Applied Thermal Engineering 131 (2018) 837–848

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Relative significance of temperature gradient components on cracking behavior in glass panes under thermal radiation

Yuzhuo Yang, Lei Miao, Cheuk Lun Chow *

Architecture and Civil Engineering Department, City University of Hong Kong, Tat Chee Avenue, Kowloon, Hong Kong

HIGHLIGHTS

- Effect of temperature gradients on cracking behavior of glass pane is demonstrated.
- Backside boundary conditions impact on temperature gradient across glass thickness.
- Temperature gradient of glass in planar direction dominates the time to first crack.

ARTICLE INFO

Article history:
Received 8 March 2017
Revised 14 November 2017
Accepted 16 December 2017
Available online 16 December 2017

Keywords:
Radiative heat flux
Glass
Thermal boundary conditions
Temperature gradient components
Cracking behavior
Finite element method

ABSTRACT

The effect of temperature gradient components on cracking behavior of glass panes under thermal radiation was studied. A series of experiments and finite element simulations using ANSYS were performed for float glass panes with one side exposed to heat. The thermal boundary conditions of the unexposed side of the glass pane were varied by putting different materials, including brass, steel or tempered glass behind it. Temperature development, temperature gradient components across the thickness and in planar directions, cracking behavior and stress were investigated. It is found that the temperature gradient component across the glass thickness is much larger than those in planar directions and would change with the thermal conditions of the unexposed side. However, the increase of stress and hence the cracking behavior of glass panes is mainly determined by temperature gradient components in planar directions under thermal conditions similar to those in the present study.

1. Introduction

Glass facades are widely used in modern architectures for many reasons. However, glass panes are easy to crack and may even fall out when exposed to a fire [1]. Consequently, high flow rate of fresh air would go through the opening to give a more hazardous fire [2]. Thus, a glass pane acts as a wall before breaking and as a vent after breaking. In view of this, the prediction of glass thermal breakage is crucial for fire-spread modeling and evacuation modeling in fire safety study of architectures with glass panes. The thermal effects of metal structures have been well investigated in structural engineering [3–7]. Thermal stress and thermal deformation were generated when the temperature distribution of a metal structure is nonuniform under thermal radiation, which will influence the related working performance. Moreover, the structure member will even fail or fracture considering the thermal stress due to temperature change, in addition to other loads, such as gravity and wind load. Such thermal effects also appear in glass material. In exposing a glass pane to a heat source, its temperature will rise and results in thermal expansion. If the incident heating is uneven, thermal expansion will not be uniform, and thermal stress is generated [8–12] within the pane, which can lead to crack initiation since glass has lower tensile strength compared with metal materials. This point was verified by physical experiments [13–18] and numerical simulations [19–20]. Most of these studies were focused on framed glass. Fracture occurs when the thermally induced tensile stresses in the shaded area reach the tensile strength. This tensile stress is derived from a critical temperature difference between the central heated portion of the glass pane and glass edge. These studies were extended [21–22] to include more nonuniform heating conditions, in which thermal bending contributed to the total stress. The fracture behavior of four-point fixed glass curtain walls under fire conditions was studied [23–24]. All cracks were found to be initiated at the supporting points. The combined effect of temperature gradient components on the exposed side and point fixing effect is the cause for glass breakage, but point fixing effect is dominant.

---

* Corresponding author.
E-mail address: cheuchow@cityu.edu.hk (C.L. Chow).

https://doi.org/10.1016/j.applthermaleng.2017.12.060
1359-4311/

All these studies only considered the temperature difference on the exposed side in studying the thermal stress field, but not the effect of temperature gradient component across thickness on the glass crack behavior. Skelly [14] calculated the thermal stress of glass pane in relation to the temperature difference on the exposed side, but firstly recommended that the temperature gradient component between the inside and outside of the window should be taken into consideration for thicker glass.

It was proposed [25] that thermal stress of a glazing edge is not only induced by the temperature difference between the exposed and shaded regions of glass on the fire side, but also by that between the ambient side and the fire side of glass surfaces. The temperature difference between the center temperature of the exposed side and the edge temperature on the unexposed side was used in predicting the time to first crack [25–26]. However, the effect of temperature difference across the thickness was not stated. Most studies only solved a plane stress problem in which stresses perpendicular to the pane were neglected. Chow [27] firstly studied theoretically the thermal stresses due to bending resulting from sudden rises in temperature of a window glass panel exposed to fire under certain boundary conditions. Thermal bending moment due to temperature difference in thickness was considered. More accurate theoretical calculations on thermal stress of glass panes were performed and compared with the measured time and location of first crack in full-scale experiments. However, the contribution of temperature gradient component across thickness to thermal stress has not been included.

When an enclosure fire occurs, the boundary conditions of the unexposed side of the glass facades are different due to the possible variation of ambient temperature from $-30\,^{\circ}\mathrm{C}$ to $30\,^{\circ}\mathrm{C}$. The temperature gradient component across thickness is much larger than that in the planar direction in some conditions, and may contribute to the thermal stress field. Thus, there is a need to consider the temperature gradient component across thickness when analyzing the thermal stress induced by temperature difference, in order to accurately predict thermal breakage of glass panes in a fire. However, there is no direct experiment or theoretical analysis carried out to study the impact of temperature gradient component across thickness.

In this work, the relative significance of temperature gradient components across thickness and in the planar direction to thermal breakage was investigated. The contributions of these two temperature gradient components to the total thermal stress were compared. The objective is to obtain a reliable conclusion on whether the temperature gradient component across thickness has significant effect on the cracking behavior, and to provide reference for related modeling of glass thermal breakage.

Experiments were carried out to realize different temperature gradient components. 15 float glass panes were heated with a cone calorimeter radiator until crack occurred. The unexposed side of the glass pane was placed on three kinds of lumps made of materials of different thermal conductivities. These lumps conducted heat from the contacting surface of the glass samples at different rates, resulting in different temperature gradient components across the thickness of the glass panes. The temperature development on the exposed and backside, crack location and time to first crack were experimentally determined and used to analyze the correlation between the temperature gradient components, both across thickness and in planar directions, and cracking of glass panes.

Simulations with the software ANSYS [28] were also performed based on the experimental surface temperatures to obtain three-dimensional temperature distributions at different times, which were then applied for calculating strain and stress fields [29–30]. The distribution of stress was compared with experimental results on cracking. The correlation between temperature variables and stress was analyzed. Regression analysis was performed to quantify the contribution of different temperature gradient components to thermal stress.

2. Methodology

2.1. Experimental studies

Float glass panes were cut into size of 100 mm × 100 mm with thickness of 6 mm and tested under steady thermal radiative heat flux. A thickness of 6 mm is an ordinary thickness of glass panes in buildings [16]. In addition, critical temperature difference and critical tensile stress in heating up 6 mm-thick float glass panes were reported in some studies [15–18]. Therefore, glass panes of 6 mm thickness were tested in this study for better comparison with those works. The glass samples were cut from one large glass sheet to ensure consistent properties. Edges of these panes were polished to remove irregularities.

The electric heater of a cone calorimeter [31] was used as a source emitting stable radiative heat fluxes. The glass pane was placed on a horizontal holder at certain distance, as shown in Fig. 1(a). The glass panes were supported in a way to ensure that only thermal stresses were induced. A heat flux gauge was used to measure the incident heat flux at the centre of the exposed glass surface. The incident heat flux was adjusted to $45\ \mathrm{kW/m^2}$ in each test.

A lump material covered with aluminum foil was placed in the holder. The glass panes were placed on the thermal conducting material with thermocouples (TC) adhered to both sides to measure the transient temperature as shown in Fig. 1(b) and (c). The axis and layout of thermocouples are shown in Fig. 1(d). K-type bare thermocouples were used to ensure sensitivity and accuracy. The thermocouples had thin and naked wires on the head end. The sheet metal commonly used at the top hot surface was replaced by aluminum foil. The thermocouples would then not affect the contact between the glass pane and the backing material. Adhesive tape was not used on the exposed surface because part of the incident heat radiation might be blocked.

The heat conductive lumps in Fig. 1 were all of the same size. The experiments were divided into three cases using different materials of the lump, including brass, steel and tempered glass. Lump materials of different thermal conductivities were used in order to get different transient temperature gradient components across the glass thickness:

Case-BR: Brass with thermal conductivity of 108 W/m K.
Case-ST: Steel with thermal conductivity of 45 W/m K.
Case-TG: Tempered glass with thermal conductivity of 0.95 W/m K.

Five replicate tests were carried out in each case. These tests were labelled as BR1 to BR5 for Case-BR on brass, ST1 to ST5 for Case-ST on steel, and TG1 to TG5 for Case-TG on tempered glass.

The time and location of the first crack were recorded. The measured temperature distributions and the crack characters in different cases were then analyzed to obtain a correlation between temperature gradient (both in planar and in thickness) and cracking behaviors.

2.2. Finite element method

Though surface temperatures, location of crack and time to crack could be experimentally acquired and correlated, the analysis would be empirical only. In order to justify the correlation and to gain physical insight, stress analysis is unavoidable. In the present study, the finite element computer package ANSYS [28]