Cable-Net Entrance Pavilion for GM Global Headquarters

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Abstract

The entry pavilion for the new General Motors' Global Headquarters at the Renaissance Center in Detroit is a large cable-net system that has been shaped to provide an efficient, stiff structure. The 14.6 meter high, 29.3 meter wide and 9.8 meter deep pavilion (48 feet x 96 feet x 32 feet) uses anticlastic cable-nets on the two vertical faces of a lens shaped building. This lens shaped plan was created to provide two circular arcs of cables that are pre-stressed against parabolic vertical cables. The result is a geometrically stiffened cable-net that resists uniform and non-uniform wind pressures and suctions. The vertical cables are stressed against a roof truss that spans to supporting vertical trusses at the apexes of the lens. These vertical trusses in turn form the system against which the horizontal cables are stressed. The major compression elements are the compression chord of the roof truss and the vertical trusses. These elements are partially braced by the cables resulting in very slender 324 mm (12.75 inch) pipe sections. The result is a self-stressed system where the tension and slender compression elements are clearly expressed and the system creates and defines a dramatic space. In addition to the system description, the results of wind tunnel studies are presented that define the magnitude and variability of the wind forces for this building.

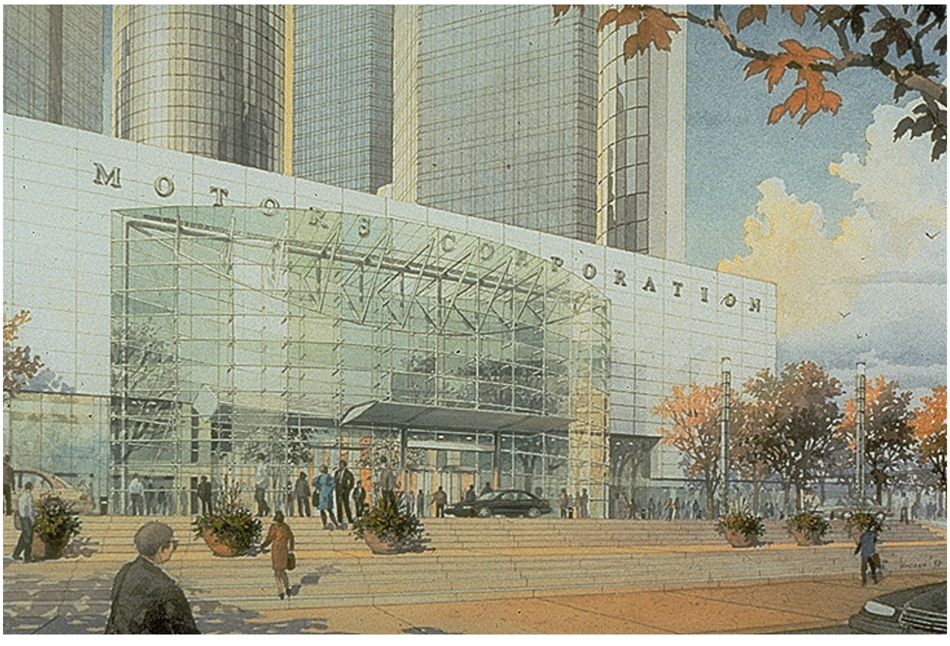

Figure 1: Architectural Rendering of Entrance Pavilion

1.0 Introduction

The new entrance for General Motors' Global Headquarters in Detroit's Renaissance Center is a dramatic structure of glass and cables. As the front entrance to the world's largest corporation, the design was developed with a high-tech, machine-like aesthetic that expresses engineering excellence. The result is an efficient, minimalist structure that clearly expresses its function.

The basic geometry is a simple extrusion. In plan it is a 29.3 meter (96 feet) long by 9.8 meter (32 feet) wide lens and stands 14.6 meters (48 feet) high.

2.0 Structural System Description and Hierarchy

The entry structure is a unified system where each of the sub-systems has a specific function that plays a particular role. Using the path of load resistance as an organizing tool, the following sequence of systems can be identified: 1) Exterior glazing; spider fittings and dead-vertical gravity cables, 2) 3 dimensional cable net system, 3) roof ribs and roof truss structure, 4) end post truss, and 5) lateral tieback to adjacent podium building.

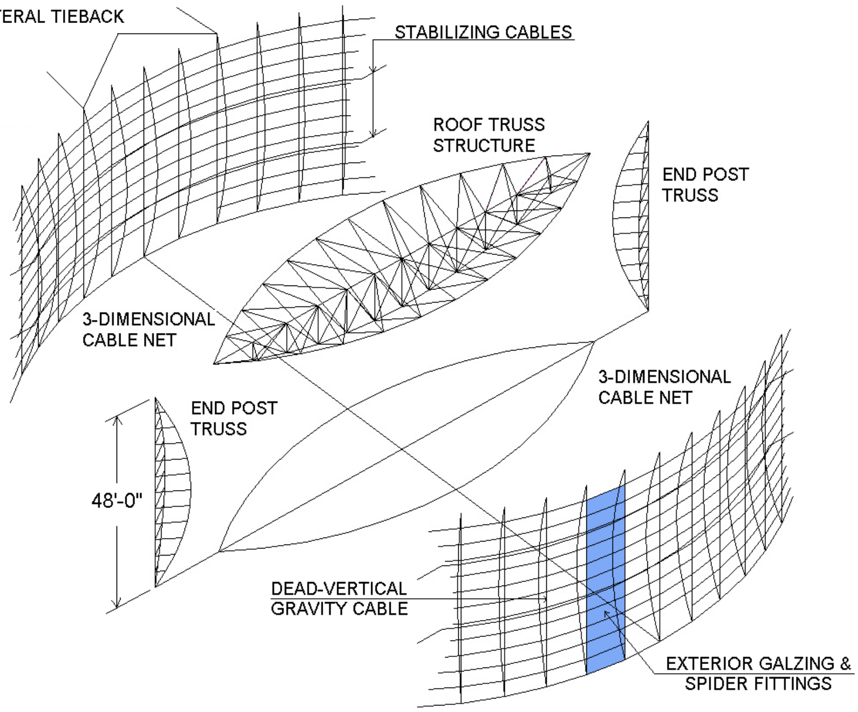

Figure 2: Exploded 3- Dimensional View of Structural System Hierarchy

The organization of the structure is based on the successive sequence of systems that resist the forces of nature. The principal imposed loads are those of wind and gravity with the wind forces dominating the design.

2.1 Glass, Spider Fittings and Dead Vertical Cables

The outer surface of the entry is single glazed with 18mm laminated glass. Silicone sealant is used to butt glaze the joints. The 305 mm (1.0 foot) distance between glass and the cable net is set by the end detail that allows the glass to pass by the support column. The lens form of the building was utilized to create a geometry by which each glass panel on the vertical surface is the same size. The glazing surface consists of straight glass panels approximately 1219mm x 2648mm (4’-0” x 8’-8”) in size. The glass follows the natural line of the pre-stressed horizontal cables segmented into straight lines around a radial arc of 24.4 m (80.0 feet). The glass is mechanically connected to the structure by custom designed “spider” fittings that transmit the wind forces and gravity loads from the glass to the supporting structure. The weight of the glass is transferred by the spider fitting to the 12mm dead-vertical cable by the extension of the cable net compression strut. The dead vertical cable is pre-stressed so as to not go into compression under design loads; therefore, the dead vertical cable greatly decreases the deflections and rotations of the roof truss. The dead-vertical cables in effect act as extremely thin columns to support the roof for the superimposed loads.

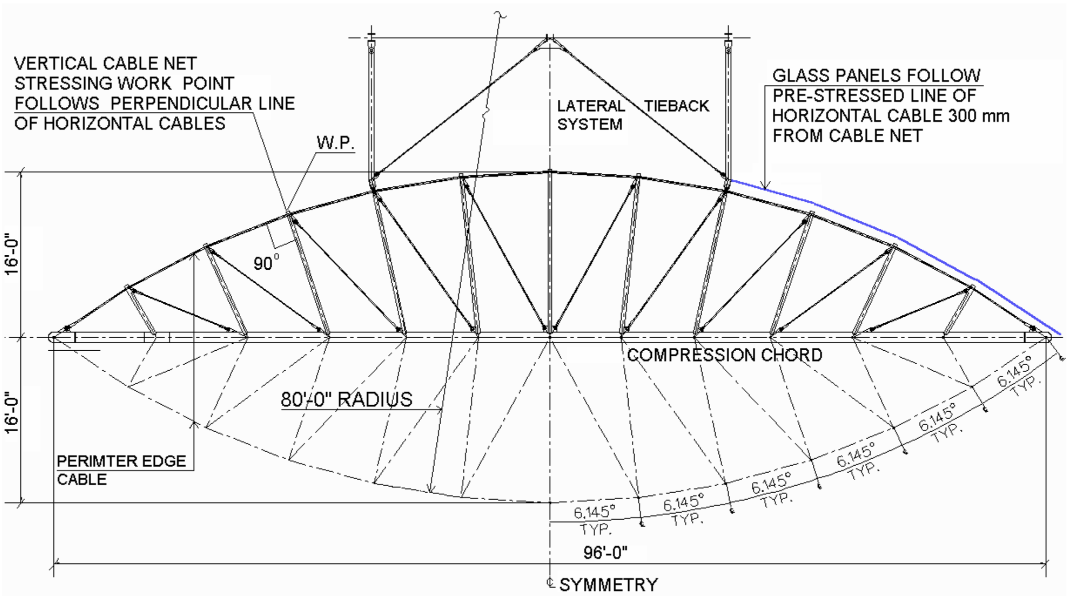

Figure 3: Plan View of Roof Truss Structure

2.2 Cable Net Walls

Wind is a difficult load to resist because of its variability. The forces created by the wind can be pressures or suctions and can be of uniform or variable magnitude and have both static and dynamic components. This is in contrast to gravity forces that have constant direction and magnitude and are thus static for a fixed structure.

Cable and glass structures can successfully resist the forces of the wind with large deflections. A case in point is the Kempinski Hotel at the Munich Airport that has been successfully designed for deflections up to 1 meter. However for the GM entrance, it was decided to use a system with high stiffness and relatively small deflections. This requires the use of a cable system that has been pre-stressed into an appropriate shape for resisting variable wind forces. A cylindrical shape wall with horizontal cables was chosen for the entry to unify the glass panel sizes on the surface. These 18mm diameter stainless steel cables are spaced vertically at 1219 mm on center (4 feet). This structure by itself was sufficient for a uniform suction but was inadequate for pressures and was sensitive to non-uniform suctions. These inadequacies were addressed by the introduction of parabolically shaped 24mm diameter vertical cables spaced at 2615 mm (8'-7") on center that pre-stress the horizontal cables and resist pressures by tension. The resulting two-way pre-stressed cable net creates an anticlastic system that resists both pressures and suctions through tension of one set of cables, and reduction of pre-stress tension in the opposing set of cables. Non-uniform loads are resisted by the stabilizing effects of the pre-stress cable net displacing to an appropriate geometry.

The horizontal and vertical cables of the net are separated by a stainless steel compression strut that tapers from 50mm (2 inch) to 25mm (1 inch). Under some load cases the strut and the vertical cables tend to roll out-of-plane. This action is restrained by the introduction of a stabilizing cable at the third points of the vertical cable. The combined dead-vertical cables and the parabolic vertical cables occur in pairs on a radial layout. This permits a uniformity and economy of detailing.

In order to create the openings in the cable net for the revolving door and the passage ways to the vestibule, the lowest horizontal cable is interrupted and terminated at a slender pipe column. The load is transferred around the openings through bending and shear in the pipe columns to the floor construction below and the adjacent horizontal cable above.

2.2 Roof Ribs and Roof Truss

The roof truss is essentially a 3-dimensional truss. The horizontal plane resists lateral wind forces while the vertical plane resists gravity forces and forms the system against which the vertical cable net trusses are pre-stressed.

The horizontal plane is organized in a leaf-like configuration that consists of 114 mm (4.5 inch) stainless steel pipes that radiate out from the 325mm (12.75 inch) main stainless steel compression chord along the radius of the work point to the upper end of the vertical cables. These ribs are sized to transfer cable net forces from opposite sides of the system as well as provide stiffness required to support the glass panels on the roof. The horizontal plane of the roof truss cantilevers out from the lateral tieback system to the east and west to help brace the end post truss and transfer wind loads back to the adjacent podium building. Here the main chord is centered between two pre-stressed 50 mm perimeter edge cables that stiffen the roof plane to counteract unbalanced wind forces from the vertical cable net.

The vertical plane of the roof truss supports the roof and the cable net walls and spans 29.3 m (96’-0”) to the end post trusses in a more traditional sense. Here the same compression element is the top chord and the bottom chord consists of an 88mm diameter cable to form a “bow truss” that follows the moment diagram for the dead load plus pre-stress forces. This truss has been triangulated for additional stability during erection.

Figure 4: 3-Dimensional Computer Image of Upper Corner: End Post Truss, Roof Truss, Stabilizing Cables, and Cable Net Trusses

2.4 End Post Truss

The two vertical end post trusses at the apex of the pavilion structure serve the dual purpose of creating a stiff truss system by which the horizontal cable net can be pre-stressed and support the vertical loads from the roof truss. The end post trusses tie together the 3-dimensional cable nets on the two vertical faces of the entrance pavilion structure by creating a stiff parabolic truss. This truss is a combination of the vertical 324mm diameter (12.75 inch) main column compression element, 2 - 50 mm parabolic cables as the stiff tension elements and 89mm (3.5 inch) stainless steel pipe struts to transition the horizontal cables between opposing faces. The two end columns also transfer vertical loads from the roof truss to 1.53 m (5’-0”) deep reinforced concrete beams supporting the pavilion. The reinforced concrete base structure is deigned to limit deflections and to resist all pre-stressing forces during construction.

2.5 Lateral Tieback System

The lateral tieback system consists of 168mm (6.625 inch) pipe, as the compression elements and 22 mm cables as the tension elements positioned vertically in the horizontal plane of the roof truss. The cables are pre-stressed between the adjacent podium building and the pavilion structure to provide a triangulated system of lateral stability to the overall structure. No vertical loads are transmitted through this system.

Detailing

The hierarchy of the structural system is mirrored in the hierarchy of structural detailing. The detailing philosophy was to eliminate eccentricities between members to provide a pure load path throughout the structure. This was accomplished by limiting members to single elements converging at unique work points in lieu of multiple or lattice type members. All the structural members clearly express the magnitude of forces that are

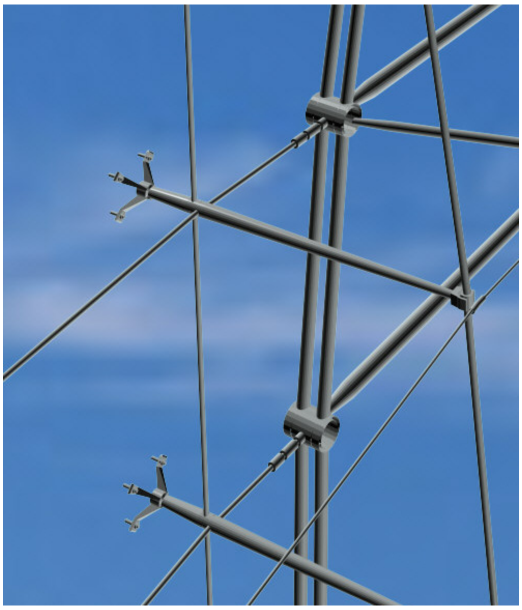

Figure 5: Computer Image: Cable Net Clamp

associated with them. Cables identify all tension members in the system, where as pipe sections where used for compression and bending type members. All the pipes and cables are stainless steel shapes that are available from most mill and fabrication shops. All connection plates, clamps and clevises are custom shaped pieces that reflect the detailing philosophy. The connection philosophy was to reduce the size of clamps and plates so that all tension members visually bisect the compression members without effort. This is most evident in the vertical cable net where the dead-vertical and horizontal cables intersect the compression strut and spider arm (Figure 5). Here the clamping bolts are hidden within the clamping plates to provide a smooth visual transition between the tension cables and the compression elements. The spider arm is sleeved over the projection arm of the compression strut and anchored by a counter-sunk bolt through the spider arm. Both the spider arm and compression strut arm are keyed horizontally to prevent rotation.

It was important to visualize these connections in 3-dimensions in order to understand the complexity of each detail and to properly resolve all component forces that converge into a single work point. Figure 5a illustrates the cable net connection to the roof truss where seven members intersect at a single work point. This connection provides a casting to form the solid shape required to clamp the continuous top perimeter roof cable. The cable net's dead vertical cable and parabolic cable are fully developed through custom stainless steel sockets that are collected by a single gusset plate welded to the casting. Each custom clevis is adjustable for construction tolerances within the end fittings. The roof truss rib pipes are all shop welded to control warping and visual appearance. Diagonal roof truss cables in the horizontal plane are connected to the casting with a custom stainless steel clevis and gusset plate. Spider arm fittings for both the roof and vertical glazing are also supported at this joint. Therefore, by utilizing a stainless steel casting all component forces are coincident with the work point eliminating eccentricities.

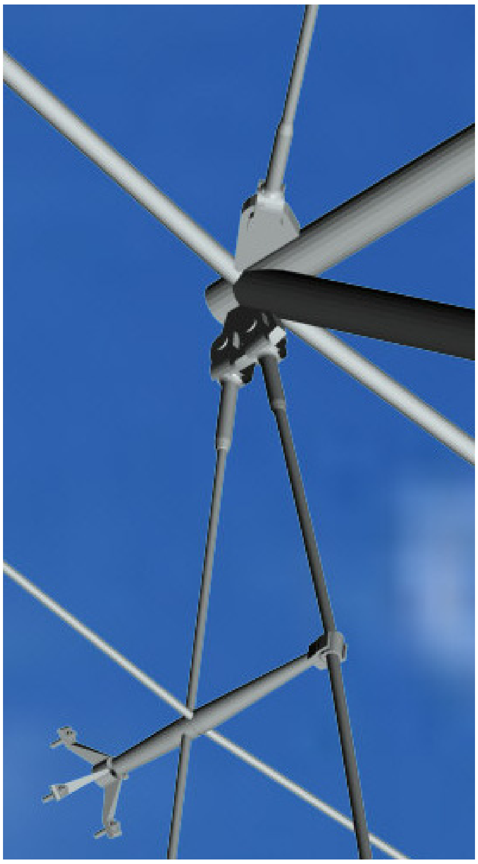
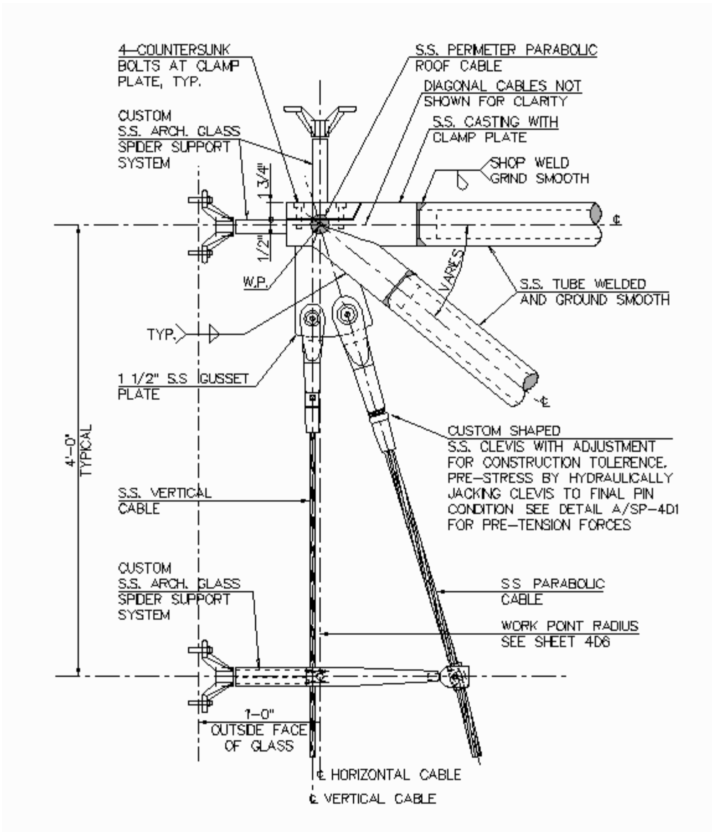

Figure 5a: Computer Image and Detail: Cable Net Connection to Roof Truss

3.0 Wind Analysis

The entrance pavilion was designed for maximum wind forces determined from a combination of wind tunnel studies and BOCA-1993 code prescribed forces. Wind climate analysis determined the extreme gradient wind speed to be 45 m/s (100-mph) for a return period of 100 years in the Detroit area. The aerodynamic pressure data for all wind tunnel tests were combined with the design probability distribution of wind speed and direction to predict differential suction and pressure for various return periods. Figure 6 illustrates maximum wind tunnel pressures and suctions for a 100-year return period.

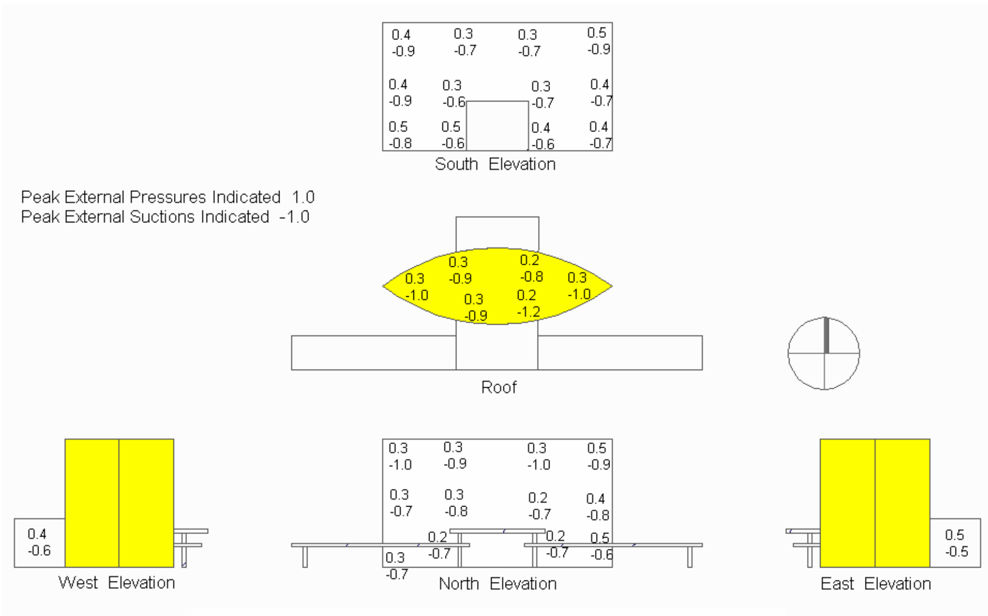

Figure 6: Wind Tunnel: PEAK EXTERNAL PRESSURES AND SUCTIONS (kPa)
100 Year Return Period

The BOCA 1993 code was also used to determine wind forces on the entrance pavilion structure. Wind loads on the main wind resisting system were based on an Exposure Category B, Importance Factor 1.0, and a Basic Wind Speed of 75-mph. The podium building roof height of 72'-0" was used as the mean roof height in lieu of the 48'-0" height of the pavilion roof because of the close proximity of the podium building. Figure 7 displays the code prescribed wind pressures on the pavilion structure.

Although the forces are not large, additional studies were conducted to determine the variable pattern of local wind forces on each vertical cable net truss. These studies provided peak mid-span shears and corresponding moments for each vertical cable net truss associated

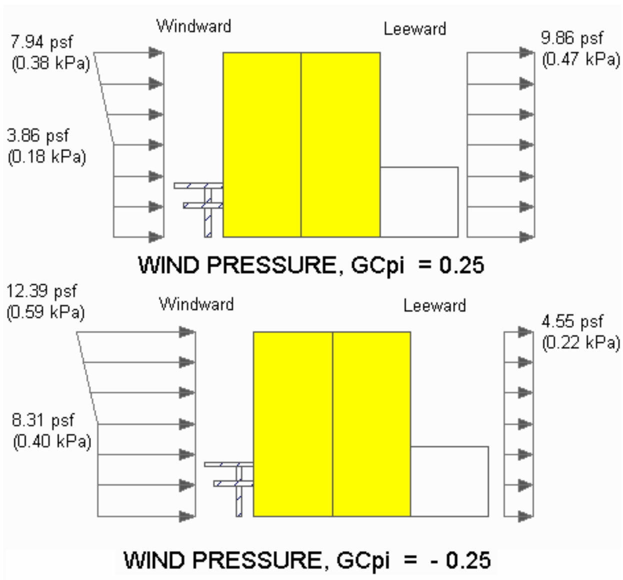

Figure 7: BOCA 1993 Wind Forces

with a modeled wind tunnel pressure tap. These forces were correlated to calculate variable wind pressures along each cable net truss to determine the range of differential wind forces. Figure 7a shows the results of this study by superimposing all truss pressures and suctions along the north face of the pavilion. The graphs clearly illustrate the variable nature of the peak wind loads on the pavilion structure. Wind suctions along each vertical truss varied from a maximum of 14.56 psf (0.70 kPa) at the top to 1.91 psf (0.09 kPa) at the bottom. Differential fluctuations in wind such as these produce magnified local effects in each truss.

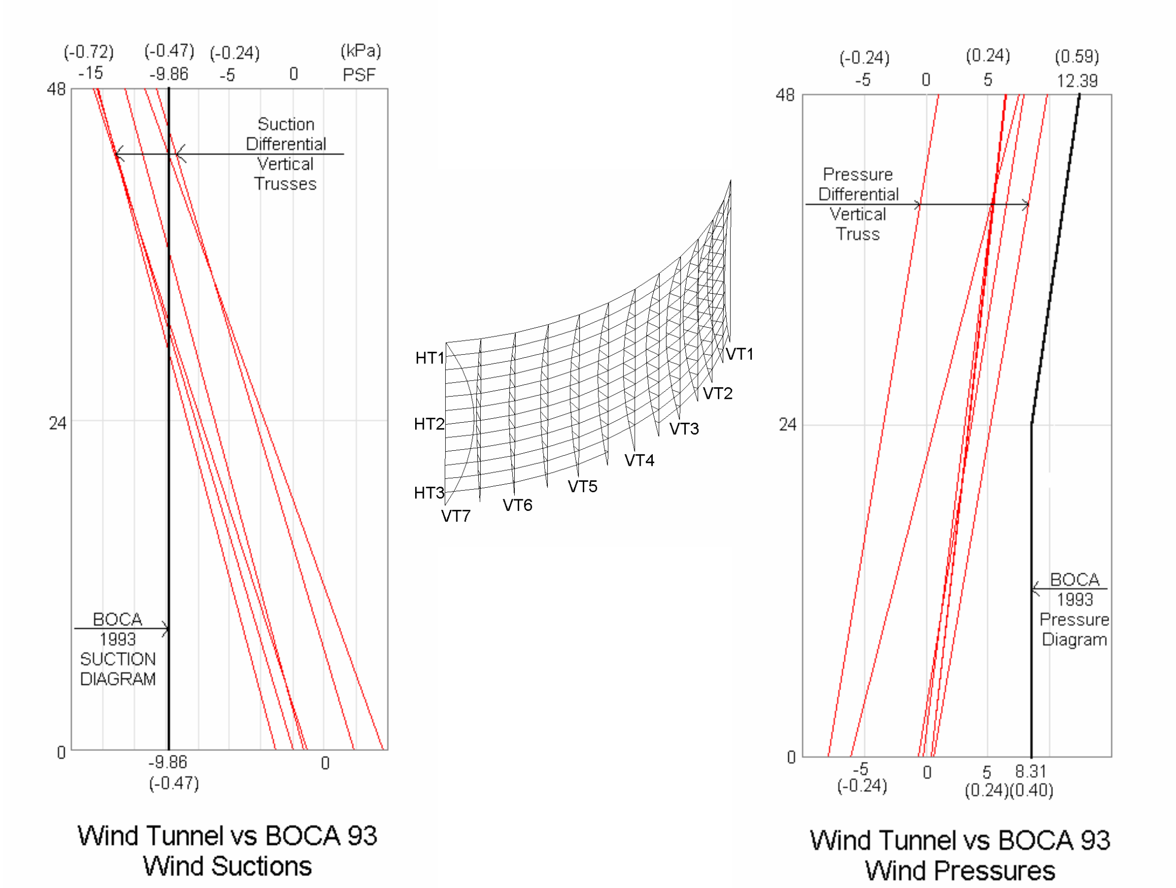

Figure 7a: Variable Pattern Wind Forces on North Face of Pavilion

Due to the large variance in wind forces on the structure, pattern wind load cases were developed to envelope the maximum probable wind distribution from both the wind tunnel and code prescribed forces. Wind tunnel pressures that were lower then the code prescribed forces were only used to check local effects on the cable truss. BOCA 1993 loads governed the overall structure and pattern loads were applied to cover the full range of differential pressures. The following is a description of some of the wind load patterns that were analyzed: 1) 100% of uniform wind loads acting normal to the structure (N-S and S-N directions, 2) Wind loads acting along E-W direction (projected on the global axis), 3) 50%, 75%, 100% pattern along the horizontal face of the pavilion. Each percentage represents 1/3 of the projected surface area. 4) 50% and 100% pattern along the vertical face of the building. Each percentage represents ½ of the projected surface. In addition to these governing load cases wind tunnel pressures were applied to incorporate the differential ranges of wind pressures on the structure.

Each load case was analyzed to verify that all design criteria was met. All pre-stress forces in the cables were to remain in tension for service load conditions assuming the pre-stress forces are only 90% of nominal values. Also, the structure must remain stable under factored (AISC-LRFD) load combinations assuming the pre-stress forces are only 90% of nominal values. Deflections were also kept to a minimum to accommodate the glazing system. Figure 8 illustrates the maximum wind deflections from all combined wind load combinations.

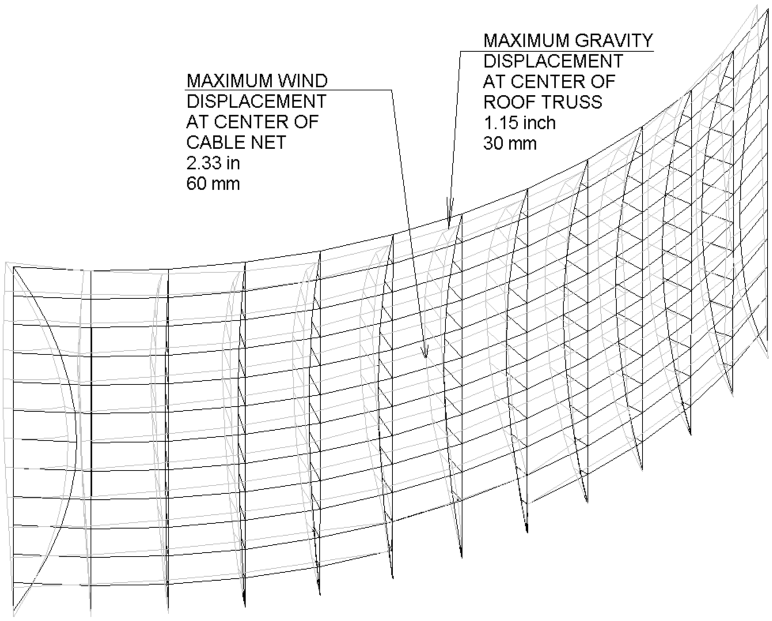

Figure 8: Maximum Deflection: Wind N-S Direction

4.0 Conclusion

The General Motors' entrance pavilion creates a dramatic combination of cables and glass with an efficient, minimalist structure that distinctly expresses its function. The pre-stressed cables within this tension structure are shaped into an eloquent geometric form that efficiently resists the imposed forces of nature and provides the stiffness required to readily maintain the structure's stability.

References

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