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Frame constraint effect on the window glass crack behavior exposed to a fire

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ABSTRACT

Thermal caused glass crack and fracture are very common in building fire, to disclose the constraint effect on the glass crack initiation and crack propagation, five constraint cases are investigated and compared mainly on the first crack initiation time, crack propagation path using a finite element program. The crack location and the growth are predicted using Coulomb–Mohr criterion and the SIFs based mixed-mode criterion, respectively. The thermal stresses distributions, crack initiation, and crack growth path are obtained and compared. It is found that the four edges fully constrained glass sustains the longest time to crack, and then is the half constrained one, the one edge constrained glass is easiest one to crack. The no constrained glass also shows a longer time to crack than the one edge constrained condition. For the one edge constrained conditions, it has the shorter endurance time, which is a dangerous glass install method used in the building windows.

1. Introduction

Glass crack and fall out exposed to fire has been taken attention several decades ago, however, it was proposed as a scientific topic to study was from the year of 1986 at the first fire safety science symposium by Emmons [1]. After that, some experimental works were carried out to study the glazing behavior exposed to fires [2–6]. The heat release rates, enclosure and local gas temperatures, heat flux distributions, glass surface temperatures, shaded glass temperatures thermally induced strains, crack bifurcation patterns and loss of integrity of the glazing assembly were systematically investigated by Shields et al. [7–10]. It was found that the temperature difference at first crack is varying from 70 °C to 90 °C under their specified experimental conditions [7–12]. Chow and Gao [13] investigated the fire smoke effect on glass crack by experiment, and analyzed the thermal stress in theory. Xie et al. [14] conducted a series of full-scale experiments in the ISO 9705 fire test room using pool fires with different pan sizes, which were located at the center of the combustion room. The results suggest that the whole piece of toughened glass cracks and falls out completely when any region of the pane breaks. On the contrary to the glass exposed to fire, a quenched glass crack pattern transition and crack propagation behavior were investigated by theoretical analysis and experiment too [15,16].

However, the theoretical and simulation works are limited developed to investigate the glass crack under thermal or fire exposing. The theoretical work either is limited to the general fracture mechanics or to the general heat transfer. Their conjunction and application on the fire induced glass crack and fall out is few reported, especially on using the finite element method to simulate the glass crack initiation and propagation exposed to fire.

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The objective of this work is to investigate the glass thermal stress building up, crack initiation and propagation using finite element method. The effects of various constraint condition of glass on the crack were investigated and compared under thermal loading.

2. Thermal stress and crack theory formula

2.1. Thermal stress model

Thermal stress is introduced by nonuniform temperature change in glass which is constrained against expansion or contraction in case of fire. In this work, it was calculated using a finite element method, which was proposed in our previous publication [17], and it was simplified here. The thermal stress was calculated using the following equations by finite element method.

$$(\lambda + 2G)\nabla^2 e - \alpha\nabla^2 T = 0 \tag{1}$$

where λ is Lame coefficient, and G is shear modulus of elasticity, e is volumetric strain, α is the thermal expansion coefficient, and ∇ is Laplacian. λ, G and e are expressed as:

$$\lambda = \frac{Ev}{(1+v)(1-2v)}, \quad G = \frac{E}{2(1+v)}, \quad e = \varepsilon_x + \varepsilon_y + \varepsilon_z$$

where v is Poisson's ratio, ε_x, ε_y and ε_z are the strain in x, y and z directions. For the detailed information, please refer our previous publication [17].

2.2. Crack models

Crack occurs when the maximum and minimum principal stresses combine for a condition which satisfies the following [18]:

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

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

SIFs based mixed-mode criterion is used to predict crack growth in present work. It assumes cracks start to grow once the following equation for the stress intensity factors is satisfied.

$$\left(\frac{K_{\rm I}}{K_{\rm IC}}\right)^{\alpha} + \left(\frac{K_{\rm II}}{K_{\rm IIC}}\right)^{\beta} + \left(\frac{K_{\rm III}}{K_{\rm IIIC}}\right)^{\gamma} = 1 \tag{3}$$

where $K_{\rm I}$, $K_{\rm II}$ and $K_{\rm III}$ are the stress intensity factors for the fracture modes I, II and III, respectively, which are calculated from the simulation. $K_{\rm IC}$, $K_{\rm IIC}$ and $K_{\rm IIIC}$ denote the individual fracture toughness values of the three fracture modes. The constant parameters α, β and γ should be empirically determined, we taken it as [19]:

$$\left(\frac{K_{\rm I}}{K_{\rm IC}}\right)^{2} + \left(\frac{K_{\rm II}}{K_{\rm IIC}}\right)^{2} = 1 \tag{4}$$

The crack size at initiation and crack growth direction can be predicted by [18]:

$$a_0 = \left(\frac{2}{\pi}\right)\left(\frac{E\gamma}{\sigma_1^2}\right) \tag{5}$$

$$V = 0.38\left(\frac{E}{\rho}\right)^{0.5}\left(1 - \frac{a_0}{a}\right)^{0.5} \tag{6}$$

$$\theta_0 = 2\tan^{-1}\left(\frac{-2K_{\rm II}}{K_{\rm Ieff} + \sqrt{(K_{\rm Ieff})^2 + 8(K_{\rm II})^2}}\right) \tag{7}$$

$$K_{\rm Ieff} = K_{\rm I} + B|K_{\rm III}| \tag{8}$$

where a_0 is the crack initiation size, E is Young's modulus, γ is the crack surface energy, V is the crack growth rate, $2a$ is instantaneous length, that is, a is the crack increment and ρ is the glass density, θ_0 is the crack direction, B is empirical factor and takes 0.1 here.