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Investigation of the thermal response and breakage mechanism of point-supported glass facade under wind load

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HIGHLIGHTS

- Glass temperature distributions, breakage time, crack initiation and final crack pattern, and fall out ratio were presented.
- The convective heat transfer coefficient at the ambient side surface were obtained using optimization calculation.
- Results have implications concerning fire resistance designs for point-supported glazing assemblies in high-rise buildings.

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ABSTRACT

Glass façade has gradually become main external wall material in high-rise buildings due to its multi-functionalization and diversification. Nevertheless, glass is relatively fragile and prone to fracture when subjected to the coupling effect of fire and external wind load that inevitably significant influences the mechanical property of glass facades in high-rise buildings. Newly formed vents caused through glass breakage are especially vital for the growth of ventilated controlled enclosure fire and play a crucial role in interactive-external tridimensional fire development. Therefore, it is necessary to explore the mechanism of thermal fracture of glass façades under wind load. In the present study, a total of nine tests were performed to investigate the fracture mechanism of point-supported glass facades under various wind speeds combined with fire. Measurements were conducted for the first breakage time, glass surface temperature, and crack initiation and propagation. Numerical simulation, based on finite element method (FEM) was conducted to predict the temperature variation at the ambient side surface of glass panel. The results have implications concerning fire resistance designs for point-supported glazing assemblies in high-rise buildings.

1. Introduction

In recent years, the glass façades are employed widely in the building industry due to its aesthetics and practicality and have become the most important external wall materials especially in high-rise buildings [1]. The point-supported glass façades are extensively used in high-rise buildings because of the stability steel structure, light of glass material, and mechanical precision [2]. Unfortunately, glass is a fragile material whose strength is far lower than concrete and steel [3]. The break and fall out of glass façades play a crucial role in interactive-external tridimensional fire development, thus are one of the most important research contents in building fire dynamics and structure fire resistance [4]. In the fire environment, the radiation and convection heat transfer under the action of flame and hot flue gas to the glass changed dynamically over time. When the glass thermal stress caused by the non-uniform temperature is greater than its own critical fracture stress, the glass facades will initiate to break and fall out, and eventually form new vents. The newly created vents are especially vital for the propagation of ventilated controlled enclosure fire, especially in which may result in backdraft or flashover phenomenon when the compartment space gathers a large number of pyrolysis products [5].

Emmons [6] first proposed in the 1st IAFSS that glass break and fall out are essential to building structural integrity under fire conditions. Subsequently, considerable researches had been conducted to investigate the breakage mechanism from the aspects of the

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theory, simulation, and experiment. A physical model was built through Keski-Rahkonen [7,8] to reveal the mechanism of glass fracture under non-uniform temperature field. It concluded that the glass pane edge is the easiest to crack for the edge-covered glazing by using the analytical method. Thereby, the correctness of the previous theoretical model was verified based on a large number of experiments conducted by Skelly et al., Pagni et al., and Shield et al. [9–13]. The fracture behavior of float, tempered and multi-layered glazing was recorded, and the critical temperature differenceand incident heat flux were also determined. In the aspect of computer simulation, a Fortran language program which was developed by Pagni et al. called BREAK1 [14] used incident heat flux as an input parameter to predict the glass surface temperature difference at the typical position and the first breakage time. Wang et al. developed the glass fracture behavior prediction software EASY [15], which could simulate the internal stress distribution and calculate the crack initiation and propagation of glass facades.

Whereas, compared to the previous studies which only concentrated on the effect of a single factor (thermal load) on glazing fracture, studies simultaneously concerning external wind and thermal load are relatively limited. For the glass curtain wall of high-rise buildings, with the rise of the floor, the influence of external wind would significantly increase, and such a large wind load would inevitably influence the mechanical property of glass curtain wall [16,17]. A failure-prediction model for glass was proposed by Beason et al. [18] in which allows the probability of failure of laterally loaded glass plates to be expressed in terms of two surface-flaw parameters, m and k. A finite element model is proposed for non-linear and breakage analysis of glass panels subjected to lateral wind load [19].

When the fire occurred in high-rise buildings, glass facades would be subjected to not only a thermal load on the fire side but also a larger wind load on the ambient side. Under this circumstance, the break and fall out behavior of glazing would be quite different from that only was subjected to thermal load on the fire side, and the mechanism of fracture initiation also would be significantly varied. The previous studies mostly concentrated on the mechanical properties of glass facades under thermal load or wind load. As far as the authors know, there was little literature concerning the breakage behavior of the glass facades under the coupling effect of wind and thermal load. Until recently, Chen et al. [20] investigated the breakage behavior of four edge-covered glass facades under the coupling effect of wind and thermal load and concluded that the combination of external wind accelerated the glass breakage under fire condition. Nevertheless, the prior study mentioned above just researched on the four edge-covered glass facade, very little study has been conducted to explore the point-supported glass facades, which are extensively adopted on the external walls of high-rise buildings in Central Business District (CBD). Therefore, there was the limited effective theoretical basis and practical guidance could be provided for high-rise buildings structural fire resistance design. For making the research get closer to the real fire scene, it is necessary to explore the fracture behavior of the glass facades under fire and external wind load, and predict the breakage time to deepen our understanding of interactive-external tridimensional fire propagation.

In this study, a total of nine full-scale tests were performed to investigate the fracture mechanism of point-supported glass facades under various wind speeds combined with fire. Measurements were conducted for the first breakage time, glass surface temperature, and crack initiation and propagation. Finite element method (FEM) calculation was carried out to predict the temperature distributions of glass panes at the ambient side surface.

2. Experimental setup

As illustrated in Fig. 1, the experimental setup mainly consisted of a gas burner, glass installation, wind tunnel, data acquisition system, and camera. A porous gas burner (0.3×0.05 m^2 surface and height of 0.6 m) was placed 0.3 m away from the glass panel, and its top surface is flush with the bottom of the glass panel. Propane was served as the fuel controlled by a mass flowmeter. In all tests, the volume flow rate of the fuel was maintained at a steady value of 40 L/min. The heat release rate (HRR) is calculated using the equation [21] and remains in a relatively stable value of 62.4 kW during all the tests. The float glass, polished at four edges, with the size of $560 \times 560 \times 6$-mm^3 was installed in the form of point-supported. To make the experiment approximate approach to the real fire scene, as shown in Fig. 2(a), four 10-mm diameter circular holes were drilled in each corner at with a diameter of 10 mm and a distance of 35 mm from the edge of the glazing. Four screw nuts, made of 304 stainless steel, and with the inner diameter, outer diameter, and thickness of 10, 30, and 4 mm, respectively, were adopted. To demonstrate the location of crack initiation, A, B, C, and D respectively represent that the crack initiated from the top left corner, top right corner, bottom left corner, and bottom right corner holes' edge. The external wind load was generated through wind tunnel and could be adjusted via anemometer feedback regulation. The fall out mass of glass was measured using a 404×360-mm^2 METTLER TOLEDO XA32001L model of an electric balance with an accuracy of 0.1 g. A CCD camera (Sony HDR-PJ790E, 50FPS) was placed at the fire-exposed side and at the same level as the center of the glass to record the process of glass breakage.

10 K-type sheathed thermocouples (TCs) with a diameter of 1 mm were attached on the glass surface to record the glass surface temperatures: nine TCs were attached at the fire-exposed surface and only one at the center of the ambient side surface, as illustrated in Fig. 2(a). measurement range and sensitivity of these thermocouples are 0–800 °C and 41 mV/°C. The temperature measurement error is assessed at ±5% in this study because of the effect of the smoke layer and radiation, which are fairly less than that in a fire test (uncertainty approximately 10–30%) [13,22]. The external wind speed was set at 0.0, 5.0, and 8.0 m/s to investigate the mechanism of thermal fracture of glass façades under various wind loads. A total of nine tests were carried out in three different wind load cases and three repeated tests of each case were conducted to assure the accuracy and reliability of the results.

3. Numerical methods

For revealing the heat transfer of glass panel under the combined effect of wind and thermal loads, a 3D heat transfer model was developed using the finite element method (FEM) implemented in COMSOL Multiphysics, version 5.3 [23], to predict the temperature distributions in the ambient (wind) side surface. Because of the limited number of thermocouples, a total of nine thermocouples were attached on the fire-exposed surface during the tests. Therefore, based on the distribution of temperature field, a total of nine regions were divided. As shown in Fig. 2(a). In this model, the size and physical properties of glass were identical with experiments. After the grid independence tests being made, a total of 18 000 ($60 \times 60 \times 5$) hexahedron elements were used and the time interval is set to 1 s.

The heat transfer equation can be expressed [24]:

$$\rho(t)c(t)\frac{\partial T}{\partial t} = \lambda(t)\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + Q(t) \quad (1)$$