FAÇADE OPTION ENGINEERING

Optimization of transparency in a mega glass lite project

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ABSTRACT

A successfully engineered structural glass structure requires a rigorous process to ensure the client receives an optimized, safe and cost efficient solution while maintaining and improving on the original design intent. The process to arrive at a logical and efficient solution is termed an Option Engineering process. This is a collaborative emergent design method Walter P Moore (WPM) promotes to ensure integration of teams to provide the communication and technology necessary to deliver rapid innovative solutions. The goal is to produce the best possible solution from the project parameters and constraints that maintain and enhance the design intent. To illustrate this philosophy, this paper presents the engineering and design process of a mega glass lite for a lobby renovation project in Dallas, Texas.

Through an iterative design and engineering process, a family of structural options is established by considering constraints of operational strength, deflection, fabrication, constructability, cost, and aesthetics. The iterative process allows for consideration and evaluation of a variety of structural options that eventually lead to a final solution that best meets the project goals.

The new exterior wall design comprises twenty 10 ft. wide by 30 ft. tall monolithic glass lites at the lobby. This paper details the evolution of the design parameters to arrive at a working design for the glass panels. Given the height of the glass lites, the goal was to provide adequate support for the high lateral wind loads while satisfying the client's request for maximum transparency and a slim transparent structural back up system.

The process of refining the design involved various considerations including: (1) different analysis procedures and comparisons of their respective modeling accuracy, (2) studies of current glass code and the prescriptions compared with analysis program results, (3) structural sealant modeling limitations and challenges, and (4) the effects of the glass support or detail conditions on the deflection and glass stresses.

From the initial design proposal of a composite steel fin and cable truss between each panel, the progression of design and engineering evolved towards the optimization of transparency and the final solution.

KEYWORDS

Mega Glass Lites, Cable Wall, Metal Fin, Structural Sealants, Glass Engineering, Structural Glass, Laminated Glass, Design Processes, Option Engineering

INTRODUCTION

Decisions taken during the early stages of design have long lasting implications on performance of the façade system. This paper is important for designers and clients to understand how iterations, from early design through development, help in steering the design intent toward a cost effective and a performance based optimized final solution. With improving sophistication of façade technology, comparative assessment of multiple options has become fundamental to the design process in order to find the best possible solution. This iterative process, known as option engineering, requires collaboration between the client, architect, façade designers, structural engineers and the project contractors.

The paper lays out the steps of the design and engineering processes of a high transparency glass façade for a tower lobby re-clad project in Dallas, Texas. Option engineering is the method used to assess the performance of multiple facade solutions based on project specific parameters such as design intent, façade system design, material properties and strength, deflection criteria, impact to existing building structure and cost implications. The process is reliant on embedding these project logics into the design process. The process also considers constructability and fabrication parameters.

PROJECT BACKGROUND

The client's main intent was to maximize transparency of the lobby with a proposed long span hybrid cable/fin truss system to provide structural support to mega lites of low iron laminated glass. Minimal structure and minimal glass capture was the architectural vision. Through the option engineering process, multiple structural backup systems were developed and compared in order to generate a performance matrix and finally arrive at the final solution of an efficient glass façade, thus adding value to the project.

Option engineering has recently gained popularity with advancement of digital tools that allow parametric modeling, simulation-based analysis and interoperability between multiple disciplines. Walter P Moore and other AEC firms have started promoting this emergent process to ensure integration between teams and rapid delivery of best available solutions.

For renovation of the tower lobby, the façade and structural engineering teams at Walter P Moore, in Los Angeles and Austin respectively, worked as an integrated team to assist the team from Gensler and James Carpenter Associates, the designers of the glass façade system. The design intent was to maximize transparency of the façade; hence, the designers proposed a system composed of full height laminated glass lites, 28 ft high x 10 ft wide, supported by pre-tensioned cable and steel fin vertical truss system providing lateral resistance for deflection. The thought behind the cable was to reduce the structure to a bare minimum and provide maximum transparency.

The SD facade design criteria was developed to analyze the structural performance of the proposed system. The preliminary approach was to minimize the pretension loads in the secondary systems to reduce the impact on primary structure and save retrofitting costs.

METHOD

Through design iterations, multiple structural system types were established using Finite Element Analysis by considering constraints of operational strength, deflection, fabrication, construction, codes, and aesthetics.

Design Criteria: Applicable engineering codes, design loads, material stress limits, and deflection limits were identified in the design criteria for the project.

Analytical Model: The general analysis model was comprised of three typical glass panels (3x30'x10') of the proposed atrium lobby wall. These panels were modeled using 1.5" thick (triple laminated) glass, 1.5"x 3" to 5" 50 ksi stainless steel vertical fins, 0.75" to 1" structural strand cables, and structural sealant that bonded the glass edge to the steel fin. Throughout the analysis process, various components were adjusted accordingly as the design evolved.

The geometry was generated in Rhino, parametrically using a digital workflow utilizing a live Grasshopper link to the structural analysis program. The parametric digital workflow allowed multiple iterative geometries to be quickly generated, processed and analyzed. The model was analyzed in Oasys GSA and CSI SAP2000 to assess glass stresses, membrane action of the glass, and deflection behavior of the structural system.

The glass was checked for maximum tensile stress under strength load combinations and deflection under service load combinations. Moment and axial forces for the fin and reactions for top fin support and bottom glass supports were simulated. Using the maximum forces from this analysis, dimensions of the structural sealant were calculated.

ITERATION 1: CABLE TRUSS SYSTEM WITH VERTICAL FINS; PINNED SUPPORT; STRUCTURAL SEALANT

The preliminary structural analysis checked the strength and deflection performance determined an appropriate cable pretension to meet a deflection criteria limit of L/50 in the wall system (where L is the height 28 ft of the glass panel and backer structure span).

Model Attributes: Per the architects' requests for a transparent and minimal structural support system, the initial model was composed of large laminated glass mega panels of height 28 ft x width 10 ft. Each glass panel was base loaded and captured along the short edges for lateral loading through a sill. Along the long edge of each mega panel a vertical fin cable truss of an 8 in depth was used to provide lateral restraint. The 3" front steel fin ran continuously along the vertical edge and a non-mechanical silicone joint was used to capture the glass. Horizontal struts run from the fin back to a vertical pre-tensioned stainless steel cable. The structural sealant was not modeled at this time. Figure 1 below shows the various structural components in the GSA model.

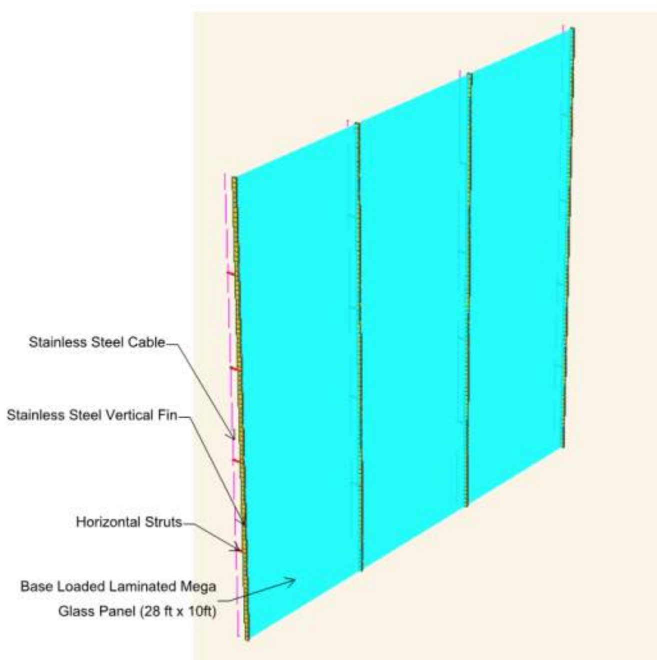

Figure 1: Façade System Baseline Model – Glass Lites Supported by Vertical fins and Pre-tensioned Cable Truss System

The cable was pretensioned to a suitable value to provide lateral resistance for deflection and minimize the working stresses in the glass. For each option, the cable pretension was varied from 10 kips to 20 kips, returning a suite of viable designs. The models were analyzed with ASD level components and cladding wind loads for glass strength checks and a 10 year mean return interval for deflections checks. Figure 2 is a summary of the preliminary design criteria used.

Summary of Facade Design Criteria

The design and deflection criteria are based upon those specified in IBC 2012, ASCE 7-10, and ASTM E1300

Self-Weight (SW)	As Computed by Structural Analysis Software
Dead Load (D)	13 psf for 1in. thick glass panels
Wind Load (WL1 WL2)	Risk Category II Building Site Wind Speed of 115 mph (ASCE 7-10) Exposure C C&C (ASD Design Wind Loads) WL1 - Windward: 26.5 psf WL2 - Leeward: 41.6 psf Deflection Limits TBD Deflection (Serviceability) based on 10 yr. MRI wind WL1 - Windward - Service: 18.5 psf WL2 - Leeward - Service: 30.1 psf
Seismic Lateral Load and Drift	__________
Temperature Load	Not Applicable
Roof Live Load (LLr)	Not Applicable

Figure 2: Façade System Preliminary Design Criteria Summary

Inference: Based on the analysis models, a pretension of 10 kips ensured acceptable glass stress levels (ignoring edge stresses) and met the deflection limits. While the higher pretension options also returned working designs, the lower the pretension meant less load acting on the primary structure. Note that the glass strength was reviewed for probability of breakage of 8 per 1000 lites for a 3-second load per GANA Glazing Manual recommendations. Therefore, these are the maximum allowed principal tension or design stress for different finishes: Annealed – 3.4ksi; Heat Strengthened – 6.7ksi; Tempered – 13.5ksi. Preliminary analysis showed that a 1.125” laminated annealed glass was appropriate. Images (Figure 3) below show an example stress plot, axial load in the fins, and deflection contours.

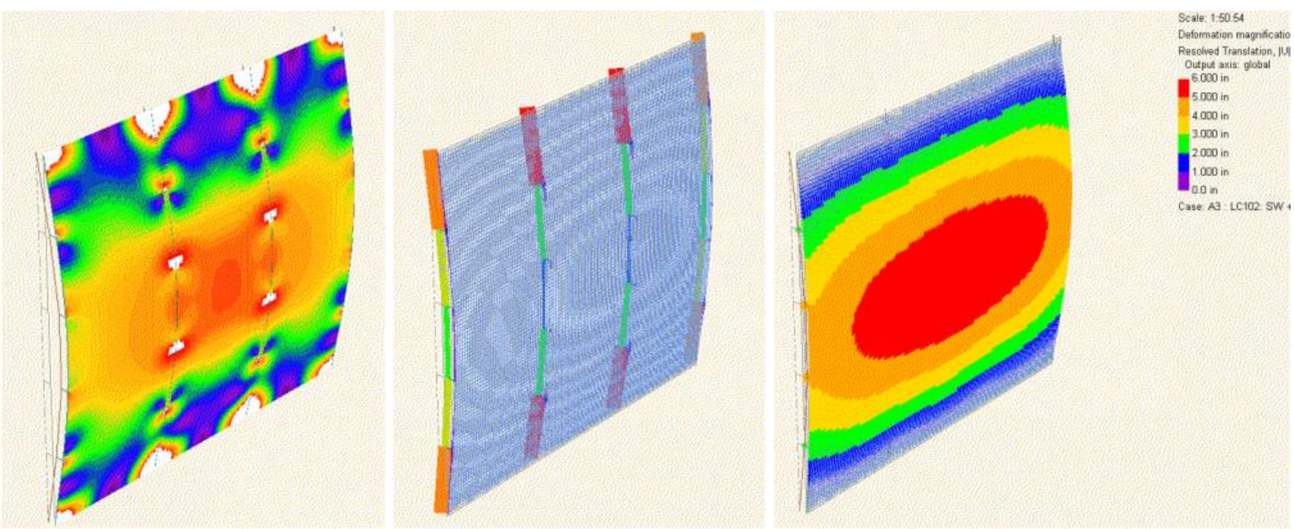

Figure 3: Preliminary Analysis: Example Stress Plot, Axial Load, Deflection Contour

In sum, preliminary pretensions and reactions for the cables, appropriate to control deflections to L/50, were developed from the analysis. The reactions were coordinated with the primary structural engineering in order to gauge the impact of the support beams and connection at the floor and soffit interfaces. Figure 4 is an extract from an Excel table listing the reactions for the model with 10 kip cable prestress.

Reactions	V	H
Cable Top	21 kip	6 kip
Cable Bottom	21 kip	6 kip
Sill Bottom	0 kip	0.6 lbf/ft
Sill Top	0 kip	0.6 lbf/ft
Fin Top	6 kip	15 kip
Bottom	4 kip	15 kip
Setting Out		
Block Bottom	6 kip	1 kip
Note:		
All reactions ASD		
Reactions are for a 10 kip cable Pre-Tension		
All reactions are PRELIMINARY		
V: Vertical reaction		
H: Horiontal Reaction		

Figure 4: Cable Interface Reactions

ITERATION 2: CABLE PRETENSION COMPARATIVE ANALYSIS

From Iteration 1, preliminary reactions to be carried by the primary structure were obtained. Given the magnitude of the reactions, it became apparent that the strength and deflection demands were problematic for the primary design. If the cable forces were too great, it could cause the primary structure to deflect above a prescribed allowable. Then the cable could go slack, rendering the system ineffective. If the primary structure was strengthened to handle the demand, it could be expensive or visually obtrusive.

Although an acceptable working façade design was available, the effect of the cable forces on the primary structure was a concern. Therefore, the studies with a range of new options were carried out to see if the pretension in the cable could be lowered to reduce reactions. The study investigated the interaction between the cable pretension, the depth of the cable truss, the size of the steel fin, and the deflection of the glass and fin system. The effectiveness to transfer loads, from the glass to the backer structure, of the structural sealant that bonded the glass edge to the steel fin was also reviewed.

Model Attributes: The analysis model was comprised of three typical glass panels (3x28'x10') of the proposed atrium lobby wall. These panels were modeled using 1.5" thick (triple laminated) glass, 50 ksi stainless steel vertical fins, and 3/4" structural strand cables. The depth of the cable truss ranged from 8 to 11 inches. The size of the vertical steel fin ranged from 1-1 ½ in wide by 3-5 in deep. See Figure 5 for an option where the cable and struts are to be removed.

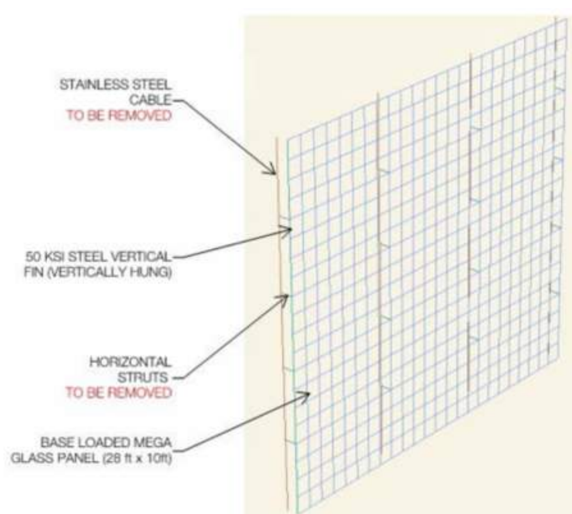

Figure 5: Façade System Modified Model with Glass Lites Supported by Vertical Fins – No Cables and Horizontal Struts

Inference: A matrix with different depths of the cable truss, sizes of the steel fin, and cable pretensions was created – See Figure 6 for an extract of the matrix.

Model Name	Option	Depth	Cable	Cable PT	Fin Size	Glass Thickness (Analysis)
SealantModel_06-1.5x5_003-2.5in	Option A	11.00 in	0.75 in	10.0 kip	1.5x5	2.500 in
SealantModel_06-1.5x5_007-2.5in-no-cables	Option A_1	11.00 in	0.75 in	NA	1.5x5	2.500 in
SealantModel_06-1.5x5_006-1.125in	Option B	11.00 in	0.75 in	10.0 kip	1.5x5	1.125 in
SealantModel_06-1.5x5_008-1.5in-no-cables	Option C	11.00 in	0.75 in	NA	1.5x5	1.500 in

Figure 6: Extract of Options Matrix

As the pretensions in the cables were reduced and eventually brought to zero, it was clear that the cable contribution in the performance of the structural backer system was minimal to none as Figures 7 through 8 tabulate. In other words, if the glass and fin configurations are held constant, the addition of the prestressed cable did not significantly decrease the glass and fin stresses. This introduced an opportunity to eliminate the cable and supporting elements completely. The impact of removing the cable was significant in the reduction of cost since the primary backer structure could be reduced as well.

Option	ASD Cable Force		ASD Strut Force		ASD Fin Forces			
	Windward	Leeward	Windward	Leeward	Windward		Leeward	
					Axial	Moment	Axial	Moment
Option A	10.5 kip	11.2 kip	0.1 kip	0.2 kip	1.01 kip	44.5 kip-in	2.73 kip	70.8 kip-in
Option A_1	NA	NA	NA	NA	0.99 kip	47.9 kip-in	2.85 kip	76.6 kip-in
Option B	14.6 kip	19.2 kip	0.4 kip	0.8 kip	1.52 kip	141.3 kip-in	8.11 kip	199.6 kip-in
Option C	NA	NA	NA	NA	2.11 kip	135.7 kip-in	7.80 kip	212.7 kip-in

Figure 7: Element Forces for the Pretension and No Pretension Options

Glass Stress:

Option	ASD Glass Stresses			
	Windward		Leeward	
	Max Tensile	T DCR	Max Tensile	T DCR
Option A	2.00 ksi	0.59	3.19 ksi	0.94
Option A_1	2.15 ksi	0.63	3.43 ksi	1.01
Option B	3.11 ksi	0.23	4.33 ksi	0.32
Option C	3.85 ksi	0.28	6.05 ksi	0.45

Glass Deflection:

Option	Service Deflection			
	Windward	Leeward	W DCR	L DCR
Option A	1.4 in	2.2 in	237	152
Option A_1	1.5 in	2.2 in	218	150
Option B	4.5 in	6.4 in	76	53
Option C	3.9 in	6.3 in	86	53

Figures 8: Glass Performance Data

The individual elements (glass, fin, and cable) were reviewed with the glass and fin interaction being reviewed in more detail. The lack of any mechanical capture element from the glass to the fin resulted in the sealant having to transfer the load from the glass surface to fin. This was not the most effective way to transfer the loads and resulted in higher glass stresses at the glass lite mid-span and the silicone joint being larger than just a simple weather sealant joint.

ITERATION 3: GLASS PANELS WITH VERTICAL STEEL FINS. PRE-TENSIONED CABLES ELIMINATED

Analysis Model: The natural progression of optimizing the system resulted in the removal of the cable completely. This action removed the pretension forces from the system. The link between the glass and the steel fin remained as the structural silicone element with no other mechanical fastening between the two elements. The steel vertical steel fins were hung and were designed to be 1.5" thick x 5" deep. The glass was a triple laminated unit, 1.5" thick, with tempered glass and SGP interlayer for stiffness.

As the analysis was being refined, the project loads were reviewed and refined as well as shown below:

Design Codes and Specifications:

ASCE 7-10; Steel Construction Manual; 14th Edition; GANA Glazing Manual; ASTM C1401-14

Design Loads:

Wind Loading:

Components and Cladding Wind Load Parameters: Risk Category II Building; Site Wind Speed of 115 mph; Exposure C
Calculated Wind Load Values:

LRFD (MRI = 700 years):	Windward (WL1_LRFD) = 44.2 psf	Leeward (WL2_LRFD) = 69.3 psf
ASD for strength design:	Windward (WL1_ASD) = 26.5 psf	Leeward (WL2_ASD) = 41.6 psf
Serviceability (MRI =10 years):	Windward (WL1_Service) = 18.5 psf	Leeward (WL2_Service) = 30.1 psf

Self-Weight (SW): The self-weight of the elements are calculated by the analysis software. There is no superimposed dead load (DL).
Seismic Loading: Negligible

ASD Design Load Cases

ASD Strength	LC1: SW + WL1_ASD	LC2: SW + WL2_ASD
ASD Serviceability/Deflection	LC3: SW + WL1_Service	LC4: SW + WL2_Service

Design Limits

Stress Limits:
Per GANA Glazing Manual, the maximum allowed principal tension or design stress is for a probability of breakage of 8 breaks per 1000 lites for a 3-second load. For fully tempered glass, this design stress is 13.55 ksi.
The steel is checked per AISC Steel Construction Manual.
Silicone stress is checked using ASTM C1401, a factor of safety of 6, and material specifications.

Deflection Limits:
Proposed glass deflection for all service load combinations is limited to L/50.
Proposed façade fin steel deflection is limited to L/50.
Proposed façade header steel deflection is limited to L/175.

Materials
Stainless Steel: Fins and header plate, Fy, min = 50 ksi- 1.5"x5" vertical fins
Glass: Fully tempered 1 ½ in. laminated with SGP interlayer -28'x 10' panels
Fasteners: Stainless Steel, Fu, min = 75 ksi

Structural Sealant: High-strength silicone, minimum tensile strength of 493 psi, allowable stress is 82 psi based on a factor of safety of 6 per ASTM C1401. (Note: this is a bespoke high capacity sealant provided by the sealant manufacturer, C1401 recommends a minimum factor of safety of 2.5 and the typical industry standard for the allowable stress is 20 psi. A performance mock up test would be used to justify this higher allowable stress).

Analysis Results: The elements of the system were analyzed for performance, and the results of the analysis are presented below. See Figures 9-14 for the glass performance, Figure 15 for the steel fin forces, and Figure 16 for the silicone calculations.

Glass Performance

Glass Stress:

ASD Glass Stresses			
Windward		Leeward	
Max Tensile	T DCR	Max Tensile	T DCR
3.08 ksi	0.23	4.40 ksi	0.32

Figures 9: Glass Stress

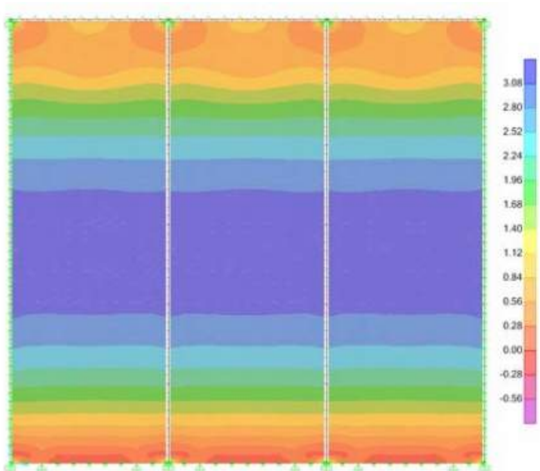

Figure 10: Maximum Tensile Glass Stress – Windward Load

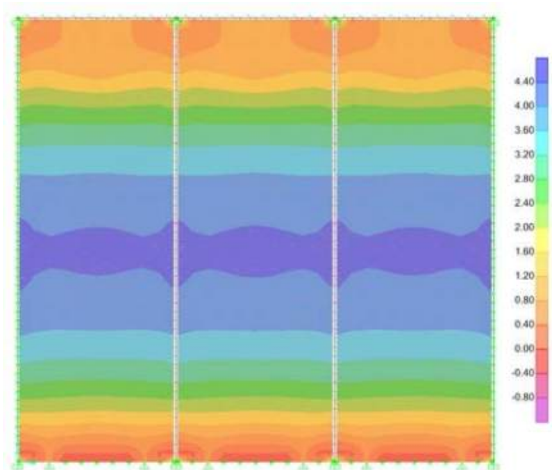

Figure 11: Maximum Tensile Glass Stress – Leeward Load

Glass Deflection:

Service Deflection			
Windward	Leeward	W DCR	L DCR
3.4 in	4.9 in	100	69

Figures 12: Glass Performance Data

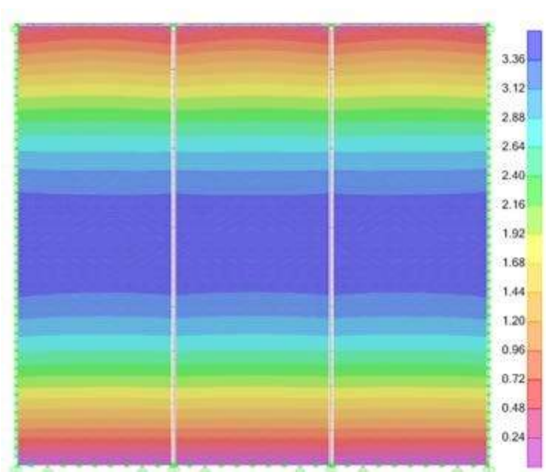

Figure 13: Glass Deflection – Windward Load

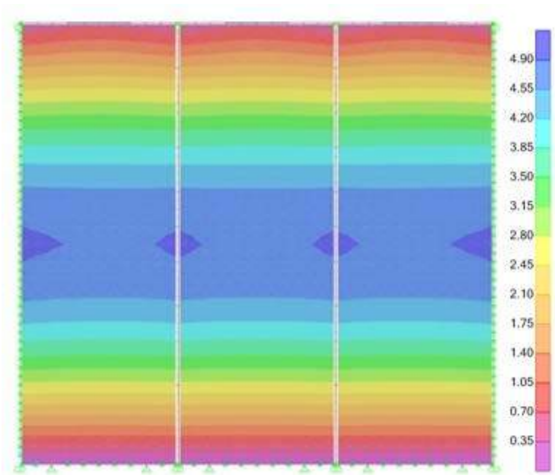

Figure 14: Glass Deflection – Leeward Load

Secondary Element Performance

Maximum Steel Fin Forces

ASD Fin Forces			
Windward		Leeward	
Axial	Moment	Axial	Moment
12.68 kip	110.2 kip-in	23.82 kip	147.9 kip-in

Figures 15: Steel Fin Data

Sealant Design

The structural sealant between the glass edge and the steel fin was designed to be the load transfer element. The bite was 1.5" thick, and the glue-line thickness is 0.5" thick. These were calculated using the maximum forces from the analysis model.

Figure 16 show the required bite sizes for different structural silicone allowable stresses. Based on architectural conditions, a high-strength silicone with an allowable stress of 82 psi was required (See Design Criteria for further detail).

Sealant Type	Direction	Nonlinear Results P Force	V2+V3 Force	Combined Force	Req. Bite
Dow Corning 895	Vertical	0.284 kip	0.329 kip	0.613 kip	6.0 in
	Horizontal	0.007 kip	0.402 kip	0.409 kip	2.3 in
SikaSil SG550	Vertical	0.284 kip	0.329 kip	0.613 kip	1.2 in
	Horizontal	0.007 kip	0.402 kip	0.409 kip	0.5 in
SikaSil SG-20	Vertical	0.284 kip	0.329 kip	0.613 kip	1.9 in
	Horizontal	0.007 kip	0.402 kip	0.409 kip	0.7 in

Figure 16: Required Sealant Bite

Inference: The structural elements of glass, steel fin and sealant work together to resist and transfer loads. In using the structural sealant as the transfer element from glass to steel, allows for a clear aesthetic. This allows for clean visual lines in the high transparency wall. The removal of the cable and hanging of the steel fin makes the system very efficient with a low reactions and thereby allows for minimal modifications and additions to the existing building.

ITERATION 4: STRUCTURAL GLASS LITES WITH FIXED TOP AND BOTTOM EDGES; NO STEEL FINS, NO CABLES

The final aesthetic required one more iteration as the client expected a cable wall, but now has steel fin backed wall. The innovation of engineering a minimal fin and using structural silicone was not enough of a positive to overcome the objections to a simple fin wall. The team looked as one additional development to address this issue.

Analysis Model: The analysis model comprised of three typical glass panels (3x30'x10') of the proposed atrium lobby wall. These panels were modeled with the top and bottom edges fully clamped and no additional vertical structural members. The glass panel was analyzed for deflection and stresses and the designed to perform as the primary structural element for the façade.

Inference: The glazing subcontractor suggested a challenging and simpler solution to the development of the design that removed all secondary structure. This logical development came out of the reaction of the client to the steel fin. He expected a cable wall but when the cable became redundant in the engineering, the steel fin backer was not an aesthetic the client was comfortable with, even though the wall system was structurally innovative with no mechanical capture of the glass and the silicone load transfer from glass to steel. This led to the continued optimization of the system and the exploration of the glass as the primary and only structural element in the façade. The 'glass only' solution was embraced by the design team and the client due its visual simplicity and the resultant maximum transparency. This solution needs further engineering study to ensure the issues of cost, constructability, building retrofit requirements and reactions all work within the project parameters. The loads, stresses, and deflections for the initial design calculations, from Sentech, are shown in Figures 17-18.

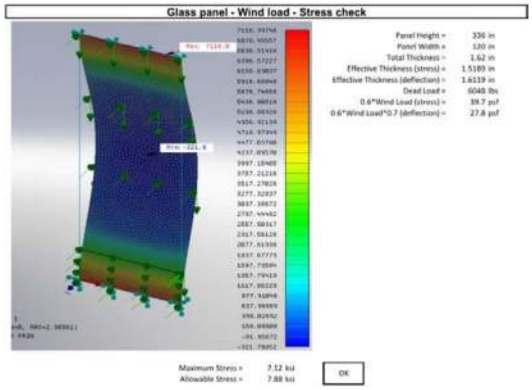

Figure 17: Sentech Glass Stress

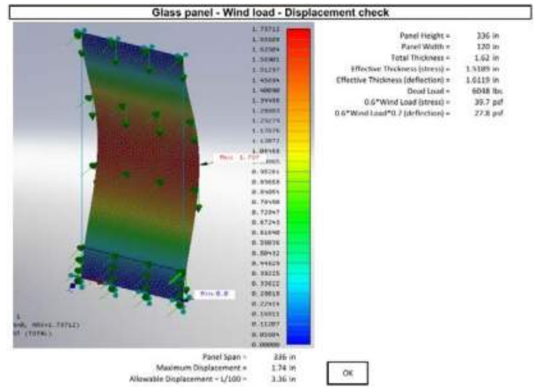

Figure 18: Sentech Glass Deflection

DATA COMPARISON

A comparison of the analysis of the various options was catalogued in Figure 19 to get an overall view of the main features of each system.

Subject	Issue	Sentech	WPM Cable 10/12/2015	WPM 11/5/2015
Wind Criteria	Exposure Category	B	C	C
	Building Height	720 ft.	730 ft.	730 ft.
Design Criteria	Allowable Breakage	1:1000	8:1000	8:1000
	Allowable Stress (field)	10.04 ksi	13.55 ksi	13.55 ksi
	Considered Edge Stress	Yes	No	No
	Deflection Limit	L/100	L/50	L/50
Loads	Critical Buckling/Eigenvalues	Yes	None	None
	Live Load	200 lbf / 50 lbf/ft.	None	None
	EQ Load	Yes	None (deemed insignificant)	None (deemed insignificant)
	Temperature Loads	Yes	No	No
Modeling/Analysis	Software	NEiNastran	SAP, GSA	SAP, GSA
	Total Glass Thickness	1.5"	1.125"	1.5"
	Glass Type	Fully-Tempered	Fully Tempered	Fully Tempered
	Laminate Type	Trosifol	SGP	SGP
	Bottom/Top Edge Support Condition	Fixed	Pinned	Pinned
	Structural Sealant Modeled	Unclear	Yes	No
	Aluminum Fins Modeled	No	Yes	Yes
	Solver	Unclear	Nonlinear Large Displacement	Nonlinear Large Displacement
Results	Max Stress	7.12 ksi	4.33 ksi	4.40 ksi
	Max Deflection	1.74 in	4.5 in	4.9 in

Figure 19: Design Comparison Table

CONCLUSION AND FUTURE WORK

A successful option engineering process was presented that through a process of iterations and feedback loops with the client, a highly transparent engineered glass façade was arrived at.

Future advances in high transparency facades depend on the capacity of the glass manufacturers to produce larger and larger glass lites, use of higher stiffness structural glass interlayers, and development of stronger structural sealants that can be shown to satisfy existing highly restrictive prescribed design codes. The balance of engineering, design and materials performance is the true goal of any structural façade. A collaborative digital work flow facilitates the option engineering process.

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Walter P Moore-Austin - Structural Engineering (Kate Tomlinson)

Façade Sub Contractor: Sentech-Austin (Alfonso Lopez)