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Numerical study on fire response of glass facades in different installation forms

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HIGHLIGHTS

- Fracture behavior is investigated by three-dimensional finite element method.
- Glass stress distributions, breaking time and the initiation and propagation of crack are presented.
- Shading and constraining condition significantly influences the breaking performance of glass facades.
- Engineering advice for facades fire resistance is obtained through analysis and comparison.

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ABSTRACT

Building façades made of glass are viewed as one of the weakest parts of a building; these can easily break in case of fire and change the compartment fire dynamic by creating a new opening for air to enter. According to the onsite survey in four cities in China, nine cases with different shaded and constraining conditions are designed to investigate the thermal response of Low-E glass façades when subjected to a fire. The Coulomb–Mohr criterion and SIFs based mixed-mode criterion are employed to predict the crack initiation and growth, respectively. The glass stress distributions, breaking time and the initiation and propagation of crack are presented, using the three-dimensional finite element method. It was found that various shaded and constraining conditions have a significant effect on the breaking behavior of glass panes. The glass panes with four edges shaded are more prone breaking than other shaded cases, but the four edges constrained pane is relatively safer. All cracks initiate either from the edge of the pane or the borderline between the exposed and shaded areas. Furthermore, practical advice to optimize the window installation design or ways to protect the glass from falling out in a fire can be obtained from the results.

1. Introduction

Architectural designs incorporating glass panels are used extensively in modern high-rise buildings [1] as they provide good aesthetics, better illumination and energy conservation for lighting systems. To learn more about these structures, authors conducted an onsite survey in eastern China, and found that many buildings surfaces are furnished with glass façades instead of concrete and steel, especially newly constructed buildings. Fig. 1 shows the framing façades widely used in the four cities. Most façades are installed in framing, such as exposed framing glass curtain wall, semi-exposed framing glass curtain wall and hidden framing glass curtain wall. Some walls are mainly fixed by two edges without shaded areas (Fig. 1d(ii)). It was found in the survey that in one modern high-rise building, even the envelope consists of different kinds of glass façades.

However, glass façade is normally the weakest part in the building envelope and can be broken easily when exposed to a big fire. This can create an inlet for fresh air flowing into the room from the outside, resulting in the fire in the compartment spreading to other floors or rooms. Following Emmons' pioneering work [2], several experimental [3–10] and theoretical investigations [11–14] were conducted to reveal the thermal breakage mechanism of glazing. The temperature gradient between the exposed and shaded region is thought to be the main cause for glass breaking when subjected to a fire. Nevertheless, prior works have focused only on four edges covered window glass panes, the variety of installations in glazing

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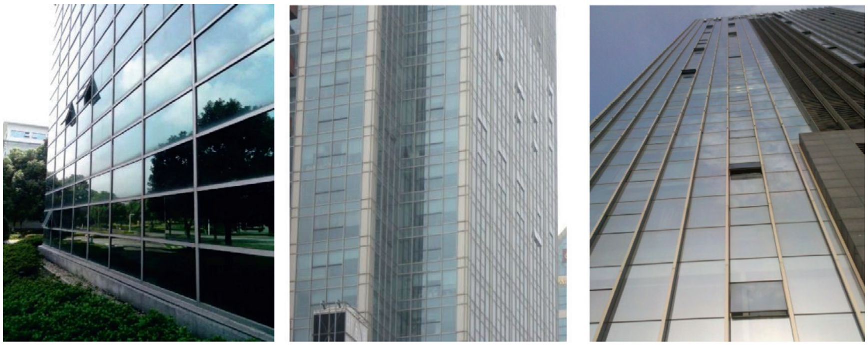

(a) Suzhou, exposed frame (b) Nanjing,vertical-hidden frame (c) Hefei, horizontal-hidden frame

(i) Hidden frame (ii) Constrained facade

(d) Huainan

Fig. 1. The glass façade in four Chinese cities.

assembly was ignored. The façades installed by various framings as shown above make it difficult to comply with the national codes, especially for fire safety. Therefore, the fire response of such glass façade systems should be studied. It is anticipated that some differences may exist between the breakage behavior of traditional four edge covered glass and other kinds of façades [15,16].

Some simulation work was carried out to predict the breaking behavior of glass in a fire [17–21]. Although some models have been proposed in the past, limited works have evaluated fire resistance properties for each kind of framing glass façade, especially using three-dimensional finite element method (FEM). To enable a range of simulations, a total of nine different cases are designed in this study to investigate the effect of various shaded and constraining conditions on thermal response of glass panels. The glass stress distribution, breaking time and the initiation and propagation of crack are also presented using three-dimensional FEM.

2. Thermal stress and crack formulas

The simulation in this study basically employs the method proposed by our previous study [20,22]. In this work, two models are employed, one is thermal stress model and another is crack model based on the stress model. In addition, the data simulated are plotted in Tecplot to obtain the contours.

2.1. Dynamic response models

The stress dynamic response model was employed in our previous study [20], and it is simply stated here. The equations of equilibrium governing the linear dynamic response of a system of finite elements is [23]:

$$\mathbf{M\ddot{U}}+\mathbf{C\dot{U}}+\mathbf{KU}=\mathbf{R} \tag{1}$$

where $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$ are the mass, damping and stiffness matrices; $\mathbf{R}$ is the vector of externally applied loads; and $\mathbf{U}, \mathbf{\dot{U}}$ and $\mathbf{\ddot{U}}$ are the displacement, velocity and acceleration vectors, respectively, of the finite element assemblage. The Newmark integration scheme can be understood to be an extension of the linear acceleration method. It is an explicit method and the most important aspects are the possibility of unconditional stability for nonlinear systems and second-order accuracy. The possibility of unconditional stability and second-order accuracy allows the use of a large time step and the explicitness of each time step involves no iterative procedure. Therefore, the effective Newmark method is taken to solve the dynamic thermal load response of glass. For detailed information, please refer [20,24].

2.2. Thermal stress model and crack criterion

A thermal stress model has also been proposed in our previous study [20], and is simply introduced here. Thermal stress is caused by difference between temperature upon different parts of the glass. If the temperature rise $\Delta T(x, y, z)$ with respect to the original state is known, then the associated deformation can be considered easily. For glass, the temperature rise ΔT results in a uniform strain, which depends on the coefficient of linear expansion α of the material [25]. The detailed method was presented in our previous studies [20,22,26].

Coulomb–Mohr criterion was employed to predict the crack initiation. Crack occurs when the maximum and minimum principal stresses combine for a condition which satisfies the following Eq. (2):

$$\frac{\sigma_1}{S_{\mathrm{ut}}}-\frac{\sigma_3}{S_{\mathrm{uc}}}\geqslant 1 \tag{2}$$

where S_{ut} and S_{uc} represent the ultimate tensile and compressive strengths and both σ_3 and S_{uc} are always negative, or in compression.

SIFs based mixed-mode criterion is used to predict crack growth in the present work. It assumes cracks start to grow once the following Eq. (3) for the stress intensity factors is satisfied [27,28].