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Yu Wang

Experimental and Numerical Study of Glass Façade Breakage Behavior under Fire Conditions

Fire Safety Engineering

Doctoral Thesis accepted by
the Chinese Academy of Sciences, Beijing, China

Springer

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Supervisor’s Foreword

Glass breakage in the fire has long been an important area in fire safety engineering. However, high rise buildings are increasingly constructed with glass façades of different types and installations, so the findings gathered for window glass cannot be directly extrapolated to such conditions. As glass façade is a non-structural and non-flammable element in case of a fire, the study of its thermal breakage behavior is always ignored and thus extremely limited despite its great significance to the enclosure fire dynamics.

Thus, the research of Dr. Wang is a significant contribution in the research of glass façades breakage behavior under fire conditions.

In this thesis, both compressive experimental and numerical investigations were conducted. First of all, full-scale frame and point-supported glass façades, incorporating single, double and coated glazing, were tested under pool fire conductions. The results determined the effects of different glass frames, glass types, and thermal shocks on breakage behavior. Small scale tests, using a Material Testing System (MTS) 810, Netzsch Dilatometer and FE-SEM, were performed at different temperatures to obtain the mechanical properties of glazing in fire. On the other hand, a three-dimensional dynamic model was developed to predict the stress distribution, crack initiation and propagation, which was meanwhile employed to reveal the breakage mechanism of different types of glass façades. The numerical results showed very good agreement with experimental results and verified the model to be capable of accurate breakage prediction. In addition, a theoretical model based on incident heat flux was developed to predict the breakage time and heat transfer in glazing. The interaction between fire and glass was thus revealed.

This thesis provides a theoretical and practical basis for fire safety optimization of glass design and significantly furthers our understanding of this important fire safety issue, which will serve as an important reference for any further research in this area.

Hefei, China
January 2019

Prof. Jinhua Sun

Abstract

In comparison with steel and concrete structures, glass facades are brittle, have much lower strength, and thus crack more easily under stresses, which make this kind of wall more prone to breakage and falling out in fire scenarios. The loss of facade integrity may also provide a channel for fresh air to enter the compartment and an outlet for the fire to spread, thereby accelerating fire development. Both flashover and backdraft could also occur resulting from such glass breakage.

The accurate prediction of glass facade breakage behavior is important to furthering our understanding of fire development and spread. However, almost all previous works were focusing on ordinary window glass. High rise buildings are increasingly constructed with glass façades of different types and installations, so the findings gathered for window glass cannot be directly extrapolated to such conditions. As glass façade is a non-structural element and nonflammable in case of a fire, the study of its thermal breakage behavior is always ignored and thus extremely limited despite its great significance to the enclosure fire dynamics. Therefore, new research in the modeling of thermal breakage of glass façades must be initiated.

This study aims to provide fundamental and in-depth investigation of breakage mechanism of glass façade in fire and reliable prediction approaches for its thermal breakage behavior. Laboratory experiments and a self-developed finite element program are the basis of the thesis.

In the experiments, full scale frame and point supported glass façades, incorporating single, double and coated glazing, were heated by a 500 × 500 mm^2 N-heptane pool fire. Sheet and sheathed K-type thermocouples were used to measure the glass surface and gas temperatures. A Gardon water cooled heat flux gauge, mounted flush to the surface of the glass sections, was employed to measure the incident heat flux on the glass. The heat release rate (HRR) of fire was calculated by the mass loss rate recorded using an electrical balance. The whole experimental process was recorded by standard video cameras with a framing rate of 50 frame/s. In addition, small scale tests, using Material Testing System (MTS) 810, Netzsch Dilatometer and FE-SEM, were performed at different temperatures to obtain the basic data of glazing.

In the numerical simulation, instead of focusing on the temperature difference, a three dimensional dynamic model was developed to predict the stress distribution, crack initiation and propagation. The model was based on three crack modes to calculate the stress intensity factors (SIFs) and strain energy release rates. The crack initiation was predicted from the stress distribution using either probabilistic or deterministic method. The crack growth can be predicted by one of the three criterions, which were 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 were calculated based on first principles of fracture mechanics. A moving crack tip mesh topology was proposed to locally refine the grid resolution in the tip region. This method is applicable for different types of glass façades due to focusing on dynamic thermal stress distribution upon glass.

A total of sixteen full scale tests were firstly performed to investigate the breakage behavior of fully exposed, horizontal-hidden, vertical-hidden and fully hidden framing coated glass façades. Critical parameters, such as the time of breakage occurrence, crack initiation and propagation, heat release rate, incident heat flux, central gas temperatures, glass surface temperatures and loss of integrity of the glazing assembly, were recorded. It was established that semi-exposed framing glass façades demonstrate greater fire resistance than fully exposed framing façades. Meanwhile, the fire resistance of hidden framing glass façades defers markedly when fire location changes. Radiation from the fire source dominates the heat exchange form to heat glazing in open space. The critical breakage condition of solar control coated glass was determined. To reveal this experimental result, Coulomb-Mohr criterion and SIFs based mixed-mode criterion were selected to predict the crack initiation and growth, respectively. The temperature measured in experiments was used as thermal loading. The time of first breaking, the first principal stress field, crack initiation and propagation were calculated and simulated. The numerical results agree well with experimental results. Excessive thermal stress resulting from temperature gradient in glazing is considered the predominant cause of framing glass breakage. All the cracks were initiated from the glass edges whatever the installation type is, but the crack initiation is located only at the frame covered edges. The stress distribution simulated using the finite element method (FEM) revealed the breakage mechanism of four different framing glass façades.

To investigate thermal performance of point-supported glass breaking behavior, a set of full scale twenty four glass panes with a dimension of $1200 \times 1200 \times 6$ mm^3 were tested. Because of their large size and structural characteristics, the glass panes have different breaking mechanisms and behavior from those identified in prior studies of edge-covered glazing. The results indicate that changes in fixing location have a considerable effect on point-supported glass façades: the closer to the horizontal or vertical center line the fixing points are located, the shorter the time a pane will take to fall out. Horizontal changes are much more sensitive than vertical changes. When the supporting points are located at 10 or 5 cm from the edges, panes show better fire resistance. The glass panes studied exhibited three kinds of breaking pattern, and direct fallout was most common, which normally occurred during the steady state of fuel combustion. It was proved that the

mechanism of breaking is the combined effect of thermal stress and mechanical stress around fixing point from where almost all cracks were initiated. The fallout fraction of point-supported glass panes is significantly more than that of edge-covered glass panes. To reveal the breakage mechanism of point supported glass breakage, uniform and non-uniform thermal loading were applied. At the fixing points, maximum tensile stress was found generated, and because of drilling holes for installation, many tiny flaws or defects exist that will facilitate the crack initiation in these areas. It was established that thermal gradient in glass may accelerate the breakage significantly, but the stress caused by fixing constraint is dominant. The simulation results agree well with experiments in terms of variation trend of breaking times, position of crack initiation, crack propagations. The mechanism of point supported glass was revealed using FEM.

A theoretical prediction model based on incident heat flux was developed to predict the breakage time and heat transfer in glazing. It was verified through conducting experiments with the fire location changed in the glass thickness direction. The fire resistance of float and tempered glass was compared and analyzed. The critical breakage conditions of single and double glazing were determined. It was also found that framing glass is more prone breakage when fire positioned at the center of pane, while point supported glass is likely to break only when the fire located at fixing point.

To investigate the micro-mechanism of breakage, a total of 71 quasi-static tensile experiments were performed at temperatures from 25 to 400 °C. The results indicate that both surface treatment and glaze temperature have significant influence on glass strength. At approximately 100 °C, critical stress reached the minimum value at which glass breakage occurs most probably. The basic properties of glazing, such as surface flaw, coefficient of linear expansion and elasticity modulus, were also obtained to evaluate the critical temperature difference a glass pane can withstand in a fire.

On the basis of the experimental and numerical results, recommendations for the fire safety improvement of glass façade are proposed. Suggestions for possible further work are made.

Keywords Breakage behavior · Glass façade · Finite element method · Installation form · Fire location · Critical condition · Micromechanism

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Nomenclature

A	Glass area (m^2)
E	Energy (kJ)
c	Specific heat conductivity (J/(kg K))
g	Acceleration of gravity (m/s^2)
h	Heat transfer coefficient (W/(m^2 K))
I	Radiation heat flux (kW/m^2)
k	Thermal conductivity (W/(m K))
L	Burner-glazing distance (m)
m	Mass (kg)
Nu	Nusselt number (–)
q	Heat flux (kW/m^2)
Ra	Rayleigh number (–)
T	Temperature (K/°C)
t	Time (s)

Greek

α	Thermal diffusivity/Combustion efficiency (–)
β	Thermal expansion co-efficient (1/K)
Δ	Difference (–)
δ	Glass thickness (m)
ε	Emissivity (–)
E	Modulus of elasticity (Pa)
κ	Absorption coefficient (1/m)
ν	Poisson's ratio (–)
ρ	Density (kg/m^3)
σ	Stress; Stefan-Boltzmann constant (–)
τ	Transmissivity (–)

Subscripts

c	Center of glass pane
cond	Heat conduction
conv	Heat convection
g	Generation; Bulk glass
0	Shaded glass edge/Scale value of Weibull distribution
R	Reference
rad	Radiation
s	Surface
st	System
sur	Surface
tot	Total
tr	Transmitted
u	Location value
∞	Ambient