# Finite Element Analysis of Structural Silicone of Warped Insulated Glass Units

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***Abstract***: *The second half of the twentieth century has ushered in new advancements in the field of architectural and civil engineering. One such material that is increasing being put to novel uses in building structures is architectural glass. Even though glass has been used in building facades since a very long time, the complexity of modern structures demands use of powerful design and analysis tools to achieve the desired goals. The current paper discusses one such application of insulated glass in a serpentine all-glass wall at the base of a building in Dallas, TX. The challenge in designing the glass to the required standards of safety come from the fact that each piece of glass is different and is warped to achieve an organic contour. Since the glass units are connected to the support structure only through a powerful adhesive called structural silicone, the warped glass units put the silicone in a state of tension. An efficient methodology was designed for analyzing the wide array of glass units and their sealants using various tools. A primary procedure was incorporated to find the worst-case glass units which were then analyzed in further detail. It was found that the structural silicone could withstand the warping of the glass units.*

***Keywords***: *Glass, Glass Warping, Abaqus/CAE, Abaqus/Standard, RFEM, Rhinoceros 3D, Grasshopper (for Rhino3D), Silicone Modeling, Hyperelasticity, Python Scripting, Design Optimization, Failure, Architecture, Civil Engineering.*

## 1. Introduction

The rapid advancement in modeling and analysis tools coupled with advances in the standardized production and assembly of building materials, as well as mechanical systems for regulating the temperatures of building interiors has enabled architects and engineers alike to come up with bold designs using novel materials. One of the attractive materials that designers are making use these days is architectural glass. Glass has been long used as a transparent glazing material in building envelopes. In the early decades of the twentieth century, the extensive use of glazed fenestration was akin to architectural modernism in countries like Germany, France and Netherlands[1]–[3]. It was only after the second world war that we started seeing genuinely creative and grand application of glass in modern structures. A closer look at some modern buildings which make use of glass creatively will convince the reader that designers are indeed pushing the limits of ingenuity and engineering. Figure 1 shows the National Centre for the Performing Arts (NCPA) which is a magnificent and gigantic structure which has an ellipsoid dome of titanium and glass surrounded by an artificial lake [4].

**Figure 1: National Grand Theatre, Peoples Republic of China.**

The second structure shown in Figure 2 is the 'Trade Fair' complex in Milan, Italy. The inspiration for the structure, which stretches nearly a mile, comes from intrinsic elements of the surrounding landscape. The concept was refined through numerous iterations using design and analysis tools which played a critical role in maintaining the continuity of the original idea. The product was the fluid-like canopy that runs the entire length of the structure.

**Figure 2: Trade Fair Complex, Milan, Italy.**

Massimiliano garnered inspiration from the intrinsic elements of the surrounding landscape. The concept was further refined through numerous iterations within the digital realm, which played a critical role in maintaining the continuity of the original sculptural sketch/model and in the eventual fabrication of the fluid fabric-like canopy that runs the entire length of the Fiera. This paper pertains to a $225 million, 20-story office and retail tower on McKinney Ave., Dallas, TX. It has been designed by award winning architect Pelli Clarke Pelli and the project includes the silver-glass high-rise, a two-story shopping center and a parking garage clad in ribbons of stainless steel. The specific scope of the project detailed in this study is the serpentine glass wall at the base of the building as shown in figure below.


**Figure 3: Location of glass wall**

The glass is held in place by aluminum mullions which are attached to the glass through a strong adhesive silicone. To achieve the required organic contours, the glass panels are warped in a direction perpendicular to the original glass plane. This is done at the site by pulling one of the glass corners while holding the other corners in place shown in Figure 4. The glass is attached to the support structure using the adhesive. A temporary scaffold holds the glass in this warped shape till the silicone is fully cured after which the silicone can hold the glass in the desired configuration. Because of this, the structural silicone near the warped edge is in a state of tensile/compressive stress. This paper studies the effect of glass warping on the integrity of structural silicone.

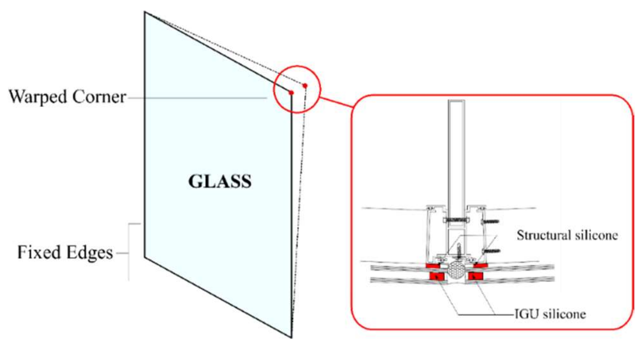


**Figure 4: The connection detail**

## 2. Determining the warping distance of each glass lite.

The initial analysis was done in the modelling software Rhinoceros 3D. The CAD model of the glass wall was imported into the software. To determine the warping distance of each panel, three of vertices were assumed to lie on a flat plane. This plane is found using vector mathematics. The warping of the glass lite is then the distance of the fourth point from this plane. By applying this logic in grasshopper software in Rhino3D, an entire system of panels (238 glass panels) were analyzed quickly and accurately. The dimensions of each glass lite (co-ordinates of the glass vertices) and the warping data and from this analysis was then exported to an external file which was then used in Abaqus/CAE to create warped models of glass.

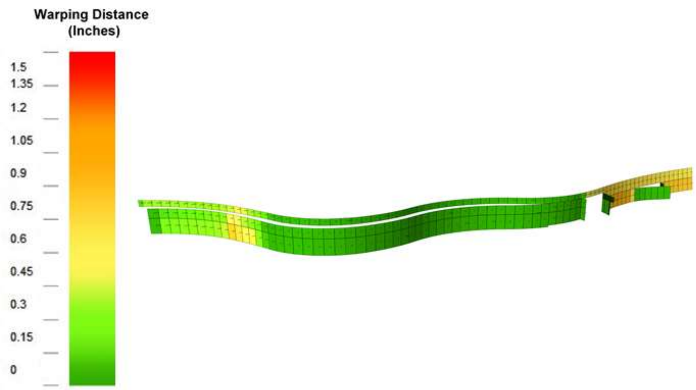


**Figure 5: Determining the warping in Rhino3D**

## 3. FE Modeling

In the analysis of warped glass for McKinney & Olive, two types of modeling techniques were used. In the first modeling technique, the glass and silicone were analyzed using shell elements in the Abaqus FEA software. A python script was used to model and analyze the glass lites. This python script could read the file produced by Rhino3D and create the glass units using shell elements. Appropriate displacements (warping distances) that were obtained from Rhino3D were applied to one vertex of the glass to simulate warping. This technique was used to help approximate the active length of the silicone that carried the load due to warping and identify the glass lites with the largest reaction forces. In the second analysis technique, only the worst case glass lites were considered. Only one ply of the worst case glass lites were built using shell elements in RFEM/RSTAB. The corresponding displacements that were obtained from grasshopper were applied to one vertex of the glass ply to simulate warping. The second technique was adopted in addition to the first technique to serve as a check and to give a global perspective on the magnitude of force required by the silicone to hold the glass vertex in place.

### 3.1 Modeling in Abaqus

In the preliminary analysis, the dimensions and warping of all the glass lites was exported from Rhino3D into ABAQUS. Each glass lite was built and the corresponding warping was applied which produced reaction forces. An example of the results for one glass unit is shown in Figure 6. Both the silicones and the glass plies were modeled as shell elements. The maximum reaction force in the z-direction reaches the peak value at the vertices and taper down as we go away from the vertex. We were interested in finding the average stress in the structural silicone near the edge where the warping was applied. The goal was finding a representative value of force that can be used to calculate the average stress near the warped edge.

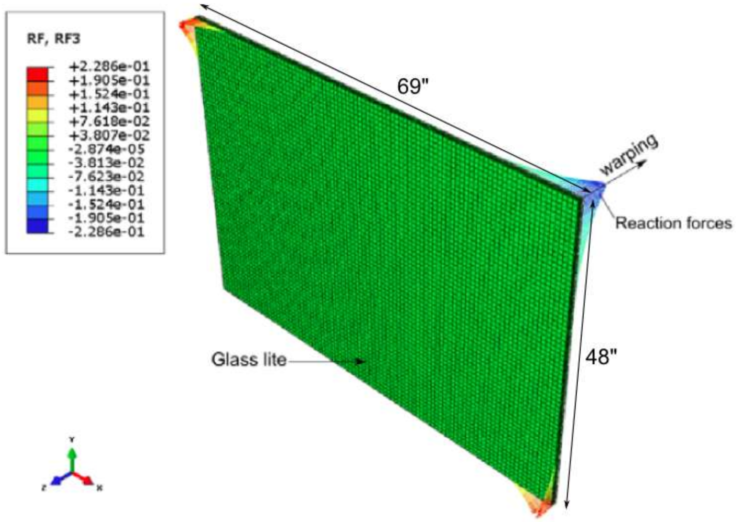


**Figure 6: Reaction forces in a glass lite**

For this, the reaction forces along one of the warped edges was analyzed. An illustration of the distribution of the reaction forces along the warped edge for a large lite and the corresponding plot of the reaction forces as a function of distance along the warped edge is shown in Figure 7. The area under the curve gives the total load that the silicone must resist on one side.

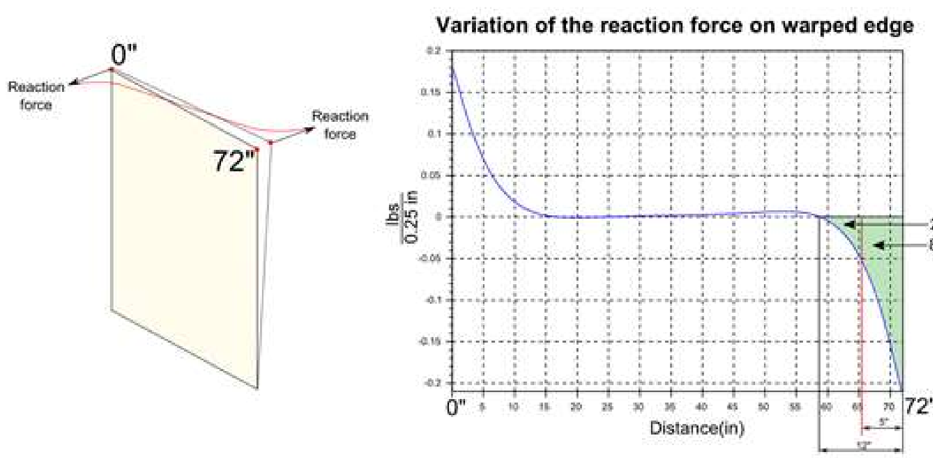


**Figure 7: Distribution of reaction force on the warped edge and the reaction force on a warped edge**

The total load is resisted by about 12" of silicone but 80% of the total load is resisted by the 5" of silicone that is closest to the warped vertex. Thus, the tributary length of silicone to compute the average stress was chosen to be 5". A total of 238 glass units were analyzed in ABAQUS using shell models and the mean of the reaction forces was computed along a tributary length of 5" around the warped vertex as shown in Figure 8. The width of the structural silicone was assumed to be ½ " and for the IGU silicone, it was ½".

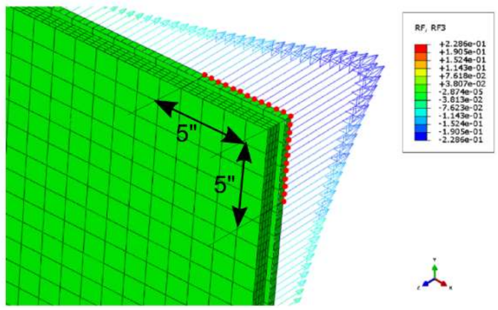


**Figure 8: Reaction forces along a tributary length**

The mean reaction force at the warped edge was computed for all the glass lites. The values are plotted in Figure 9. The worst case glass lites are marked in red and The glass lites with no or almost zero warping was excluded from this analysis. The negative sign represents direction (negative z-axis) and not compression.

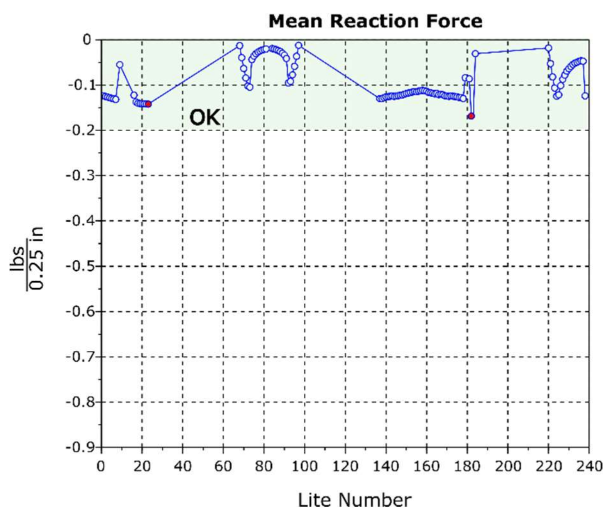


**Figure 9: Mean reaction forces in glass lites**

All the nodes in the model were spaced 0.25” apart and the mean reaction force is assumed to act on each node such that the average stress in silicone near the warped edge is computed as

$$\sigma = \frac{P}{A} = \frac{RF}{Area} = \frac{RF_{mean}}{spacing\ between\ nodes\ \times width\ of\ silicone}$$

Spacing between nodes = 0.25”
Width of silicone = 1”

The mean reaction forces and the corresponding average stress for worst case lites is

| Lite # | Mean Reaction force (lbs) | Stress (psi) | Allowable Stress (psi) |
|---|---|---|---|
| 23 | 0.142 | 0.57 | 1.0 |
| 182 | 0.169 | 0.68 | 1.0 |

### 3.2 Modeling in RSTAB/RFEM

The results from the RFEM/RSTAB analysis is shown in Figure 11. Only the worst case glass lites were considered in the RTAB/RFEM analysis. Appropriate displacements were applied to vertices 1 and 2 of glass plies 1 and 2 to simulate required warping. The reaction forces were used to compute the average stresses in the silicone.

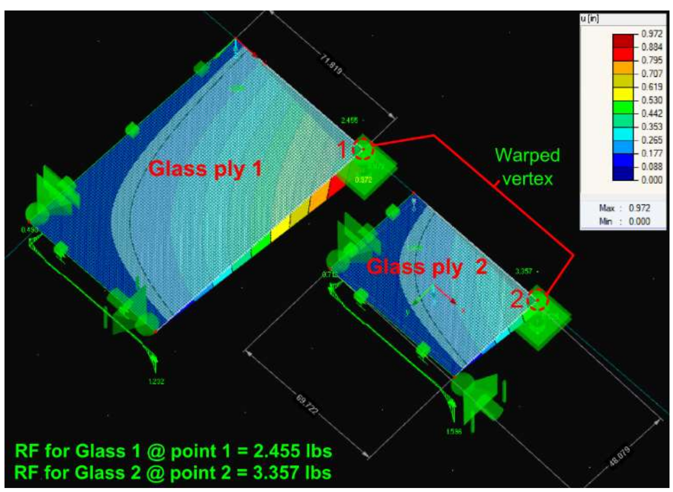


**Figure 10: Reaction forces using RFEM**

The total reaction force at the vertex is half on the actual reaction force since only one ply was considered in the analysis instead of two plies. The total reaction force at the warped vertex and the active are of the silicone is used to compute the average stresses in the silicone near the warped vertex as

$$\sigma = \frac{P}{A} = \frac{RF}{Area} = \frac{Total\_RF}{A_1 + A_2}$$

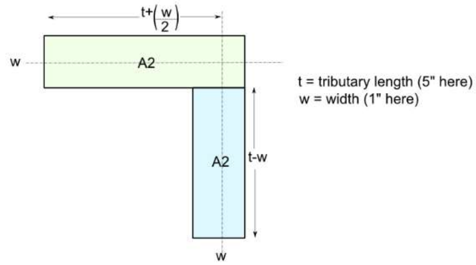


**Figure 11: Active area of silicone near the warped vertex**

It can be seen that the stresses in the silicone due to warping when it is 1" wide is in close agreement with the results obtained from the Abaqus shell modeling.

| Lite # | RF one ply (lbs) | Total RF (lbs) | Stress (psi) | Allowable Stress (psi) |
|---|---|---|---|---|
| 23 | 2.455 | 4.910 | 0.52 | 1.0 |
| 182 | 3.357 | 6.714 | 0.71 | 1.0 |

## 4. Conclusion and future work

A design methodology was adopted to analyze a large array of glass units efficiently using Abaqus in conjunction with other sets of tools like Rhino3D and RFEM. The integrity of the structural silicone was analyzed in two of the worst-case glass lites. The most important insight provided by this study was that even though the warping load was carried by a larger length of silicone, majority of the load was carried by the silicone near the warped vertex. It was concluded that for the stress in the silicone to be less that the allowable, the width of the structural silicone is required to be 1" and that of the IGU silicone has to be ½". This study makes use of shell elements and the work can be further expanded to analyze full 3D glass models in Abaqus.

[1] H. R. Hitchcock and P. Johnson, *The international style: Architecture since 1922*. WW Norton, Incorporated, 1932.
[2] N. Pevsner, *Pioneers of the modern movement from William Morris to Walter Gropius*. Faber & Faber, 1936.

[3] T. C. Bannister, “Sigfried Giedion, Space, Time and Architecture, the Growth of a New Tradition: Cambridge (Mass.), Harvard University Press, 1941. Pp. 601; 321 Ill.,” 1944.
[4] X. Wu, Z. Gao, and Z. Li, “Analysis of whole erection process for steel shell of National Grand Theatre.,” *Jianzhu Jiegou XuebaoJournal Build. Struct.*, vol. 26, no. 5, pp. 40–45, 2005.