A Method of Evaluation for Thermal Stress in Monolithic Annealed Glass

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Abstract

It is well known that thermal breakage occurs in monolithic annealed glass when the glass is heated unevenly by solar irradiance. The uneven heating is frequently caused when the edges of the glass are shielded by the window frame or shadows while the central portions are exposed to solar irradiance. Typical uneven heating conditions cause tensile stresses around the edges of the glass. This paper presents a theoretically based procedure to conservatively estimate the level of thermal stress induced in a glass plate by the specified thermal loading conditions. This procedure is based on the results of a finite element analysis parametric study and engineering judgment. The method allows the designer to judge whether the probability of failure associated with the estimated thermal stress exceeds a specified value.

Introduction

Thermal breakage is one of the most common factors that leads to the breakage of annealed window glass in buildings. Thermal breakage occurs when thermal gradients are induced in the glass by uneven heating of glass. The uneven heating can be caused by solar irradiance or other heat sources of heat. However, this paper is focused solely on the treatment of thermal stresses induced by solar irradiance.

When a glass plate is subjected to solar irradiance, some of the energy is reflected from the surface of the glass, some of the energy is absorbed by the glass, and some of the energy is transmitted through the glass. The energy that is absorbed by the glass increases the its temperatureof the glass above the previously existing equilibrium condition. If the glass is is supported in such a way that thermally induced expansions are not restrained, and if it is uniformly heated,and if the support system can accommodate the thermally induced expansion of the glass there will be no stresses induced in the glass by a uniform temperature increase. However, if part of the glass is shielded from the direct effects of the sunlight by the edge support system or by shadow patterns, the glass will be unevenly heated resulting in the development of in-plane tensile and compressive stresses. When the thermally induced tensile stresses interact with critical edge flaws, thermal breakage can result [1].

In most thermal breakage situations, the edges of the glass are subject to higher tensile stresses than the surfaces of the glass. In addition, the stress concentrating effects of edge flaws are generally more severe than the stress concentrating effects of surface flaws. These circumstances combine to create a situation where thermally induced glass breakage usually initiates at the glass edges. While the generalities of the solar induced thermal stress problem have long been understood by those working in the glass industry, there is very little information available to explicitly describe the mechanics of thermal stresses in glass. As a result, most thermal stress evaluation methods are based more on empirical methods and experience than explicit engineering formulations.

The purpose of this paper is to review a recently developed thermal stress evaluation method and to present modifications that allow a conservative treatment for typical shadow conditions. The thermal stress evaluation method incorporates a simplified process to conservatively estimate the magnitude of the maximum tensile stress along the glass edges, given the solar irradiance and the total solar absorption of the glass. This simplified method incorporates results of a parametric study utilizing finite element analysis (FEA). In addition, the thermal stress evaluation method includes a probability of breakage chart that relates the allowable edge stress to the perimeter of the rectangular annealed glass plate for various probabilities of breakage. This probability of breakage chart is based on an edge strength failure prediction model (ESFPM). The ESFPM parameters used in constructing the probability of breakage chart were based on the results of a large number of glass tests to failure.

Simplified Method to Conservatively Estimate Thermally Induced Edge Stress

The simplified method for conservatively estimating thermally induced edge stresses is focused on estimating stresses in thin rectangular plates with four sides of continuous support. Typical edge support conditions are such that a thin strip of glass around the perimeter of the glass plate is shielded from the direct effects of sunlight by a glazing bead or the window frame. The width of the perimeter strip that is protected from the direct effects of the sunlight is referred to herein as the edge bite. In addition, most continuous edge support conditions are such that the edges of the glass are relatively free to slip in the plane of the glass so that a reasonable level of thermal expansion or contraction can be accommodated without the introduction of support induced stresses. If glass under evaluation is supported in some other manner, the character of the thermal stress distribution will be significantly different than that discussed in this paper [2].

One of the most commonly discussed examples of thermal stress breakage occurs on a clear cold winter day. During the cold night, the glass uniformly cools to an equilibrium condition that depends on the temperature inside the building, the temperature outside of the building, the interior surface film coefficient, and the exterior surface film coefficient. Early in the morning, when the sunlight begins to shine on the glass, the exposed area of the glass is heated. As the exposed area of the glass warms, it expands. This forces the unheated edges of the glass around the perimeter of the plate into a tensile stress condition parallel to the edge of the glass. A complete discussion of the character of thermally induced stresses in rectangular glass plates with four edges of continuous support is presented elsewhere [2].

Finite element analysis (FEA) provides a convenient tool to investigate the development of thermal stresses in thin rectangular glass plates subjected to uneven heating conditions caused by solar irradiance. There are two general approaches to the use of FEA to evaluate this problem. The first approach involves the development of a detailed three-dimensional FEA model that is used to evaluate the development of thermal stresses in a glass plate of any specific geometry, with specific window frame conditions, with a well defined set of shadow conditions, and exposed to a very specific set of solar conditions. The

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second approach involves the use of a two-dimensional FEA model to determine the variation of temperature with time along the horizontal and vertical centerlines of a rectangular glass plate with a specified thickness and set of support conditions. This information is then combined with basic principles of mechanics to conservatively estimate the magnitude of thermally induced edge stress in a rectangular glass plate. This second approach is used in this paper.

The following equation can be used to estimate the magnitude of the nominal edge stress, $\sigma_{thermal}$, experienced by a glass plate subjected to a specified solar load:

$$\sigma_{thermal} = TSF \times SL \qquad (1)$$

where $\sigma_{thermal}$ is expressed in kPa, TSF is the thermal stress factor expressed in kPa/(W/m²), and SL is the solar load expressed in W/m². The magnitude of the solar load, SL, is found by multiplying the total solar absorptance of the glass (expressed as a fraction) by the maximum solar irradiance impinging on the surface of the glass. The magnitude of the maximum solar irradiance impinging on the surface of the glass can be determined from standardized charts based on the latitude of the building site and the orientation of the window. The TSF is determined through the use of either two- or three-dimensional FEA [2].

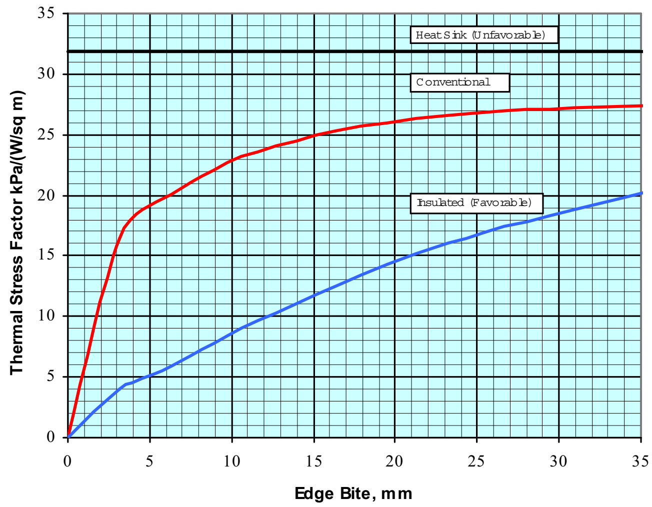
To simplify the use of equation (1), the thermal stress factor chart presented in Figure 1 has been developed for 6 mm rectangular annealed glass for three different sets of edge support conditions. These edge support conditions include the most favorable edge support condition, the least favorable edge condition, and an edge condition that is representative of typical thin-walled aluminum frames.

The most favorable edge condition occurs when the glass edge in the glazing pocket is insulated so that no heat flows through the glass boundary within the edge bite. This means that the only mechanism for heat flow into or out of the glass in the edge bite region is through conduction within the glass. This set of edge conditions results in the development of the lowest level of thermal stress when a glass plate is subjected to solar radiation.

The most unfavorable edge condition occurs when the glazing pocket is assumed to have a large thermal mass (heat sink condition) that prevents the edges of the glass from warming when the main body of the glass is exposed to solar irradiance. Therefore, in development of the model that represents the most unfavorable conditions, it was assumed that the glass boundary within the edge bite remains at its initial equilibrium temperature throughout the entire thermal exposure. This closely represents the case where the edge of the glass is glazed in a system with a

Fig 1

Thermal stress factor chart.



massive heat sink with minimal thermal isolation. Such a situation occurs if the edge bite is encased in concrete or in a thick-walled metal frame. This case represents the most critical situation for the development of thermal stresses. In addition, the magnitude of thermal stress estimated using this assumption is believed to provide a conservative estimate of the maximum tensile stress that can be generated in a glass plate subjected to a linear shadow pattern.

The conventional condition is defined in this paper based on the characteristics of thin-walled aluminum framing members with the glass edges supported by rubber perimeter gaskets on the interior and exterior surfaces. In this conventional model it is assumed that the rubber gaskets are set on both sides of the glass around the entire perimeter and that the glass is set on two conventional setting blocks with sufficient edge clearances so that there is no glass to metal contact. It is believed that these conditions provide realistic estimations for edge stresses associated with thin-wall aluminum window frames and conservative results for typical wood and vinyl window frames.

Probability of Breakage Chart

Laterally loaded rectangular glass plates with four-edges of continuous support generally fail as the result of the interaction between surface tensile stresses and stress concentrating surface flaws. Most current glass thickness selection charts presented in the United States are based on the glass failure prediction model (GFPM). The GFPM provides a rational procedure to relate the probability of breakage (POB) of a uniformly loaded glass plate to the magnitude of the applied load, the surface flaw characteristics of the glass, and the duration of the loading [3]. However, the maximum tensile stresses and the critical flaws associated with thermal breakage are almost always located along the edges of the glass. Thus, a modified failure prediction model must be used to model the thermal stress situation. The thermal stress failure prediction model is patterned after the GFPM, except that it relates the POB of the glass to the distribution of edge stresses and the characteristics of the edge flaws, instead of surface stresses and surface flaws. In addition the treatment of thermal stresses in the current method is based on a longer load duration than is the case with the GFPM. Details of the formulation and calibration of the edge stress failure prediction model (ESFPM) are presented elsewhere [2].

The concept of an acceptable POB for glass subjected to uniform wind loads is well accepted within the glass design community. However, a clear definition of the acceptable POB for glass subjected to thermal loadings is not as well defined. Logically, the acceptable POB for a particular situation should be based on a number of factors including the number of lites in the building and the consequences associated with thermal stress breakage.

For wind load applications, an acceptable POB associated with the occurrence of the design wind event typically ranges from 0.001 (1 lite per 1 000) to 0.008 (8 lites per 1 000). However, it seems reasonable that the designer might wish to contemplate the use of POB's as low as 0.0001 (1 lite per 10 000) for thermal stress designs, depending upon the application. The final selection of the acceptable POB for thermal stress designs is the responsibility of the glass designer.

Finally, to use the ESFPM to determine the allowable edge stress for a particular situation, it is necessary to establish a reasonable duration for thermal loadings. While it is reasonable to use a 60-second duration loading for wind loading situations, thermally induced edge stresses usually last more than 60 seconds. While no exhaustive effort has been made to establish a definitive duration for thermal loading, it seems reasonable to use a 60-minute duration for thermal loadings. This judgment is based upon previous experience observing thermal loadings situations and FEA results.

Figure 2 presents the ESFPM

relationship between the perimeter (expressed in m) of the rectangular glass and the allowable edge stress (expressed in MPa) for POB's ranging from 0.0001 (1 lite per 10 000) to 0.008 (8 lites per 1 000).

Evaluation of Thermal Stress Condition for a Specific Situation

To demonstrate use of the thermal stress method, a 6 mm thick annealed glass plate with a 52% total solar absorptance is considered. This glass plate has rectangular dimensions of 2 m x 3 m and is supported with a conventional thin-walled aluminum frame with rubber gaskets on each side of the glass. The glazing system provides for an edge bite of 16 mm and it has no shadow exposure. Using Figure 1 and these design conditions, it is seen that the TSF is equal to about 25 kPa/(W/m^2). Based on the location of the building and the orientation of the glass it was determined that the glass will be exposed to a design solar irradiation of 780 W/m^2. The solar load for this glass is then found to be 406 W/m^2 by multiplying 780 W/m^2 by the total solar absorptance of 0.52. Then, using equation (1), the maximum thermal edge stress, $\sigma_{thermal}$, is found to be about 10.1 MPa.

Examination of Figure 2 shows that the maximum allowable edge stress for an edge perimeter of 10 m, is equal to about 10.8 MPa for a POB of 0.008 and it is found to be about 5.9 MPa for a POB of 0.0001. Thus, use of this glass plate would be acceptable for a POB of 0.008 and not acceptable for a POB of 0.0001.

If this annealed glass plate is subjected to a linear shadow, the TSF should be taken to be the maximum value of about 32 kPa/(W/m^2) based on the earlier comment regarding the conservative treatment of shadows. In this case, the maximum thermal edge stress would be found to be about 13.0 MPa. This level of stress is unacceptable for the full range of POB's considered in Figure 2.

Summary

This paper outlines and describes the method for a thermal stress evaluation procedure (TSEP) for annealed glass. The TSEP incorporates results of finite element analyses (FEA) to estimate the magnitude of the thermally induced stresses and an edge strength failure prediction model (ESFPM) that is used develop the method for determining the significance of the calculated thermal stress in monolithic annealed glass.

Thermal gradients are induced in an annealed glass plate when the central area of the plate is subjected to solar irradiance while the edges of the glass are shielded by edge support conditions. The thermal gradients can be made more complex if the glass is shaded by the framing system or building. The thermal gradients in the glass can induce tensile stresses along the edge of the glass. The magnitude of the edge tensile stresses depends on the solar properties of the glass, solar irradiance, perimeter, and glazing system. Depending upon the severity of the situation, sufficient thermal stress may be induced to overcome the edge stress capabilities of annealed glass. The conditions that influence the thermal stress breakage of annealed glass have been widely recognized within the glass industry. The method presented was developed to conservatively estimate the magnitude of the thermal stress induced in a rectangular annealed glass plate as a function of the solar absorption properties of the glass, the solar loading condition, size and support condition. This method is based on the results of a finite element analysis parametric study. Procedures are also presented that allow the calculated stress to be compared to an allowable thermal edge stress associated with an acceptable probability of breakage (POB). The allowable stress information is based on the use of an edge strength failure prediction model (ESFPM) that relates the allowable edge stress to the perimeter and various POB's.

It is likely that a more detailed analysis for a particular situation could result in lower estimates of the thermally induced edge stress. However, it is believed that the stresses predicted by the method described in this paper will not be exceeded. Thus, this method of evaluation for thermal stresses in monolithic annealed glass should provide for conservative glass designs.

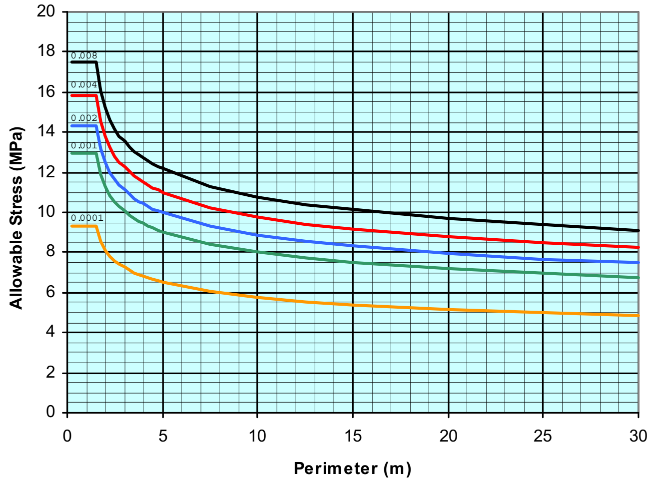


Fig 2

Probability of Breakage (POB) chart.

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