THERMAL ANALYSIS OF COMPLEX GLAZING

Design optimization using a transient systems simulation program and bidirectional scattering distribution function window definition

Adrian Turcato
Transsolar Klima Engineering
Turcato@transsolar.com

Chris Stutzki
Stutzki Engineering
Chris.stutzki@stutzkiengineering.com

Erik Olsen
Transsolar Klima Engineering
Olsen@transsolar.com

ABSTRACT

The use of bidirectional scattering distribution function incorporated in a transient systems simulation program, allows engineers to accurately determine glazing surface temperatures for complex glazing assemblies in architecturally ambitious projects. Understanding the thermal behavior of complex glazing assemblies is increasingly critical to high-performance facades - for structural, condensation and occupant comfort considerations. Bidirectional scattering distribution functions account for the way that radiation with different angles of incidence are transmitted through and reflected from glazing. To date these functions have been more widely applied in daylight analysis and not in thermal analysis, partially due to a lack of thermal analysis tools utilizing these functions. Newly included bidirectional scattering distribution function features in a transient systems simulation software allow a more precise accounting for heat flow through glazing assemblies, including air gap temperatures and glass surface temperatures. This newly extended capability was used to investigate the thermal stress in glazing assemblies for two projects: Grace Farms in New Canaan, Connecticut (built and occupied) and the new Little Caesars' corporate headquarters in Detroit, Michigan (under construction), both located in humid continental climates. These projects, both using glazing innovatively, required additional structural analysis of the glass due to differential thermal loading (Grace Farms with ~3000 linear feet of 12-14 feet tall curved double-glazed insulated glass units and the Little Caesars' headquarters with a highly-articulated curtain wall façade). In the case of Little Caesars' project, the calculation allowed for designers to identify dangerous levels of thermally induced stress in the assembly design. These case studies represent two of the first real-world examples of this methodology.

KEYWORDS

Innovative or unique, structure and seismic, component performance, glass performance, architectural glass, case study

INTRODUCTION

The two projects discussed in this paper are Grace Farms, CT, designed by the Japanese architects SAANA and the new Little Caesars' corporate headquarters, MI, designed by Detroit-based SmithGroup LLC. Both projects have innovative facades that are key to the buildings' architectural expression. Grace Farms, an 86,000 sf community center, has around 3,000 linear feet of 12-14 ft high curved double-glazed Insulated Glass Units (IGU). The glazed façade wraps around the entire building uninterrupted. The building tries to define a new relationship between the interior and exterior; the transparency of the envelope is key to achieving this. The new Little Caesars' headquarters relocates the company's corporate offices from suburban Detroit to the downtown area. This new large investment in the downtown built environment is a statement of pride in contributing to Detroit. The façade itself, as the most visible part of the building, has high symbolic value, positioned right across from the main entrance to Detroit's Little Caesars' Arena. The complicated, highly articulated geometry, is composed of triangular, 14 ft tall glass units, folded with a tight radius at the vertical center axis. Glazing assemblies for both projects included laminated interlayers.

The complex issues surrounding the constructability of these facades required designers to use innovative techniques in the process of ascertaining viability and longevity of a given assembly. The importance of the façade to the architectural intent meant that room for compromise in the complexity of the façade geometry was limited. Of primary concern in these cases was the amount of thermal stress that would be present in the IGUs at various worst-conditions throughout the year. As various components attain extreme temperatures, differential expansion or shrinking causes components to fail, and ultimately the entire glazing system. IGU failure represents both a safety issue as well as simply a financial burden on building owners, as prematurely failed IGUs can decrease tenant or occupant satisfaction with the building and eventually will require either ad hoc replacements or an entire façade retrofit.

A newly developed feature of the well-known transient systems simulation program TRNSYS 18, which relies on Bidirectional Scattering Distribution Functions (BSDF), can calculate accurate temperatures for components of glazing systems, including for both steady state and dynamic scenarios. Steady state calculations of this nature have previously been possible with LBNL Window, however the ability to do dynamic simulations has previously been unavailable. Using the results of these calculations, thermal stress in complex glazing assemblies can be calculated. Designers therefore can anticipate conditions that could cause premature failure of the glazing, and change aspects of the façade design to eliminate the potential of undesirable outcomes.

The main benefit of BSDF is usually seen as its ability to handle complex glazing assemblies. In this case, it is rather the fact that the calculation method allows for the determination of accurate surface temperatures – even when interior shades are included.

BACKGROUND

BSDF are used frequently for modeling daylight in complex fenestration and shading. As originally described by Heckbert in 2001, BSDF calculations take account of the scattering effects of light as it passes through an IGU. These techniques are used extensively in academic settings, but also more recently in professional settings as well. However, BSDF doesn't only have applications to daylight simulation, but also to thermal simulations in glazing. It represents an improvement over simpler methods as it can more accurately account for the transmission, reflection, absorption and scattering of the thermal radiation passing through complex IGUs. TRNSYS 18, officially released earlier this year, now contains the ability to perform BSDF calculations for thermal simulation of glazing (McDowell et al., 2017). This new feature was based on earlier work completed by Schöttl (Schöttl, 2013). TRNSYS 18 uses a Klems method to bin both incident, reflected and transmitted light into two hemispheres of 145 patches (Mitchell et al., 2006). As a result of these calculations TRNSYS 18, is able to output detailed information about a glazing assembly including air gap and glazing surface temperatures, as well as dynamic U-values and Solar Heat Gain Coefficients (SHGC). The IGUs optical properties are calculated using Lawrence Berkeley National Laboratory's (LBNL) Window as input to TRNSYS 18. These new features in TRNSYS 18 were validated in two ways to ensure their accuracy (Hiller, Schöttl, 2014). First, they simulated an IGU given steady state conditions and compared the results to those generated by a comparable model generated exclusively in LBNL Window v7.2.34.0. And second, they simulated an IGU and wall assembly under dynamic conditions and compared the results to experimental results gathered from a physical test box.

On the other hand, the analysis of structural stress in building products is less experimental. The use of Finite Element Analysis (FEA) to evaluate stress in an IGUs glazing and sealants is a well-established practice. In the case of IGUs two situations exist where thermally induced stress has been identified to contribute to the unit's failure. These two situations are, temperature gradients within one layer of glass, and extremely high or low temperatures in the air gap of an IGU (Sonntag et al., 2014; Stutzki et al., 2013).

a) Temperature gradients within one layer of glass are due to shading patterns. These temperature differences can cause dangerously large tensile stress, predominantly along glass edges that are covered by glazing channels or pressure caps and are therefore cooler than the main glass surface exposed to the sun.

b) Temperatures in the air gap of insulated glass units fluctuate with indoor and outdoor conditions. As the temperature of the gas in the gap changes it either expands or contracts putting negative and positive pressures on the glass itself and the IGUs secondary seal. In normal flat IGU's this pressure is easy accommodated. The glass panes can easily deform under the pressure changing the volume of air gap and thus relieving the pressure on the secondary seal. However, for curved glass this deformation is not possible. The curved geometry of the IGU in these cases imparts a substantial higher stiffness to the glass panes. As such extreme temperatures in the air gap can make the IGU at risk of failure. Cold temperatures create low pressures in the air gap, and can cause serious bending stress in the glass. Hot conditions cause high pressures in the air gap and can lead to excessive strain in the silicone of secondary seal.

METHOD

The BSDF calculations was completed using a detailed heat transfer model run by TRNSYS 18. The model accounts for all heat transfer effects according to the International Standards Organization (ISO) standard 15099, "Thermal performance of windows, doors and shading devices", using BSDF to account for the scattering effects glazing has on incoming solar radiation (ISO, 2013). The BSDF is calculated using input values generated by LBNL WINDOW 7 and TRNSYS 18.

The calculation of the stress in the IGUs was performed using ABAQUS, a multi-purpose Finite Element Analysis (FEA) program. The glass and the airspace, as well as the secondary seal and the spacer were all modeled using 3-D solid (brick)elements, and geometrically nonlinear formulations. The volume elements of the air space, defined with the physical properties of air, expand for given temperature increases, and the internal pressure is then accurately calculated considering the deformations of the glass and the increased volume of the air gap due to the stretching of the secondary seal. The data from TRNSYS 18 provides detailed temperatures for each layer surface, even for laminated glass. These temperatures allow an accurate accounting for the stiffness of the interlayer material, which decreases with higher temperatures. These calculations provide tensile stresses in the glass, as well as strain in the secondary silicone seal. The results of this calculation are then compared against failure criteria. For glazing, this is the probability of breakage of 8 in 1000 IGUs, or 1 in 1000 IGUs, depending on safety requirements, as provided by the manufacturer. For the secondary seal, the failure criteria was determined based on experimental data.

Grace Farms

For the BSDF calculations Grace Farms' highly curvilinear façade was simplified to a single section of south-facing façade, as the south was determined to be the worst-case scenario. The high levels of solar radiation on the south, especially for low angle winter sun, make high temperature gradients and thus high thermal stress the most likely. The calculations were completed under steady state conditions. An exterior temperature of -13.7 °F was used. This is the 50-year extreme low, taken from weather data for White Plains, NY, the closest weather station of similar distance to the coast. Solar radiation and sun angle data was used for a clear day on December 21st, to account for the lowest sun angles. Interior shades were considered in both parked and extended positions. The shade is "parked" when the shades are horizontally retracted. This results in the shades being folded up and for a limited area the shades are closer to the glazing than when extended. Based on measurements the shade material was estimated to have a solar reflectance of 0.4. Further details on the geometry can be found in Figure 1. The Grace Farms FEA was conducted using a full 3-D meshing of the IGU, including volume (brick) elements representing the air space. The complicated geometry required the geometry to be modelled at numerous points to ensure that the worst-case scenario was properly established.

The IGU was made up of two identical panes of laminated low-iron glass. Each pane consists of two 10 mm layers with a 0.76 mm interlayer. The airspace is 12.2 mm. The custom glazing LBNL WINDOW file was provided by the façade consultant. While glass structural properties are very standard for flat glass, they are not well established for other geometries, as such conservative values were used. Subsequent testing results confirmed that the conservative values were within an acceptable range.

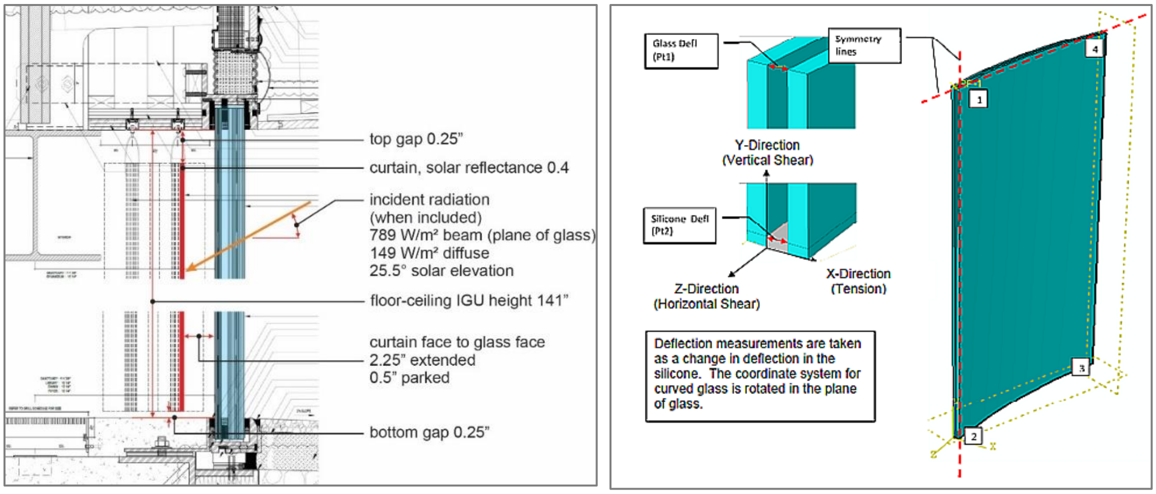

Figure 1. Critical dimensions for glass surface temperature analysis

Little Caesars

For the BSDF calculations Little Caesar's façade geometry was simplified as follows. The two main glass facade orientations where calculated to face 44.4° and 10.2° off of due east, rotated towards the north. The vertical 5° tilt was deemed to have negligible impact on the results. Calculations for each glass orientations were completed separately and combined to form the complete understanding of the folded glass geometry. The custom glazing LBNL WINDOW file was created in LBNL Optics to match the specifications of the façade consultant. The calculations were completed under dynamic conditions for a full year of weather data. The calculations where completed for both a typical year and 30-year extreme cold scenario. with the following assumptions. Weather data, including ambient exterior temperatures and hourly solar radiation, was used from the TMY3 weather file "Detroit Metro AP 725370". The amount of radiation received on the façade was determined by TRNSYS18 considering the geometric relationship of the glazing to the sun's azimuth and altitude for a given time step, as well as the intensity of the solar radiation at that moment. For the typical year case a constant wind speed was assumed to be 11.2 mph, which translates to an outdoor convective heat transfer coefficient of 3.1 Btu/hft²F (17.8 W/m²K). For the worst-case wind speed was assumed to reach up to 17.8 mph, which translated to an outdoor convective heat transfer coefficient of 5.8 Btu/hft²F (32.8 W/m²K). Interior shades were considered in both retracted and extended position. The shades thermal and optical properties were developed in LBNL WINDOW, its solar reflectance was 0.3. The shade was located 12" from the glazing assembly, with a 12" gap at the top and bottom. Further details on the geometry can be found in Figure 2. The air flow behind the shade was calculated dynamically for each time step using the stack effect equation. Similar to Grace Farms, a FEA was conducted using a full 3-D meshing of the IGU, including volume elements representing the air space. One full IGU was modelled for the FEA, this is a 14 ft x 6.5 ft triangle bent such that there is an approximately 145° angle between the two halves.

The IGU for the simulation model was made up of two panes of laminated low-iron glass. Each pane consists of two 10 mm layers with a 1.52 mm interlayer. The airspace contains 10% air and 90% argon. Again, similar to Grace Farms, while glass structural properties are very standard for flat glass, they are not well established for other geometries, as such conservative values were used. Subsequent testing results confirmed that the conservative values were within an acceptable range.

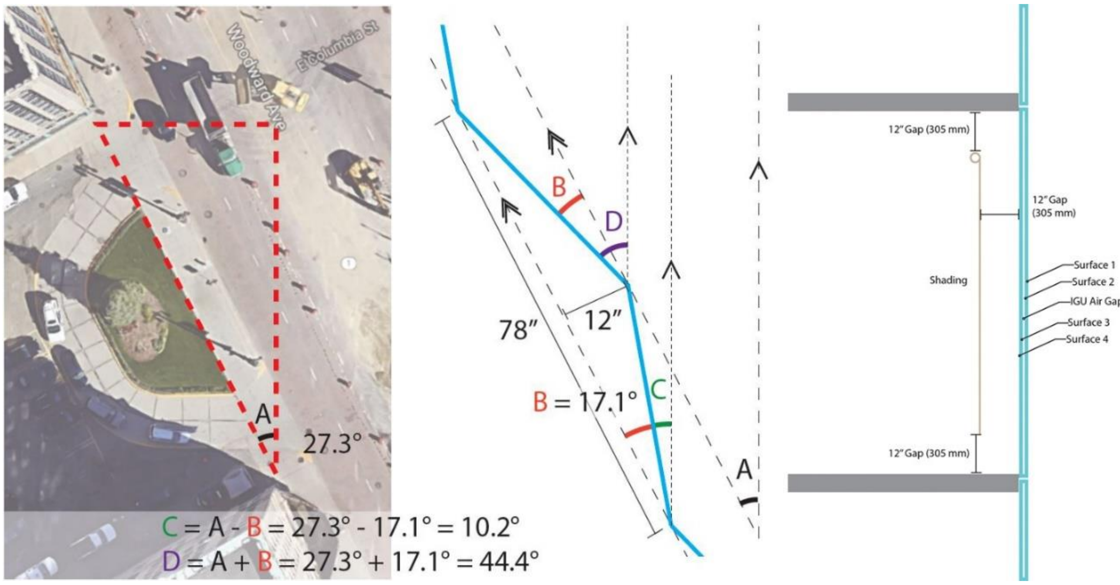

Figure 2. Left: glazing orientation, right: shade geometry

DATA

Due to space constraints, results will be shared primarily for the novel BSDF calculations. The data of primary importance are the temperature profiles across the IGUs. Typically, this is the temperature of the outer surface of the outer pane of glass, the temperature of the inner surface of the outer pane of glass, the temperature of the air gap, the temperature of the outer surface of the inner pane, and the temperature of the inner surface of the inner pane. The temperature results presented in the following section represent the average surface temperature of the glass and do not account for any local variations (especially with height or edge effects).

Grace Farms

Average temperatures for each surface and the airspaces were calculated for both curtain positions, with and without sun. These temperature profiles are plotted in the Figure 3. The temperature difference of concern in this case were primarily the difference surface 1 and surface 4 (Table 1), and the difference between shaded and unshaded areas on the same surface, either surface 1 or surface 4 (Table 2). The calculated values for these critical temperatures are as follows for varying shade position and solar radiation values:

Table 1. Temperature difference between surfaces

	Outside glass surface (surface 1)	Inside glass surface (surface 4)	delta
Extended curtains with sun	18.3 °F (-7.6 °C)	87.8 °F (31.0 °C)	69.5 °F (38.6 °C)
Parked curtains with sun	18.7 °F (-7.4 °C)	89.8 °F (32.1 °C)	71.1 °F (39.5 °C)
Parked curtains with sun (top of window)	18.7 °F (-7.4 °C)	94.1 °F (34.5 °C)	75.4 °F (41.9 °C)
Extended curtains without sun	-6.3 °F (-21.3 °C)	30.4 °F (-0.9 °C)	36.7 °F (20.4 °C)
Parked curtains without sun	-6.2 °F (-21.2 °C)	31.1 °F (-0.5 °C)	37.3 °F (20.7 °C)
Extended curtains without sun (bottom of window)	-6.3 °F (-21.3 °C)	25.5 °F (-3.6 °C)	31.9 °F (23.1 °C)

The highest calculated temperature difference between surface 1 and 4 occurs when the sun is present and the curtain is parked (the delta is 41.9 °C). On a single surface the largest difference is calculated to also occur when the curtain is parked (the delta is 32.1 + 0.5 °C = 32.6 °C).

Table 2. Surface delta between sun conditions

	Glass surface with Sun	Glass surface without sun	delta
Extended curtains (surface 1)	18.3 °F (-7.6 °C)	-6.3 °F (-21.3 °C)	24.7 °F (13.7 °C)
Parked curtains (surface 1)	18.7 °F (-7.4 °C)	-6.2 °F (-21.2 °C)	24.8 °F (13.8 °C)
Extended curtains (surface 4)	87.8 °F (31.0 °C)	30.4 °F (-0.9 °C)	57.4 °F (31.9 °C)
Parked curtains (surface 4)	89.8 °F (32.1 °C)	31.1 °F (-0.5 °C)	58.7 °F (32.6 °C)

The highest calculated temperature difference between part of a surface that is in the sun and part that is out of the sun occurs for surface 4 when the curtain is parked (the delta is 32.6 °C).

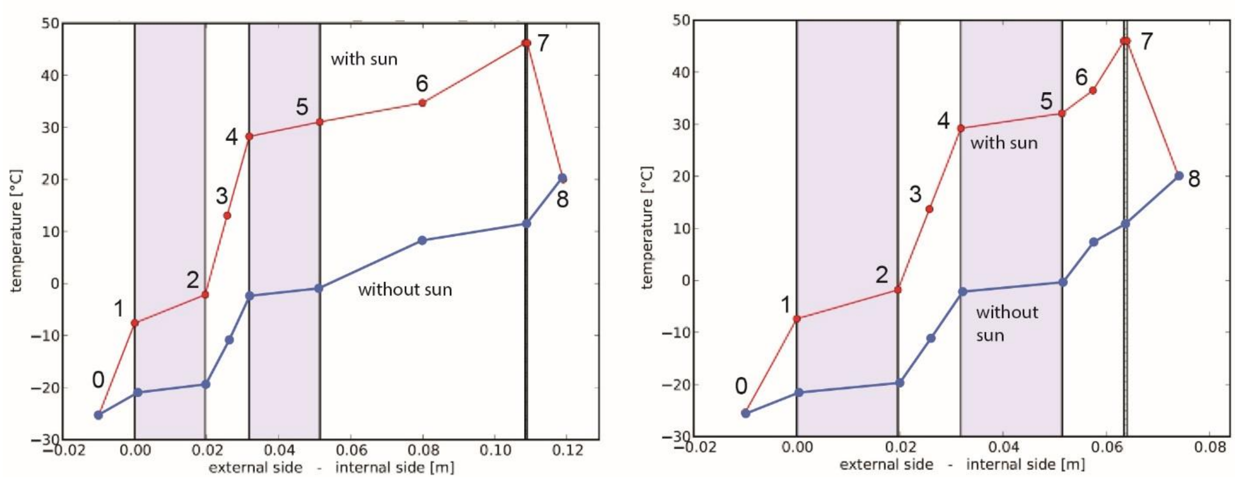

Figure 3. Surface and cavity temperatures, left: with curtains extended, right: with curtains parked. 0- outside air, 1- IGU outside surface, 2- outer pane inner surface, 3- IGU cavity, 4- inner pane outer surface, 5- IGU inside surface, 6- curtain-IGU air gap, 7- curtain, 8- indoor air.

Little Caesars

For Little Caesars', due to space limitations results will only be presented for the case of minimum air gap temperatures, which was ultimately found to be the most problematic structurally. However, results were also originally compiled for: maximum air gap temperatures, maximum temperature difference between surfaces in each pane (between surface 1 and 2), and maximum temperature difference between different orientations on a single surface (10° and 44 ° north of east). The air gap temperature is calculated as the average of the air gaps of the adjacent pane orientations. In the cases where shades are down, interior temperatures refer to the temperature between the shades and the IGU.

The typical-year minimum-gap temperatures occurred before dawn during cold winter conditions. In the case of the extreme cold year minimum air gap temperatures occurred in the evening, low levels of radiation in January, which strike the glazing primarily in the morning, were not sufficient to raise the glass temperature significantly above extremely cold exterior ambient temperatures. In both cases these temperatures occurred after sustained periods of minimum ambient temperatures. As well, minimum temperatures were found to occur when shades were closed. The shades effectively insulated the glass assembly from warmer interior temperatures. Both orientations (between 10° and 44 ° north of east) show the same temperatures at the time step when minimum temperatures are reached because neither is receiving any solar radiation at that moment. The temperature profile across the surfaces and air gap, for minimum air gap temperature, is shown in Table 3 and Table 4, for a typical meteorological year and extreme year, as described above. The air gap temperature time series is also shown in Figure 4 and Figure 5 (typical year and extreme year respectively), alongside key environmental variables such as ambient air temperature and solar radiation levels.

Table 3. Temperature of surfaces at timestep of minimum, typical year

Exterior	Surf 1	Surf 2	Gap	Surf 3	Surf 4	Interior
1.5 °F (-17.0 °C)	2.4 °F (-16.5 °C)	4.8 °F (-15.1 °C)	25.9 °F (-3.4 °C)	47.0 °F (8.4 °C)	49.5 °F (9.7 °C)	63.1 °F (17.3 °C)

Table 4. Temperature of surfaces at timestep of minimum, extreme cold year

Exterior	Surf 1	Surf 2	Gap	Surf 3	Surf 4	Interior
-19.5 °F (-28.6 °C)	-17.5 °F (-27.5 °C)	-14.1 °F (-25.6 °C)	13.6 °F (-10.2 °C)	41.3 °F (5.2 °C)	44.8 °F (7.1 °C)	62.7 °F (17.1 °C)

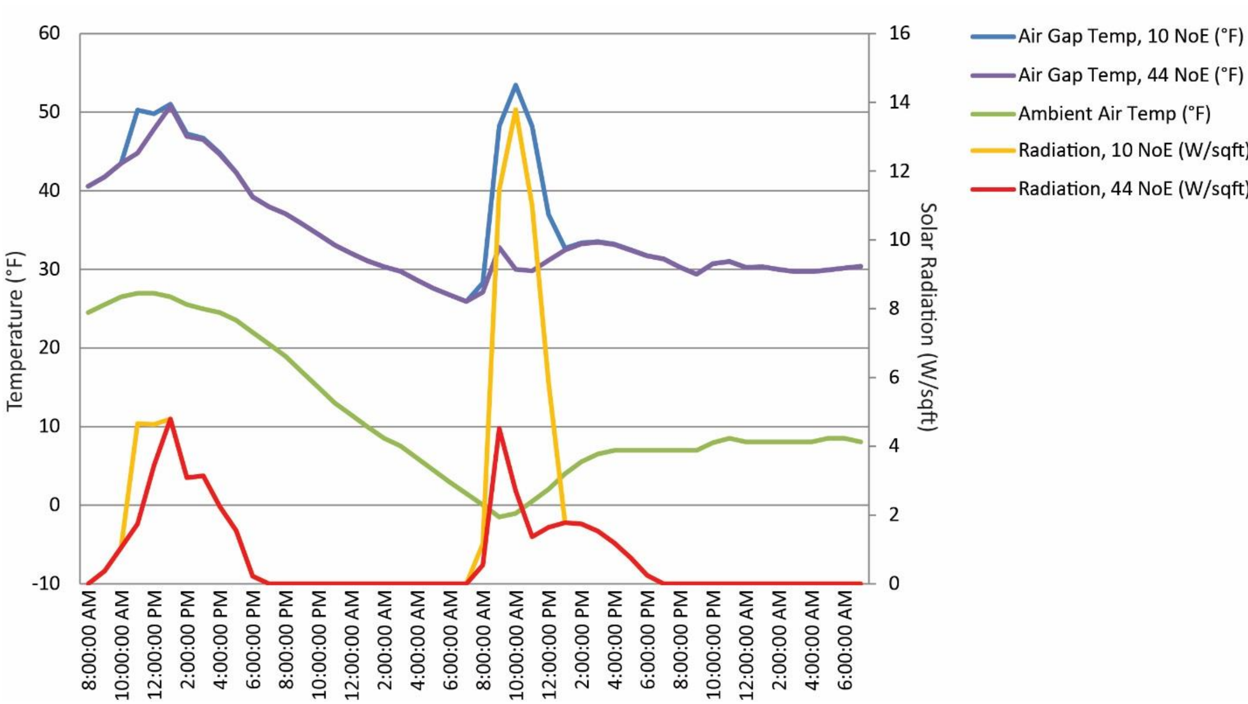

Figure 4. Temperature and Solar Radiation Profile for 24 hrs Before and After Air Gap Minimum for Typical Year

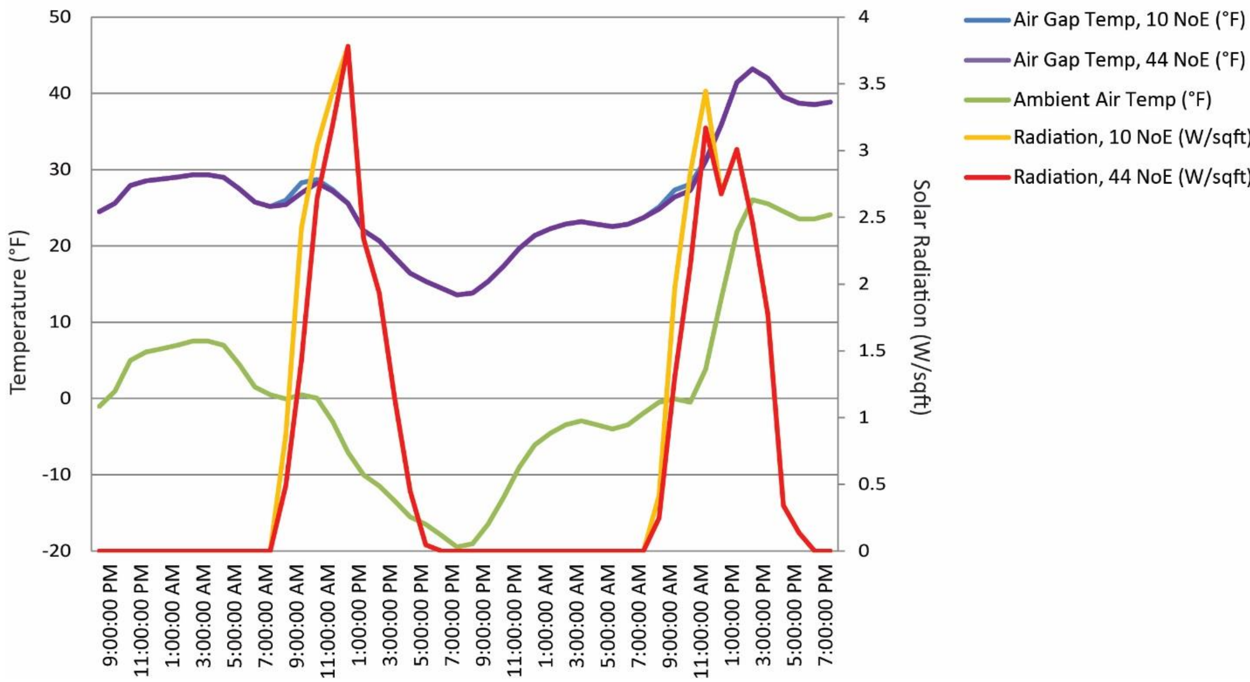

Figure 5. Temperature and Solar Radiation Profile for 24 hrs Before and After Air Gap Minimum for Extreme Year

EXPLANATION

For Grace Farms, it was originally anticipated that the glazing would experience issues around the edges, where the glass is sitting in the sill channel. It was expected that during cold winter mornings, when the sun heats the visible part of the glass, the edges would remain cold and experience a large thermal gradient. This was especially a focus of attention due to the fact that the glass was annealed and not tempered. Annealed glass is not as strong as tempered glass. Tempered glass was rejected by the architects to maintain the extremely clear view through the glass and to minimize any reflection. The thermal and structural simulations revealed that temperature differences within the pane was not a problem at all. In fact, the architectural concept helped to mitigate this phenomenon. Due to the low solar absorptance of ultra-clear glass, the pane does not absorb as much heat during exposure to the sun, and can maintain acceptable temperature differences even on the coldest days.

Ultimately the real challenge related to the narrow edge seal for the curved insulated glass. The joint effort of detailing and simulation yielded an innovative solution. A conventional engineering approach would have resulted in an edge seal width of approximately 1.75 inches. The architects' vision, however dictated a continuous glass curtain with a minimal edge seal, much narrower even than regular IGU's. The physics of curved glass posed a challenge but also provided an opportunity. Curved glass cannot deform to accommodate high pressures from a heated air gap; this would normally require much thicker edge seals. On the other hand, the stiffness provided by the curved geometry also allowed the pressure from interior air to be transferred effectively from the side edges of the glass to the top and bottom. As a result, very narrow edge seals were able to be used on the vertical edges, with the bulk of the pressure carried by extra wide seals at the head and the sill of the glass. This allowed the majority of the seals to be well hidden in the glass' head and sill channels. This innovation was only possible with an accurate understanding of the temperatures that would be experienced by the air gap, as well as by the interlayer, which loses strength as it heats up.

In the case of Little Caesars, extreme cold, extreme heat, and temperature differences within panes and assemblies were all initially suspected as conditions that could cause problematic levels of stress in the glazing. Ultimately the scenario of the most concern was the coldest winter night, the 30-year historical air temperature minimum. The uneven sun impact on the two surfaces in different angles to the sun was determined not to be a problem. In the case of extreme cold, thermal simulation results indicated that the airspace in the IGU would reach temperatures low enough to cause structural issues. The low temperatures caused enough contraction of the air in the air space that high bending stress at the center fold of the glass, near the edge, was present.

These results indicated a borderline acceptable level of risk of IGU failure. Further strength testing of the planned IGU assembly was time prohibitive, so an alternative façade assembly was sought out. Initially a double glazed IGU was chosen to reduce the thermal heating and cooling demand of the building. Reducing the performance of the façade was not an option due to space constraints for the HVAC system in the building. To meet both sets of requirements simultaneously a single pane laminated glass was chosen (thereby eliminating the temperature issue of the airgap) and in order to maintain the façade's thermal performance, the laminated glass took advantage of a newly available low-e film.

CONCLUSION AND FUTURE WORK

In both the case of Grace Farms and Little Caesars the failure of an IGU represented a significant risk to the building owner. For these innovative and complex facades glass or seal failure was not necessarily any additional liability in terms of endangering humans. The risk for clients was in the high cost of re-manufacturing and replacement of the uniquely shaped (curved), and oversized (in the case of Grace Farms 14ft x 10ft) laminated glazing units. The simulations as described in this paper allowed structural stress in IGUs to be calculated where other types of testing would be cost/time prohibitive. This provided contractors and owners the confidence that risk was sufficiently minimized to proceed with innovative glass facades.

As a result of this analysis an innovative design for edge seals was employed at Grace Farms, and at Little Caesars an unexpected source of risk was identified, and changes to the design were made to mitigate these issues. In this context BSDF calculations have proved themselves a highly useful tool in the design process, when complex or atypical facades are considered. Now that this model is integrated into the thermal calculation method of TRNSYS 18, BSDF is available to practitioners for application to projects (and not just for daylight design). More accurate and costly methods for ascertaining stress in glass will continue to exist, such as mockups, however in cases where the timeframe doesn't allow BSDF will also be an important tool.

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