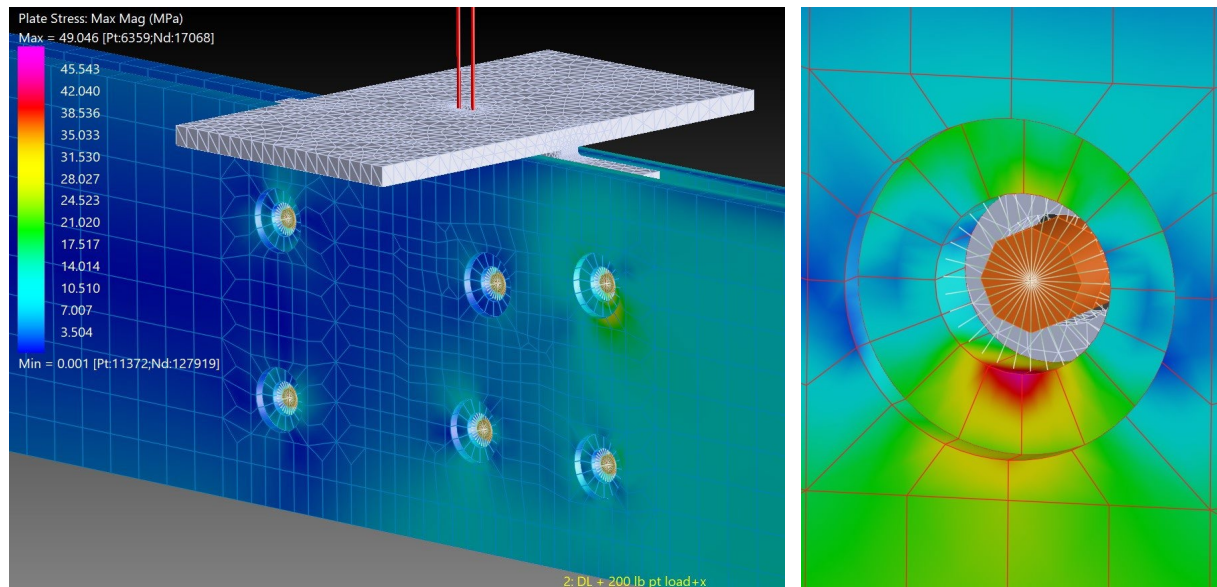


Fig. 14: Countersunk bolt holes in the FEA model (left). Detail (right) illustrating the interpolated multi-point link assembly between the bolt and the bolt hole indicating a high stress concentration within the lower half of the bolt hole edge.

2.3. The Trolley Plate

The trolley plate to which the glass beam is bolted, and which itself is bolted to the underside of the trolley, was modeled for analysis using tetrahedral brick elements to capture the internal stresses within the complex, fabricated shape. Although the overall outline of the plate is rectangular, a large circular cutaway exposes the sheaves and cable operation within, and the cables themselves must travel through holes bored at angles through the relatively narrow thickness of the plate. The lower section of the plate is also removable to allow for maintenance of the cables and sheaves from below the sculpture. A solid FEA model allows for detailed review of stress throughout the cross section of the plate, especially at the bore hole locations with potentially high bending stresses (Figs. 15, 16, and 17).

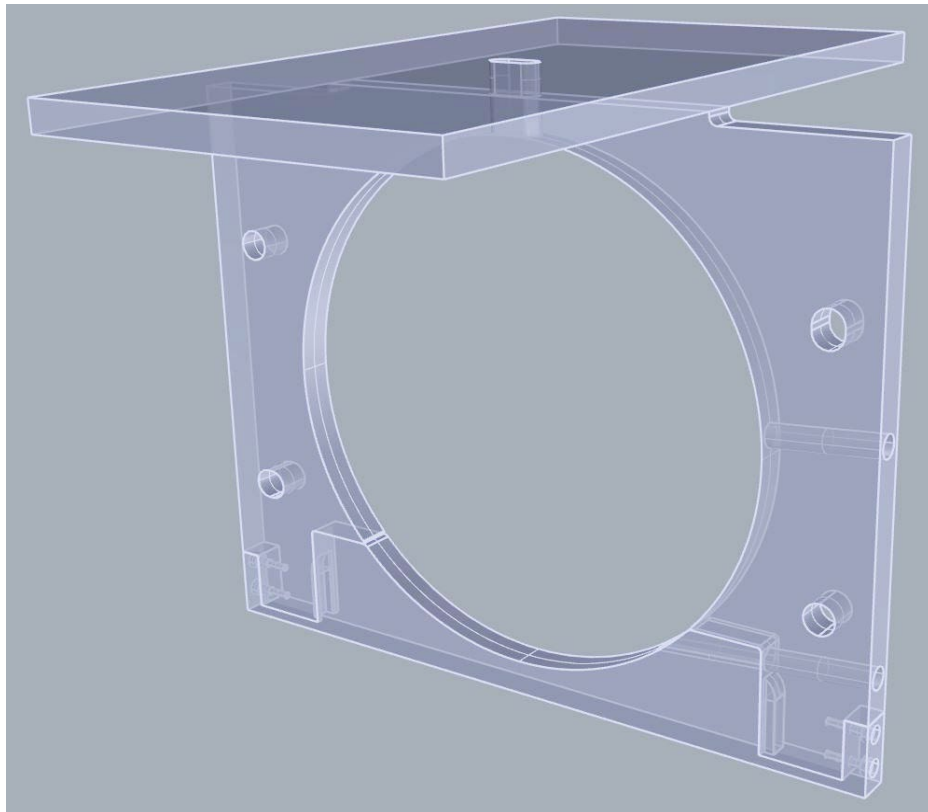


Fig. 15: 3D fabrication model of trolley plate, with bore holes for cables ghosted in along the right side of the plate. Image courtesy of TriPyramid.

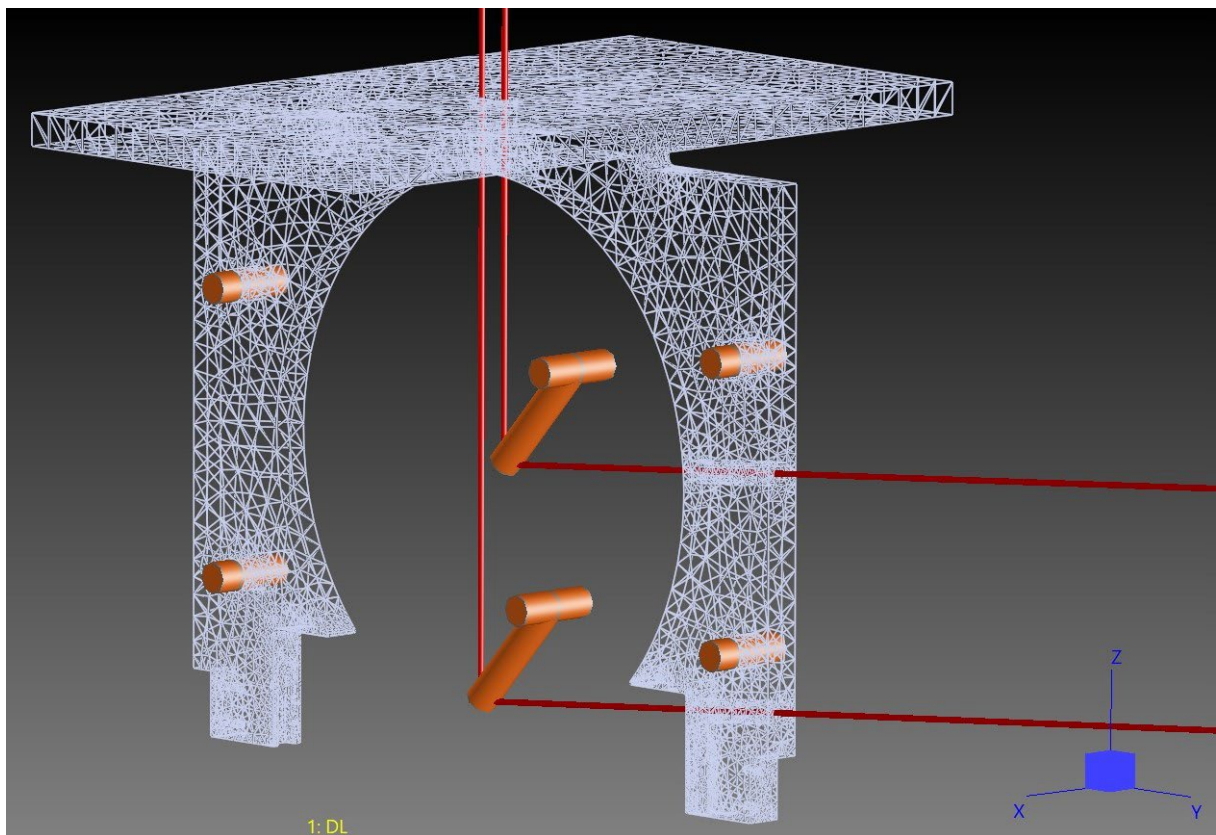


Fig. 16: Solid FEA model of trolley plate indicating outlines of the tetrahedral brick elements.

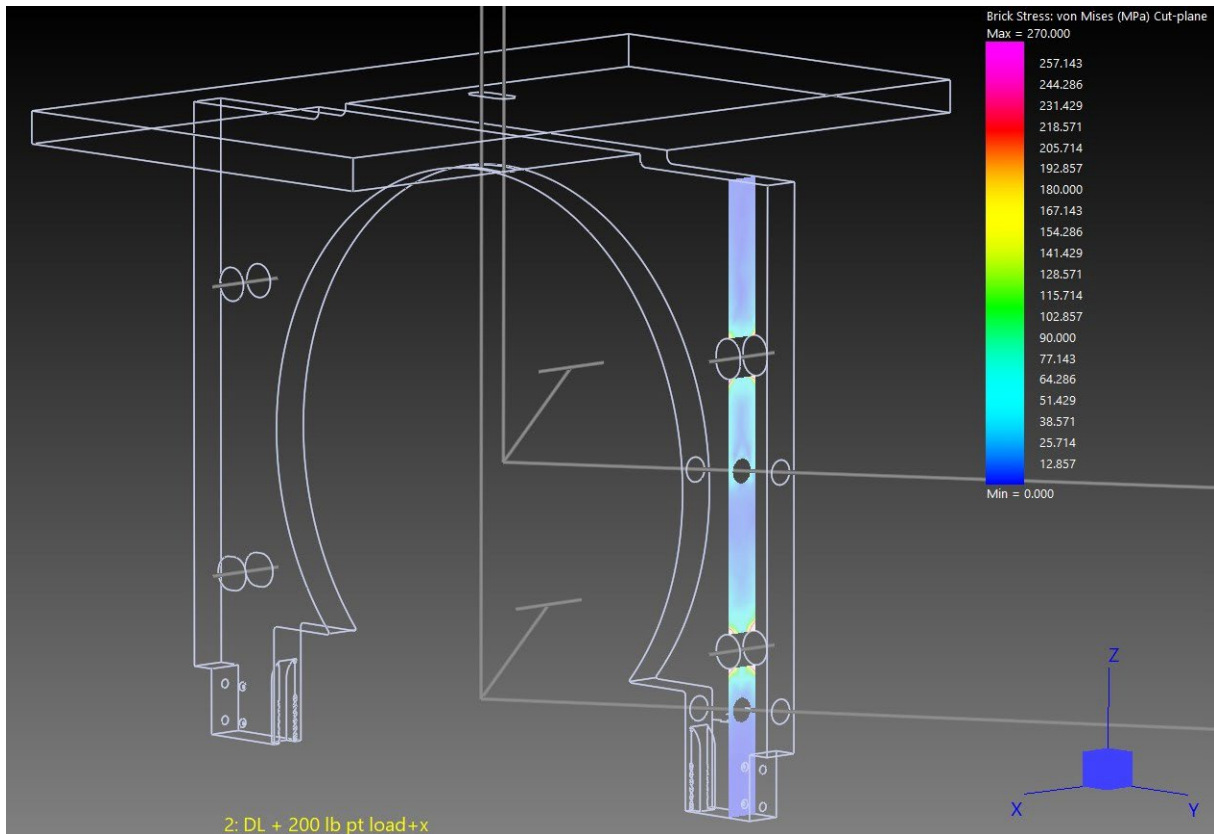


Fig. 17: Cutting plane through solid FEA model of trolley plate indicating von Mises stress under potential “abuse” case.

As the trolley plate is bolted to the underside of the trolley, which drives the sculpture back and forth along an existing structural steel girder, reactions from the FEA model were provided to Creative Conners, the mechanical engineer, for their design of the trolley (Fig. 18). With the entire sculpture balanced by the counterweight, and under normal operation, the trolley should feel a relatively uniform downward force as it moves; however, because of the potential for unusual, unbalanced loading situations (i.e. “abuse” cases), the trolley is also designed to resist rotation in all directions.

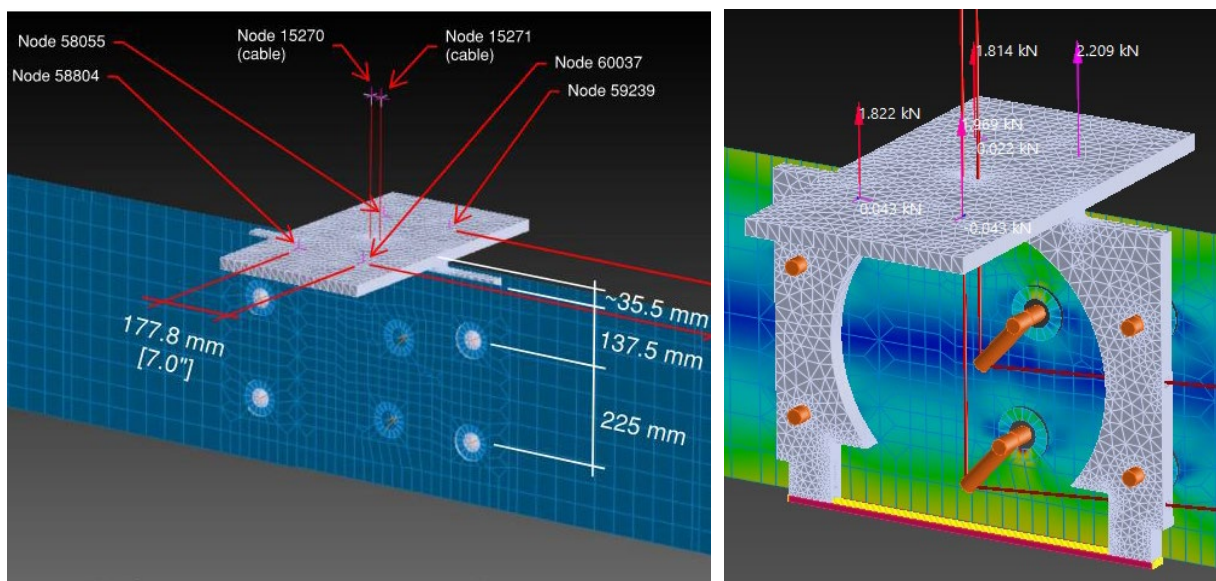


Fig. 18: Example of reaction information provided to the mechanical engineer, Creative Conners, for their use in designing the trolley. At right are trolley plate reactions under the more balanced, standard operation case.

2.4. Ongoing Fabrication Level Detail Development

While the structural analysis for the major elements of the sculpture has already been completed, the development and refinement of details is ongoing, informed by the analysis results. TriPyramid has developed a 3D digital fabrication model of the sculpture in order to visualize and refine the various components and connection details of the piece, at a level of precision suitable to create fabrication drawings. This model is ostensibly a living representation of the piece, constantly evolving as design decisions are made and details are finalized (Figs. 19, 20, 21, and 22).

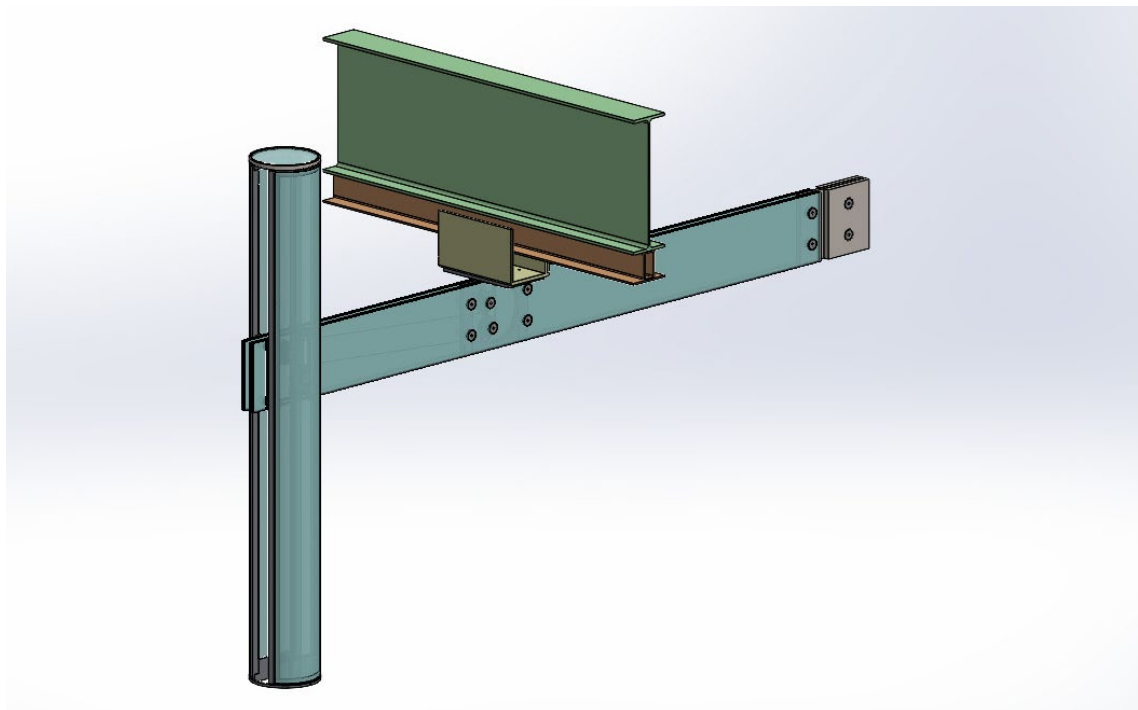


Fig. 19: 3D digital fabrication model of the sculpture. Image courtesy of TriPyramid.

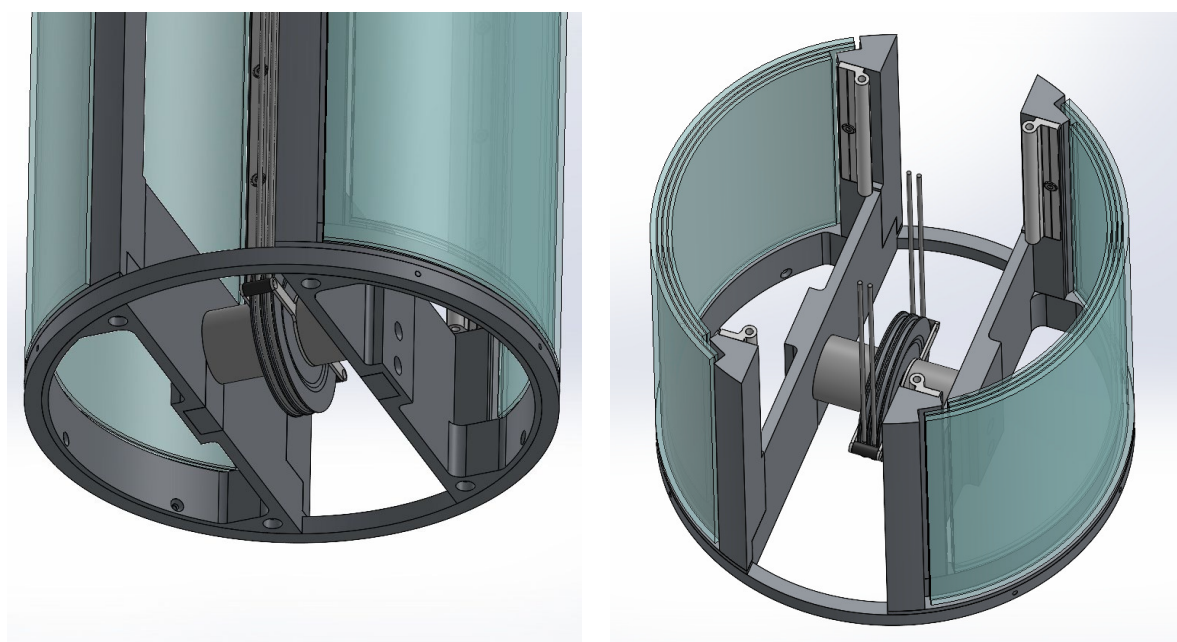


Fig. 20: Details of travelling sheave at glass cylinder base. Images courtesy of TriPyramid.

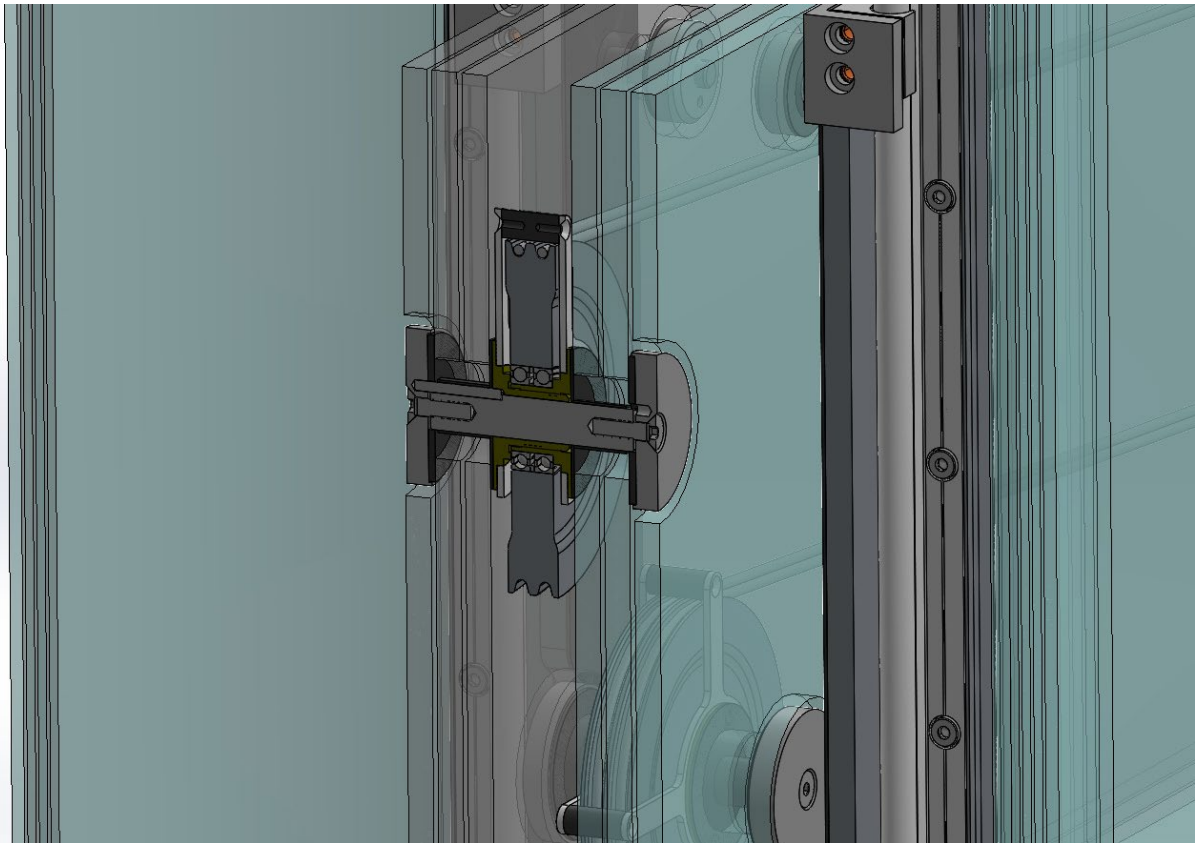


Fig. 21: Section cut showing detail of upper sheave connection to glass beam. Image courtesy of TriPyramid.

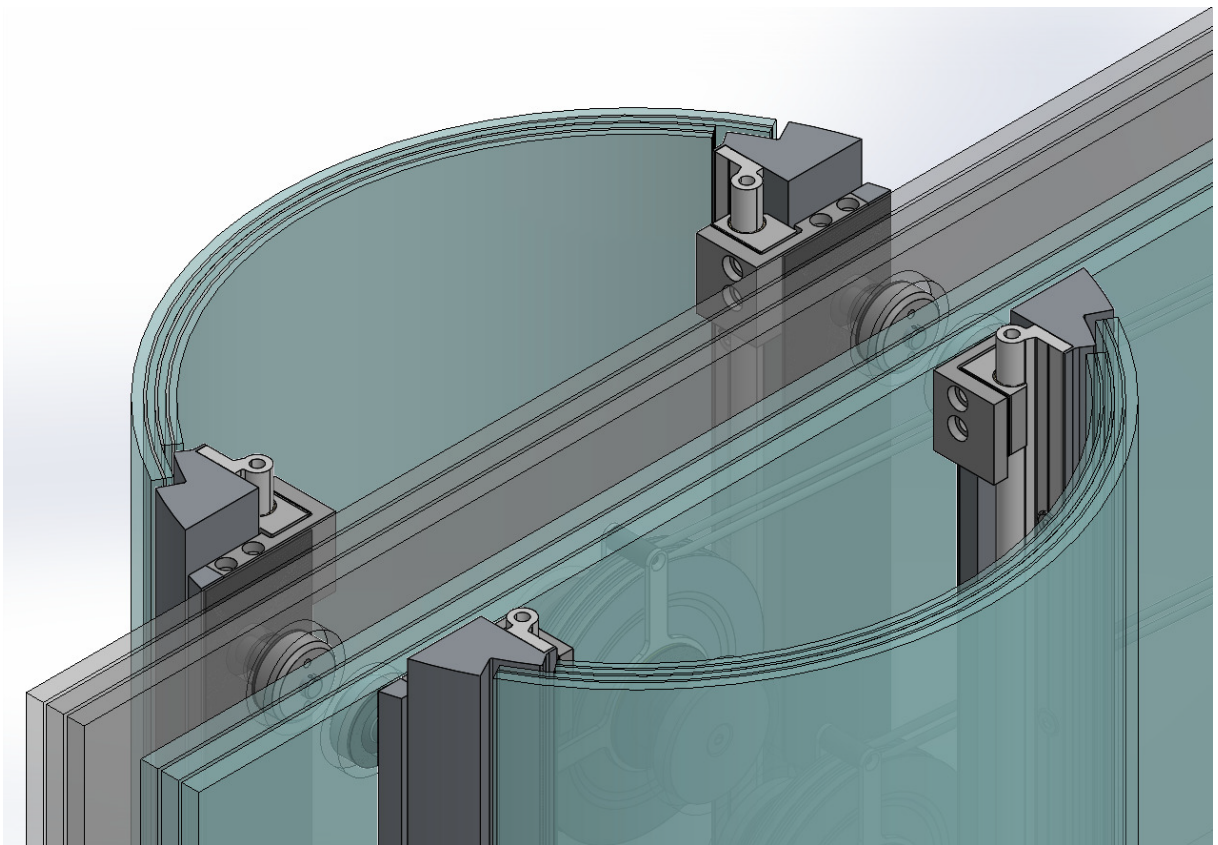


Fig. 22: Section cut showing sliding interface details between glass cylinder and glass beam. Image courtesy of TriPyramid.

3. What's Next?

Evaluation of a quadruple-laminated annealed glass half cylinder sample with equal radius and make-up to the project glass is ongoing, along with review of mirror-like coating pattern options (Figs. 23 & 24). Remaining steps for the project, slated to be completed in January of 2027, are as follows:

- Installation of a secondary steel beam, mounted below the steel girder, on which the trolley will ride
- Fabrication of all assemblies
- Onsite installation of motors and rigging
- Automation and control programming
- Coordination with the building's Lutron system to allow occupancy sensors to feed data to the N-05001 control system
- Installation of the preassembled glass beam and the two glass semi-cylinders
- Reeving
- Press Play!



Fig. 23: Glass half cylinder sample review. Courtesy of the artist. © 2025 Sarah Oppenheimer.



Fig. 24: Glass half cylinder sample review. Courtesy of the artist. © 2025 Sarah Oppenheimer.

Acknowledgements

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