Proposed Modification of THERM Finite-Element Models Taken from the National Fenestration Rating Council's Thermal Rating Program for the Analysis and Estimation of Thermal-Induced Glass Stress Under Solar and Shadow Loading Conditions on Fenestration Products

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ABSTRACT

Solar load conditions and shadowing are key factors in thermally-induced glass breakage, as seen within the fenestration and building industry. Glass tints, low-emissivity (low-e) coatings, gas fill, insulated glass spacers and frame systems all play an important role in influencing this breakage. Simple modifications can be made to existing National Fenestration Rating Council (NFRC) two dimensional (2D) models to estimate this stress and the corresponding glass breakage potential. By completing these checks early in the design cycle, design options, customer expectations, and environmental conditions can be fully accounted for. The NFRC rating system has created an extensive archive of fenestration thermal analysis files that is available for further analysis and study. The use of these file allows the inclusion of effects that are not normally considered and that are unique to the fenestration product, for example, frame and insulated glass (IG) spacer material. The NFRC file archive is available for additional study and modification as proposed by this paper.

INTRODUCTION

Tinted and reflective glass, films and low emissivity (low-e) coatings are used throughout the residential and commercial fenestration industry. Improvements are made every day, making these materials lower cost and higher performing, placing them in ever higher performance applications. Daytime solar absorption adds heat energy to the fenestration product. Insulation and low-e coatings block the flow of heat within the product and to its surroundings. Shadowing from landscaping or near-by buildings complicates the problem. All of these effects create thermal stress within the glass plate. If the thermal stress is high enough it can lead to cracking, which is considered to be a design, product, or warranty failure. See Table 1 for a table of common effects.

These effects produce five types of loads within the glass; (1) gas law changes of the gas within the IG, which cause bending movements within the plate, (2) coefficient of expansion difference between the frame and glass, coupled together via the glazing bead material or boot, (3) moisture changes within the frame material, if wood is used as a material, (4) wind and ventilation induced pressure differentials across the product and (5) thermal loads within the plate, possibly complicated by solar loads. The primary focus of this paper will be in regard to the thermal load and thermal load effects.

Warm center and cooler edges are a common design consideration, although under some conditions the reverse is true. For this paper the dominant issue will be to consider warm center, cool edge thermal stress. Edge damage creates a focal point for the crack to start, particularity if the edge is under tension, lowering the effective strength of the glass plate. Heat strengthening is commonly used to compensate for thermally induced stress; however this is not always economical, or worse, not always anticipated by a novice designer. Novel fenestration products and unique applications also resist common sense prediction into their possible success or failure. Shadowing from landscaping or near-by buildings complicates the problem, as do interior blinds and heating vents blowing on the product. A design aid can be found within the THERM model (Mitchell 2006) used to rate the product thermally. The following discussion will demonstrate the use of the THERM model to solve this particular glass design issue.

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Table 1. Common Thermal Stress Effects

Exterior	Fenestration Product	Interior
Solar load	Glass type, temper, and thickness	Temperature and dew point
Temperature and dew point	Solar absorption	Emissivity
Film coefficient	Low-e coatings	Film coefficient
Shadowing	Films	Blinds/Window Treatments
Wind pressure load	IG spacer type and design	Ventilation pressure load
	Frame type and design	
	Frame to glass attachment	
	Glass edge quality	

SOLUTION

Warm center and cooler edges create thermal stress within the glass plate. This tensile stress is characterized by a break line 90 degrees perpendicular to the glass edge. From Roark, (1938) temperature differences within a plate create stresses that can be estimated by:

$$\sigma_{edge\_tension} = E_{glass} \cdot COE_{glass} \cdot (T_1 - T_0) \tag{1}$$

where

$\sigma_{edge\_tension}$	=	glass stress
E_{glass}	=	modulus of elasticity
COE_{glass}	=	thermal coefficient of expansion
T_1	=	high glass temperature
T_0	=	low glass temperature

Many fenestration manufacturers have an extensive NFRC database of THERM models to rate their products per NFRC procedures. Since it's inception in 1991 the NFRC has provided methodology to fairly rate products as presented to the public, by thermally rating the whole product (glass and frame). The THERM program is a 2D heat transfer Finite Element Analysis (FEA) program that was developed specifically for fenestration analysis, funded by the US Department of Energy. THERM is created, supported and distributed by the Windows & Daylighting Group at Lawrence Berkeley National Laboratory (LBNL). Free downloads of the software are available from http://windows.lbl.gov/software/therm. THERM 5.2 was used exclusively for the analysis to follow.

Main effects considered in this analysis are solar load, glass absorbency, fenestration design, environmental and use conditions, (Zhong-wei et al. 1999). Internal blinds and heating ventilation air-conditioning (HVAC) venting onto the glass are non-obvious conditions that can be accounted for via the THERM model, provided the film coefficients and other specifics of the situation are known.

The THERM model provides change of temperature within the glass pane. Glass stress is estimated from the temperature difference within the plate. Glass probability of breakage is estimated from glass stress, (Zhong-wei et al. 1999). Zhong-wei et al. (1999) and Stahn (1980) support a 20-90% increase due to three-dimensional (3D) shadows over stress results found from a lineal shadow simulated with the THERM program.

Detailed 3D FEA, fluid flow models, and experimental measurement will also provide excellent detail on the stress field with the fenestration product, (Zhong-wei et al.1999). However, as seen from this paper, the THERM model solution provides an efficient design solution compared to alternative methods.

RESULTS AND METHODOLOGY

The fenestration product used in this paper is an aluminum clad wood product, with ¾ inch glazing with a casement sash operating design. The starting point for the model is a finished NFRC THERM model completed by a certified, third party modeling consultant. A nominal load of 248 Btu/hr-ft^2 is assumed as a higher than expected, generic application to overemphasize the effects for low-e's and tints. This value can be increased or decreased depending upon the expected environmental conditions. NFRC winter night conditions are used for model boundary conditions; 0°F (-18°C) exterior, 70°F (21°C) interior, with a 15 mile per hour wind perpendicular to the exterior surface and free natural convection on the unit interior.

As a simulation of a shadow covering the frame, further cooling the fenestration edge, a heat flux is placed on the glass surface 2.5 in. (50.5 mm) above the daylight opening by modifying the model boundary conditions. The heat flux value for both the interior and exterior surface is calculated from the product of the solar load and the expected solar absorptions of each lite. The heat flux addition is the only modification of the existing THERM model. As this is completed the model can be solved. The temperature changes within the glass lites can be found from the model output. For thick single glazing (1/2" thick) applications temperature prediction errors can be expected to be large (Powles et al. 2005). This is caused by the THERM program simulating the solar absorbency all at the surface of the glass as a boundary condition versus continuously through the glass thickness. For common residential and commercial insulated glass applications, this error averaged

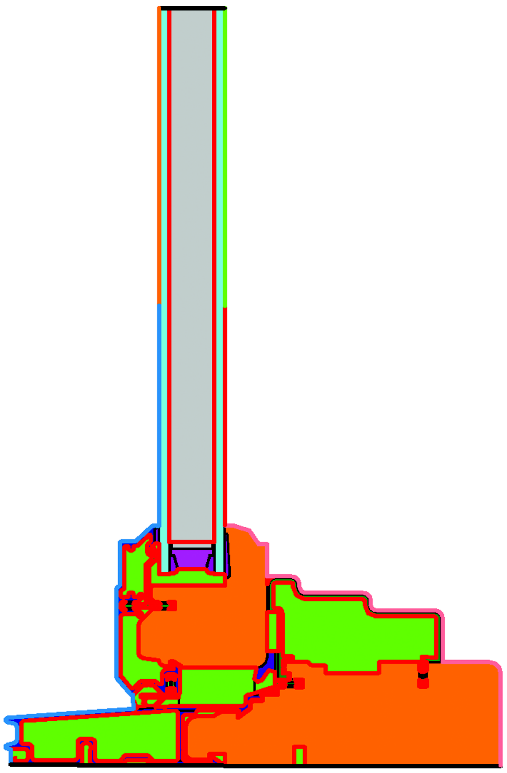

Figure 1 *Casement jamb THERM model.*

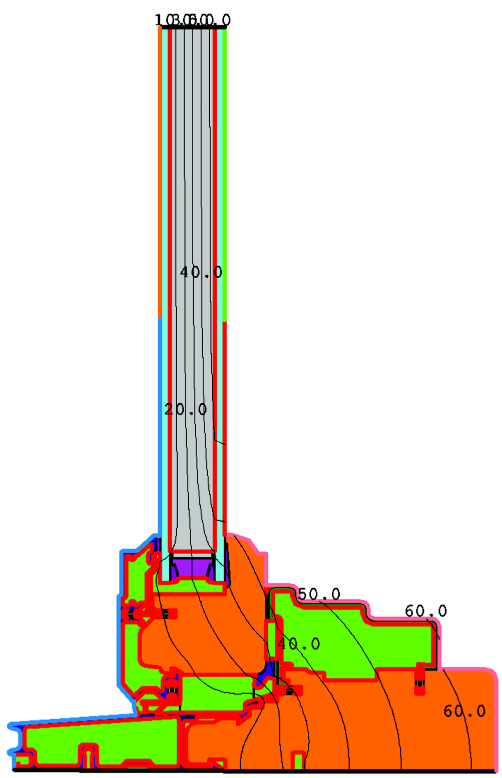

Figure 2 *Isotherm plot, night time, no shadow or solar load, 10°F per isotherm.*

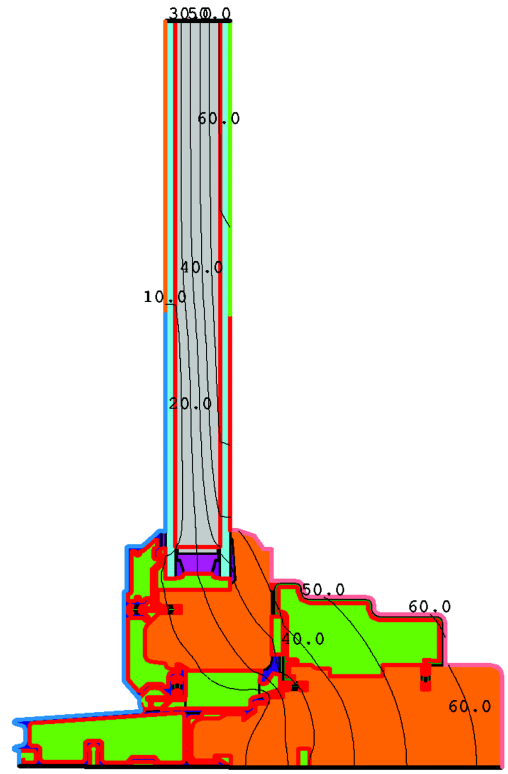

Figure 3 *Isotherm plot with solar load and shadow covering the frame and glass edge, 10°F per isotherm.*

for the glass considered 0.6°F (0.3°C) or 32 psi (0.22 Mpa) induced glass stress. This error was estimated by comparing mid-point absorptance temperature estimates vs. the THERM model. Further work would be required to accurately model single glazing applications, perhaps by splitting the heat flux between interior and exterior surfaces.

Glass stresses and potential breakage can be estimated from these modeled temperature changes within the lites. Night temperatures and stress designate values without a solar load. Shadow values are a result of solar load and shadow placed on the glass and frame edge. See Table 3, Analysis Results Summary Table for results, numbering the exterior lite #1 and the interior, room-side lite, #2.

Probability of Breakage

Given a1410psi (9.7 MPa) glass stress the corresponding probability of breakage is 1/10,000 lites (Beason and Lingnell 2002). Further estimates can be approximated from each stress condition. Also note that this simple shadow condition simulated in this example increased the stress in the glass from 20-90%.

Comments on Results

As the performance and energy efficiency improves for the fenestration product, glass stress increases on the interior

Table 2a. ASHRAE Film Coefficient Table (ASHRAE [1]: Film Coefficient Table) IP

Indoor Radiation and Convection Coefficient (h_1) (Still Air Conditions) Indoor Coefficient[a], h_i, Btu/h·ft²·F Indoor glass Surface Emittance, e_g						Temp. Diff.	Glass Temp.	Room Temp.
0.05	0.10	0.20	0.40	0.34	0.90	F	F	F
0.45	0.51	0.61	0.81	1.25	1.31	5	65	70 (winter design)
0.53	0.58	0.68	0.88	1.31	1.37	10	60	
0.62	0.67	0.76	0.96	1.38	1.44	20	50	
0.68	0.73	0.81	1.01	1.42	1.48	30	40	
0.73	0.77	0.86	1.04	1.44	1.50	40	30	
0.76	0.81	0.90	1.07	1.46	1.51	50	20	
0.79	0.84	0.92	1.10	1.47	1.52	60	10	
0.81	0.88	1.00	1.25	1.79	1.87	60	135	75 (summer design)
0.78	0.84	0.96	1.20	1.73	1.80	30	125	
0.74	0.80	0.91	1.15	1.66	1.73	40	115	
0.69	0.75	0.86	1.09	1.59	1.66	30	105	
0.63	0.68	0.79	1.02	1.50	1.57	20	95	
0.53	0.59	0.70	0.91	1.39	1.45	10	85	
0.46	0.51	0.63	0.83	1.30	1.36	5	80	

$h_i = h_c + h_r = A(\Delta t)^{0.25} + [e_g \sigma(T_g^4 - T_i^4)]/(T_g - T_i)$ where $A = 0.27$

Table 2b. ASHRAE Film Coefficient Table (ASHRAE [1]: Film Coefficient Table) SI

Indoor Radiation and Convection Coefficient h_1 (Still Air Conditions) Indoor glass Surface Emittance, e_g Indoor Coefficient h_i, W/(m²·K)						Temp. Diff.	Glass Temp.	Room Temp.
0.05	0.10	0.20	0.40	0.84	0.90	°C	°C	°C
2.6	2.9	3.5	4.6	7.1	7.5	3	7	20 (winter design)
2.9	3.2	3.8	4.9	7.3	7.7	5	15	
3.4	3.7	4.2	5.3	7.7	8.0	10	10	
3.7	4.0	4.5	5.6	7.9	8.2	15	5	
4.0	4.3	4.8	5.8	8.1	8.4	20	0	
4.2	4.5	5.0	6.0	8.2	8.5	25	-5	
4.4	4.6	5.1	6.1	8.3	8.6	30	-10	
4.5	4.8	5.5	6.9	10.0	10.4	30	55	24 (summer design)
4.3	4.6	5.3	6.7	9.7	10.1	25	50	
4.1	4.4	5.1	6.4	9.3	9.7	20	45	
3.8	4.1	4.8	6.1	8.9	9.3	15	40	
3.5	3.8	4.4	5.7	8.5	8.8	10	35	
3.0	3.3	3.9	5.1	7.8	8.2	5	30	
2.6	2.9	3.6	4.8	7.5	7.8	3	28	

$h_i = h_c + h_r = A(\Delta t)^{0.25} + [e_g \sigma(T_g^4 - T_i^4)]/(T_g - T_i)$ where $A = 1.77$

Table 3a. Analysis Results Summary Table, IP

Solar Load	248 Btu/h-ft^2							
			Heat Load		Delta_temp Lite #2		Stress Lite #2	
	Lite #1	Lite #2	Lite #1	Lite #2	Night	Shadow	Night	Shadow
	Solar Abs	Solar Abs	Btu/h-ft^2	Btu/h-ft^2	F	F	psi	psi
Clear insulated glass (IG), air filled	0.081	0.062	20.1	15.4	18.0	26.8	945	1410
IG low-e on surface #2, argon	0.240	0.019	59.6	4.72	27.0	32.7	1420	1720
IG low-e on surface #3, argon	0.116	0.132	28.8	32.8	27.0	48.2	1420	2530
Tint lite #1, low-e on surface #3, argon	0.529	0.078	131	19.4	28.4	43.9	1490	2300
Tint lite #2, low-e on surface #2, argon	0.238	0.181	59.1	44.9	28.4	56.1	1490	2950

Table 3b. Analysis Results Summary Table, SI

Solar Load	783 W/m^2							
			Heat Load		Delta_temp Lite #2		Stress Lite #2	
	Lite #1	Lite #2	Lite #1	Lite #2	Night	Shadow	Night	Shadow
	Solar Abs	Solar Abs	W/m^2	W/m^2	C	C	MPa	Mpa
Clear IG, air filled	0.081	0.062	63.4	48.5	10.0	14.9	6.52	9.70
IG low-e on surface #2, argon	0.240	0.019	188	14.9	15.0	18.2	9.78	11.8
IG low-e on surface #3, argon	0.116	0.132	90.8	103	15.0	26.8	9.78	17.5
Tint lite #1, low-e on surface #3, argon	0.529	0.078	414	61.1	15.8	24.4	10.3	15.9
Tint lite #2, low-e on surface #2, argon	0.238	0.181	186	142	15.8	31.2	10.3	20.3

lite. Placing the low-e coating on surface #2 reduces the glass stress (verses surface #3 placement) on the interior lite. Tints increase the interior lite stress, however, these products are less common in the north at the temperature extremes seen in this example. Environmental conditions, product design and shadowing effect the probability of glass breakage.

CONCLUSIONS

The THERM program is proposed to be a way to model 2D fenestration sections under thermal and solar load. THERM section models are readily available from the fenestration manufacturer and NFRC database. The models account for the material and design of the unique fenestration product. The model can be loaded to account for the design conditions of interest. While the THERM program cannot model 2D shadow, sufficient background materials exist to estimate the worst case conditions. Knowledge of the glass stress and likelihood of breakage will help the novice designer and the designer working in unique situations to size and specify materials that will withstand the expected environmental conditions. With training and experience, the THERM program analysis can be completed in a highly efficient manner.

Further research is suggested to further study the relationship between edge shadow stress and maximum 3-D shadow stress from various conditions. Additional substantiation through theory or experimentation is needed. The full significance of the proposed modifications and the development of a complete set of design parameters is a suggested topic of further research. Further method development would be required to model single glazing applications.

ACKNOWLEDGMENTS

The writer gratefully acknowledges the support provided by Marvin Windows and Doors and my wife Nancy Fisher.

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APPENDIX A

Modeling Procedure

NFRC thermal modeling is completed on most fenestration products sold today. Model data is readily available for 2D heat flow and can be used to simulate shadow conditions on fenestration products. For example, a sunny winter morning with a shadow covering the frame:

This shadow condition will cause increased stress within the interior lite by heating the center portion over the cooled edge portion. Glass stress can be approximated by observing the glass high and low temperature conditions within the inner lite.

This method is a simple approximation and is not the worse case load give by 3D shadow effects. However, it is very simple to perform and accurately accounts for tints, low-e coatings, frame and spacer effects and variable wind and temperature conditions.

Steps

1. Start with approved NFRC models of the center-of-glass condition using the Lawrence Berkeley National Laboratory's Windows 5.2 program and the 2D cross-section model using the THERM program.
2. Given a design solar load using the Windows 5.2 program, calculate the energy absorption of each lite.
3. Modify the Therm boundary conditions 2.5” above the daylite opening to include the absorbed energy of each lite.
4. Under steady state conditions the glass lite stress can be calculated from:

$$\sigma_{\mathrm{edge\_tension}} = E_{\mathrm{glass}} \cdot COE_{\mathrm{glass}} \cdot (T_1 - T_0)$$

5. Other shadow and environmental conditions can be checked. Worst case shadow conditions can be approximated by $1.9 \cdot \sigma_{\mathrm{edge\_tension}}$ modeled from a lineal edge shadow.