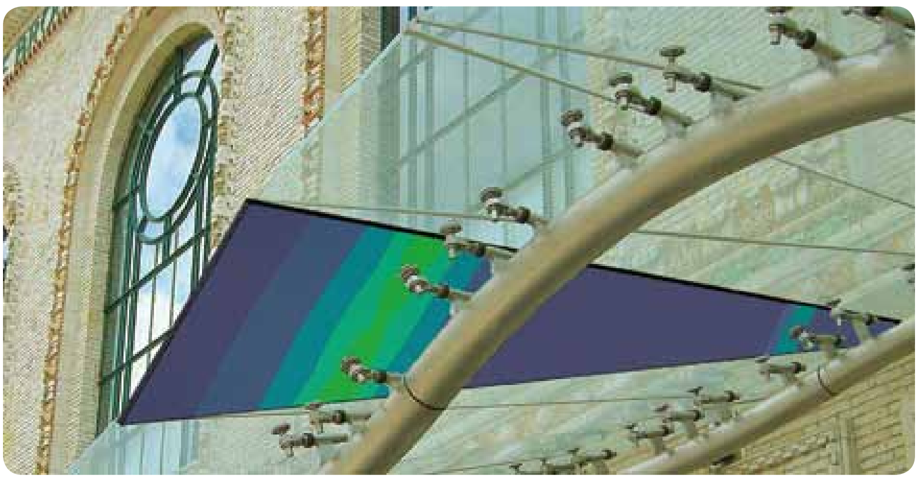
Breaking Architectural Barriers with Structural Glass

Stutzki Engineering employs Abaqus FEA to help design the material in a new role



The architectural integrity of the Brooklyn Academy of Music's undulating glass and steel canopy dramatically demonstrates how point-supported glass can play a structural role in a building.

Glass breaks. When it reaches a certain stress level it doesn't yield, it shatters, without warning or predictable focal point. But mankind has been creating beauty and utility out of glass for over 4,000 years.

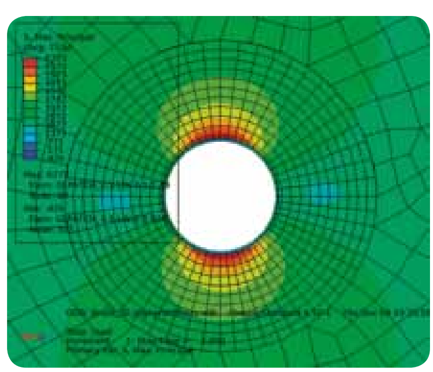
Until recently in modern architecture, the "building envelope" was dominated by steel and cement. Although glass was an integral component of almost every structure, windows and façades were there just to let in light or be purely decorative. But in the early 1990s, a movement towards incorporating a greater proportion of glass into structures began to take hold, enabled by new material formulas and installation technologies. These gave architects greater design freedom to bridge interior and exterior climates.

Glass goes beyond mere aesthetics

As glass has moved closer to center stage in architecture, it has also taken on a new role as a structural, load-bearing component. Heavy steel supports, and strong aluminum mullion systems that capture glass panes by their edges, are now making way for thin cables, glass fins and point-supported glass (PSG).

PSG attaches directly to a structure with bolted fittings that run through holes in the glass itself. It can be tempered, laminated and built to different thicknesses to bolster it for its new supporting job. Yet because PSG is now an intimate part of the building envelope, its installation and long-term performance must be finely tuned. The stress and strain in the glass, as it shoulders weight and interacts with the materials it's attached to, must be accurately predicted and accommodated through every season and weather extreme.

Despite considerable success in Europe, adoption of PSG has been slower in North America. "The methods for working with PSG are not yet found in any code or standard in this country," notes Chris Stutzki, founder of Milwaukee, Wisconsin-based Stutzki Engineering Inc. "Basically you have to rely on your own due diligence because this technology is so advanced. Those of us who work with PSG undertake extensive peer reviews that insist on predictive failure scenarios. Engineered responses are at the center of designing with glass."



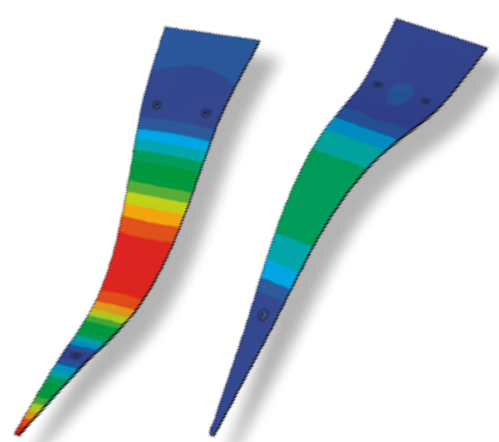
Abaqus FEA image of the "glass patch" area around the chamfered hole in a glass lite. Note the tighter meshing around the center of the hole, used to achieve the greatest predictive accuracy where stress is highest. The stress distribution is horizontal across the opening (rather than completely circular) due to the glass' propensity to bend slightly.

Modern twist on Brooklyn building features glass in a novel role

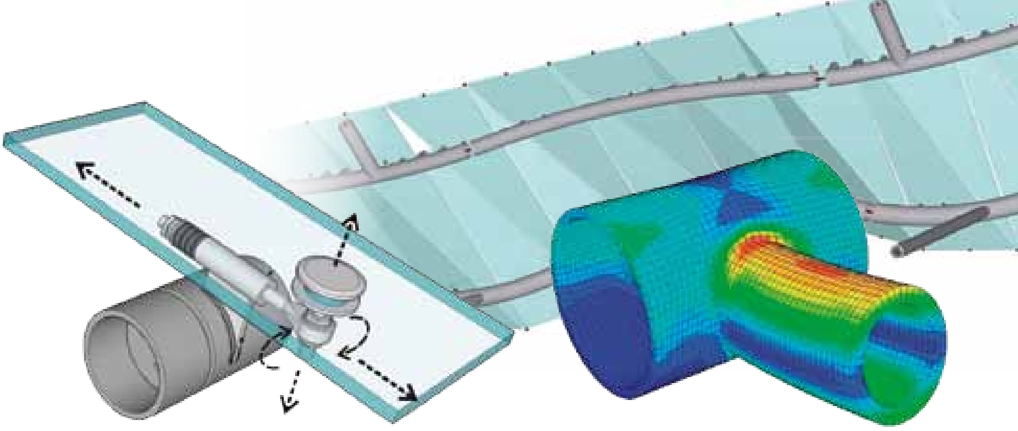
A particularly striking example of Stutzki Engineering's mastery of PSG is the firm's work on the glass canopy of the Brooklyn Academy of Music (BAM, architect: H3 Hardy Collaboration Architecture), chosen as a "Best Small Project Under $10 million" by New York Construction.

The original BAM building was given a modern twist in 2008 with a long, undulating glass ribbon canopy across its front. The 132-foot canopy is made up of 65 triangular panes (also known as "lites") of one-inch thick, laminated (a soft polymer interlayer sandwiched between two glass plies), tempered glass. Aligned head-to-toe, each "lite" weighs 500 pounds.

Each pane is pierced by three rotating points (two at its base, one at its apex). The points are connected via spring-loaded shock-absorbers to two waveform, 12-inch diameter, stainless-steel tubes. The tubes tie back to steel columns that penetrate the front wall of the building and are grounded indoors. The glass is part of the main structural system of the canopy: It carries the tension of the triangular system back into the upper steel pipe along the front wall.



Abaqus FEA of deflection (left) and field stress (right) in a single glass lite in the canopy. These analyses are incorporated into full-scale models of the entire canopy to ensure structural integrity.



The glazing bracket (left) is designed to provide ductility as the glass responds to the loads in the canopy structure. Stutzki Engineering uses Abaqus FEA (right) to analyze the steel components in the canopy, as well as those that are glass.

Defining the loads, modeling the stresses

The engineers' first task in creating the canopy was to define its load path. "We started by asking the question, what happens if one glass ply fails?" says John Knowles, project engineer for Stutzki Engineering. The first line of defense against such an event was the laminated glass itself—if one ply were to break, the remaining ply had to take over the full load. The second line of defense was structural redundancy—if one entire glass lite broke, could its neighbors take over? "We needed to avoid a 'zipper effect' where a single failure would lead to total collapse of the structure," says Knowles.

Full-scale computer modeling of the entire canopy structure was performed with the German structural beam analysis program RSTAB. But in tandem with this "big picture" analysis, in order to focus in on the stresses affecting the critical glass lites and steel connections, Stutzki Engineering used Abaqus Finite Element Analysis (FEA). "Stress peak analysis with FEA, validated with physical testing, is essential for safe glass design," says Stutzki.

For greatest accuracy in identifying the stress peaks where the points are installed, particularly fine FEA meshing around the chamfered edges of the holes in the glass was employed using the CAE meshing module in Abaqus. In this case the group did not use the software's automatic mesh refinement but rather "seeded" regions separately to control mesh density in this "glass patch" area. "When meshing our models, we took particular pains to define the interface between the washer and the glass and determine whether to link the elements using single ties, or full contact," says Knowles. "We concluded that using multiple contact definitions between glass and the point fasteners was the only way to accomplish realistic stress results. Although it takes a bit more compute time, we can run our models with the equipment we have in our office and we get very accurate results."

Abaqus was also employed to model an entire glass lite so that the different loads on a complete pane could be analyzed and incorporated into the design of the full canopy. A typical model used 106,088 C3D8I elements (four elements over the thickness of each laminated glass ply, one element of thickness for the interlayer between two plies) with close to two million degrees of freedom.

Abaqus FEA simulates critical fittings

Abaqus was used to prove out the design of the all-important glazing bracket as well. This included the nylon washers that prevent direct steel-to-glass contact, the pivoting steel points themselves, and the Belleville springs that act like shock absorbers. The standard material models available in Abaqus were used to define the homogenous materials (nylon, glass) used in the models. For modeling steel connections however, the Stutzki engineers typically use elastic plastic material definitions. "The complete bracket fitting is designed to introduce the ductility that is missing from glass alone," says Knowles. "Using Abaqus to analyze the behavior of the various components lets us visualize all the different forces affecting the glass. With steel alone it's not a problem because it yields a bit when overloaded. But with sensitive glass pieces, we need to predict exactly what force is going into each pane."

Additional stresses on the PSG structure, including minute movement in both the steel tubes and the building walls, and the more significant effects of temperature and loading over time, were also accounted for in the structural analyses.

Proving out the loads with real-world testing

To validate the analyses of all their PSG projects, Stutzki Engineering has conducted extensive real-world testing at the Milwaukee School of Engineering. By gluing strain gauges around the holes in glass lites and then applying hundreds of pounds of point pressure with a loading ram, the team has measured physical stress within different configurations of panes and compared the test results to the predictions of their FEA models.

Using the Abaqus capability to integrate Python scripting, the group has been able to automatically run multiple permutations and combinations of load cases. Not only did this help them cut modeling time from a day to an hour, it also enabled them to pinpoint the modeling methods and design configurations that best correlate with real-world tests. This gives Stutzki Engineering the confidence to use the models as proven knowledge-templates for their PSG design work going forward.

Installation is the final challenge

With their BAM canopy and fitting designs verified and finalized, Stutzki Engineering still needed to ensure that the structure was installed properly. The canopy's glazing brackets needed to be "tuned" during installation so that all forces and moments were transferred correctly into the final position of each glass lite.

"In many ways, the installation of the glass canopy was actually one of the most straightforward parts of the project because we already had the data we needed to get it right," says Stutzki. From their Abaqus FEA test correlations, the team knew exactly what loads were allowable, and even desirable, to properly balance the finished canopy. As each glass lite was connected to the points and then the underlying steel supports, the installers used gauges to measure how much the associated Belleville spring was being compressed. They could then calculate the allowable force on the lite and manually adjust each spring accordingly.

"Every point-supported glass project we take on is unique," says Stutzki. "We've now developed our knowledge of both materials and technology to a level where we can apply realistic simulation in a systematic way to rapidly arrive at the optimum design solution for every challenge. Abaqus FEA helps us visualize what you can't see whenever you are working with glass."

For More Information
www.stutzkiengineering.com