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Development of a dynamic model for crack propagation in glazing system under thermal loading

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ABSTRACT

The present study reports on the development and validation of a finite element program, GLAZ-CRACK, for predicting crack initiation and propagation of glass in fire or under other thermal loadings. The model is based on three crack modes to calculate the stress intensity factors (SIFs) and strain energy release rates. The crack initiation is predicted from the stress distribution using either probabilistic or deterministic method. The crack growth can be predicted by one of the three criterions, which are SIFs based mixed-mode criterion, energy release rates based mixed-mode criterion and SIFs based maximum circumferential stress criterion. The crack spread rate and crack direction are calculated based on first principles of fracture mechanics. A moving crack tip mesh topology is proposed to locally refine the grid resolution in the tip region. Predictions for the SIFs of a central horizontal crack in a square plate, a central horizontal crack in a long plate and a single edge cracked plate under plane stress condition show good agreement with either the previous predictions of ANSYS or the theoretical values. Exploratory calculations of a single crack under thermal loading have shown that the crack initiation and crack propagation pattern agree with the experimental observations.

1. Introduction

In typical fire scenarios, the breakage and fallout of a glass pane can result in a change of the fire dynamics due to the new supply of fresh air. The fire may develop to flashover depending on conditions or could spread to adjacent rooms. When a window glass pane is exposed to fire or other heating effects, its temperature will increase, resulting in thermal expansion. If such expansion is uneven and not matched by expansion of the window frame, thermal stresses are generated within the pane and this can lead to crack initiation. The risk of breakage of the glass depends on several variables, including stress, edge strength, area under stress, time duration of the stress and presence of edge defects [1]. Once cracks are initiated in the glass, they will propagate with high velocity over 2000 m/s and potentially form some islands [2] which could lead to the fall out of the fragmented pieces and affect the integrity and the performance of the glass structure.

Emmons [3] pioneered the research on glass fracture in fires and found that cracks are induced by the thermal stress resulting from the temperature gradients within the glass pane when it is non-uniformly heated [4–8]. Shields et al. [9–12] carried out a series of experiments to investigate both single and double glazing behavior exposed to fire. They reported on the measurements of heat release rates, enclosure and local gas temperatures, heat flux distributions, glass surface temperatures, shaded glass temperatures thermally induced stains, crack bifurcation patterns and loss of integrity of the glazing assembly. The authors concluded that temperature difference at first crack was 80 °C [9–12]. Skelly et al. [13] found that the temperature difference between the pane centre and the edge was 90 °C when the first crack was initiated. Keski-Rahkonen [4] predicted the theoretical temperature difference for crack initiation to be 70 °C. Chow et al. [14] also investigated glass breakage in fires experimentally and conducted theoretical analysis of the resulting thermal stress. It was found that the temperature difference between the glass pane and the material covering the cold edge is important for fracture initiation [14]. Xie et al. [15] conducted a series of full-scale experiments in an ISO 9705 fire test room using pool fires with different pan sizes positioned at the centre of the room. The results suggested that the whole piece of the toughened glass cracked and fall out completely when any region of the pane broke.

Among the theoretical studies, Joshi and Pagni [6,7] developed a three-parameter cumulative Weibull function as breakage criterion, which has since been widely used. Pope and Bailey [16]

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Nomenclature

a_0	critical crack length in the Griffith theory, m
a	crack increment, m
B	empirical factor for combination of K_{I} and K_{III}
$\mathbf{C}$	damping matrix
$\mathbf{D}$	elasticity matrix
E	Young's modulus, Pa
G_{I}, G_{II}, G_{III}	strain energy release rates, J/m^2
G_{IC}, G_{IIC}, G_{IIIC}, G_{C}	ultimate energy release rates, J/m^2
k	Kolosov constant
$\mathbf{K}$	stiffness matrix
K_e	final effective stress intensity factor, Pa (m)$^{0.5}$
K_{Ieff}	effective stress intensity factor, Pa (m)$^{0.5}$
K, K_{I}, K_{II}, and K_{III}	stress intensity factors, Pa (m)$^{0.5}$
K_{IC}, K_{IIC} and K_{IIIC}	fracture toughness, Pa (m)$^{0.5}$
m	shape parameter in Weibull distribution
$\mathbf{M}$	mass matrix
$\mathbf{P}$	global vector of nodal forces
$\mathbf{Q}$	global vector of nodal displacement
r	average distance from the crack tip node to adjacent nodes, m
$\mathbf{R}$	vector of externally applied loads
S_{ut}	glass ultimate tensile strength, Pa
S_{uc}	ultimate compressive strengths, Pa
t, Δt	time, time increment (time step), s
ΔT	temperature difference, K
$\mathbf{U}$	displacement vector of the finite element assemblage
$\dot{\mathbf{U}}$	velocity vector of the finite element assemblage
$\ddot{\mathbf{U}}$	acceleration vector of the finite element assemblage
V	crack speed, m/s
x_n, x_b, x_t	global coordinates in the directions of normal, binormal and tangent to the crack front
α	coefficient of linear thermal expansion, 1/K
α, β and η	constant parameters used in crack growth criterion
γ	crack surface energy, J
ε and δ	Newmark parameters
$\vec{\boldsymbol{\varepsilon}}_0$	initial strain vector
$\vec{\boldsymbol{\varepsilon}}$	strain vector
$\vec{\boldsymbol{\sigma}}$	stress vector
θ_0	growth angle
ν	Poisson's ratio
σ_0	scale parameter in Weibull distribution, Pa
σ_1, σ_2 and σ_3	principal stresses, Pa
σ, σ_x, σ_y and σ_z	stresses, Pa
σ_b	Weibull random variable, a given stress, Pa
σ_t	tensile stress, Pa
σ_u	location parameter in Weibull distribution, Pa

Subscripts

min	minimum value
max	maximum value

developed a Gaussian glass breakage model and implemented it in the Fire Dynamics Simulator (FDS) [17]. Fewer studies have investigated the three dimensional thermal stress and crack growth in glass under thermal loadings [14,18,19]. Although Chow and Gao [14] calculated the specified thermal stresses for the given cases by the fitted temperature correlation, they did not generalize it into a thermal stress model which could be applied to other glasses. Recently, Tofilo and Delichatsios [12] developed a simple lumped model to predict the time of the first crack, but the temperature difference between the glass temperature and ambient temperature must be assumed.

Crack propagation is a basic mechanism which leads to material failure. Fast fracture generally occurs through rapid crack propagation. Among the literatures, much attention has been focused on the crack formation and propagation in polymers [20], metals [21], rocks [22], glass [23,24], layered materials [25] and others [26,27] under normal mechanical loadings. Less effort has been devoted to the dynamic crack propagation process especially for crack propagation induced by thermal stress.

Crack growth simulation based on stress is the process of modeling crack evolution in a structure through time or with increasing load. This encompasses all aspects of the modeling process from initial data preparation to visualization of results, prediction of crack growth and evaluation of structural integrity. Although many commercial programs can perform an accurate stress analysis of a cracked structure, they cannot generally predict the onset of the cracks and their subsequent propagation.

The present study aims at developing a numerical model for crack initiation, propagation and fall out in glass or other brittle materials under thermal loading. A dynamic thermal stress and crack propagation program has been developed to simulate the crack initiation and propagation for glass under thermal loading using fracture theory. The predicted thermal stress distribution and stress intensity factors (SIFs) have been compared with published results for selected validation cases.

Upon initiation, a crack in a glass pane will propagate rapidly. The sequential initiation of multiple cracks leads to the formation of islands away from the frame. The fall out of the glass portions in these islands affects the integrity of the whole structure. It is therefore important to predict the crack initiation and its propagation path. The novelty of the present study is that a three-dimensional stress approach is developed for predicting crack initiation in a glass pane under thermal loading and its propagation path. The approach has the advantage of predicting the size of the falling pieces of glass and subsequent vent dimensions. It has been implemented in a computer program which can easily be combined with CFD tools such as FDS (Fire Dynamics Simulator) for a more dynamic coupling between the fire and glass response.

2. Mathematical modeling

2.1. Thermal stress modeling

Cracks are caused by the stress accumulated within the glass pane. In the present study, the main cause of breakage is the thermal stress induced by the temperature difference within the glass pane. Although the constraint by the window frames will inevitably induce mechanical stresses following expansion of the glass pane in elevated temperatures, the maximum expansion for the glass pane is less than the gap between the frame and the glass in the experiments in most cases. And so stresses induced by frame are not considered in the present stage of the research.

Temperature loading acts as a residual stress, it is the integral of the negative thermal stress. Numerical integration requires the knowledge of the temperature at the integration points. If the temperatures are given in the nodes, an interpolation has to be performed to obtain the integration point values. In the present work, the glass pane zone is firstly divided into a number of blocks, and then temperature as thermal loads are introduced into