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The effect of glass panel dimension on the fire response of glass façades

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HIGHLIGHTS

- Fire resistance of glass decreases with the panel dimension increase.
- The glass panel with a larger aspect ratio presents better fire resistance.
- Tiny flaws found by SEM tests on glass surface enhance the numerical results.
- Combination of thermal stress and weakest link theory reveal the mechanism.

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ABSTRACT

Different sizes and shapes of glass products are increasingly employed in building envelopes, but little is known about the effect of glass panel dimension on the fire safety of glass façades. In the present work, two experiments with glass dimensions of $300 \times 300 \times 6$ mm^3 and $600 \times 600 \times 6$ mm^3 were conducted to verify a finite element method model in the authors' in-house software. Then, a total of 27 numerical cases were designed. The glass panel with dimensions from 100×100 mm^2 to 1000×1000 mm^2 and length-to-width aspect ratios of 400:1, 100:1, 25:1, 25:4, 4:1 and 25:16 were studied. The breakage time, stress distribution and crack path were calculated and demonstrated. It was established that the fire resistance of glass decreases with the panel dimension increase regardless of the mesh size and number. While the glass panel with a larger aspect ratio presents better fire resistance. The stress distribution variance caused by size and shape effect is responsible for the different fire performances of glass façades, but the number and distribution of small flaws and defects in glazing are also important. The results are intended to provide references for fire safety optimization of glass façades.

1. Introduction

Glass façades are increasingly used in high-rise buildings, but due to its brittleness, the glass may break and fall out very easily when subject to a fire [1,2]. The fallout of glass can form a new vent that will allow fresh air entrance and fire spread, accelerating the fire development significantly and initiating the occurrence of flashover or backdraft. In addition, glass surfaces are considered open in current structural fire design, and clear evidence on the breakage of windows and glass façades are missing. The shortcomings of our design assumptions are especially evident in new buildings, where glass façades seem to resist the fire much longer than old windows. Thus, it is of great importance to deepening the understanding of glass façades breakage in fires [3–5].

A large amount of work has been conducted to investigate the breakage mechanism of glass breakage. Pagni et al. [6] developed a mechanical model and implemented it into BREAK1 to predict the glazing breakage time. Shields et al. [7,8] conducted full-scale experiments in ISO 9705 to investigate the thermal performance of single glazing in the center and corner fire. Harada et al. [9] changed the imposed heat flux and lateral restraint to study their effect on the wired and float glass breakage behaviour. Recently, structural glass behavior in the fire was investigated as well [10,11]. It was established that many factors can considerably influence the glazing crack initiation, such as the thermal load [7,8], smoke movement [12,13], glass installation type [14,15] and category [9,16]. A consensus has been reached that the excessive thermal stress resulting from temperature gradient is the primary cause of glass breakage [4,17].

As the result of an architectural movement in improving the building aesthetics, glass panels with different dimensions are

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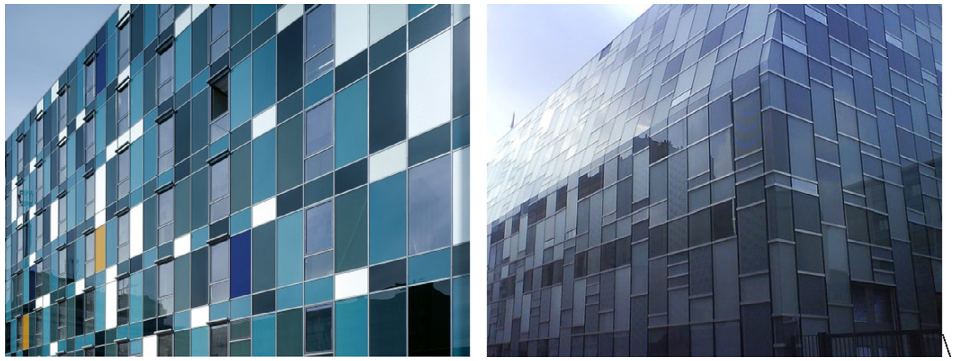

Fig. 1. The glass façades with different dimensions used extensively in modern constructions.

increasingly employed, especially in newly constructed buildings [18], as shown in Fig. 1. The glass panels with different sizes and shapes indeed bring a new sense of construction, but make the buildings face more potential fire risk and fail to comply with the national fire safety codes. This phenomenon is much more common in the Far East, such as mainland China, Hong Kong and Singapore [19]. What is more, the previous study has shown that the size effect has a significant influence on the strength and fire resistance of buildings structures, such as concrete, rock and metal [20,21]. In particular, the thermal stress resistance of ceramics may also be affected by specimen size and shape [22]. Similar to the above materials, it is anticipated that the fire resistance of glass façades would differ markedly when the panel dimension changes. However, to the authors' knowledge, there has been no study concerning glass panel dimension effect on the fire resistance of glass façades to date, so no adequate scientific reference can be provided to deal with the fire risk caused by glass dimension variance. This ignorance hinders the fire safety design and risk assessment of a construction when considering the glass envelop in engineering [23].

Considering the expense and time-consuming of experiments, it is very difficult to conduct experiments of the glass panel with different dimensions under uniform thermal loading, so it is an important alternative way to investigate this issue using a numerical method. In the present work, two experimental tests are first conducted under uniform thermal loading for the verification of numerical model. Then, focusing on the stress distribution, the thermal performance of glass panel with different dimensions and length-to-width ratios are studied using finite element method (FEM). A total of 27 cases are designed and the breakage time, stress distribution and cracking behaviour are calculated and presented. The results are compared and discussed in detail.

2. Numerical principle and verification

In this study, two models are employed: one is thermal stress model and the other is crack model based on the stress model [24,25]. The equation of equilibrium governing the linear dynamic response of a system of finite elements is [26]:

$$M\ddot{\mathbf{U}} + C\dot{\mathbf{U}} + KU = R \quad (1)$$

where **M**, **C** and **K** are the mass, damping and stiffness matrices; **R** is the vector of externally applied loads; and $\mathbf{U}$, $\dot{\mathbf{U}}$ and $\ddot{\mathbf{U}}$ are the displacement, velocity and acceleration vectors, respectively, of the finite element assemblage. The effective Newmark method is taken to solve the dynamic thermal load response of glass.

A 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):

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

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.

A Stress intensity factors (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].

$$\left(\frac{K_{\mathrm{I}}}{K_{\mathrm{IC}}}\right)^2 + \left(\frac{K_{\mathrm{II}}}{K_{\mathrm{IIC}}}\right)^2 = 1 \quad 3$$

where K_{I} and K_{II} are the stress intensity factors for the fracture modes I and II, respectively, which are obtained from the simulation. K_{IC} and K_{IIC} denote the individual fracture toughness values of the fracture modes I and II.

The above in-house FEM software, called EASY, has been verified by full-scale experimental studies in items of breakage time, crack initiation position and path [29]. In addition, it has been proved that the self-developed software can predict as good results as that from BREAK1 [30,31] and commercial soft software ANSYS [25]. Using the FEM software, it is believed to obtain the reliable results of glass fire performance.

However, whether the FEM model is suitable for the calculation of glass panel with different dimensions has not been verified to date. Thus, two tests were conducted. A self-designed apparatus was employed to provide the uniform thermal loading, as shown in Fig. 2(a) and (b). The distance between the radiation panel and glass is 1.5 m and the temperature increase rate was 10 °C/min controlled by an intelligent temperature-controlled meter with a thermocouple located in the small compartment air. After the air temperature reached 600 °C, the temperature will be maintained for 20 min. The glass panels with the dimensions of 300 × 300 × 6 mm^3 (Test 1) and 600 × 600 × 6 mm^3 (Test 2) were heated to break. The edge of the glass panel was polished. A total of seventeen K-type thermocouples were attached to the fireside surface of glass panel both in exposed and covered areas, as shown in Fig. 2(c). The frame shading width was 20 mm and the gypsum was inserted between the frame and glazing as an insulation material. For more information about the setup, please refer to our previous work [32].

The temperature curve and crack path of Test 1 is illustrated in Fig. 3. Although the temperatures in upper layer are slightly higher than lower parts due to compartment hot gas convection, the