Fire Safety Journal 101 (2018) 18–24

Contents lists available at ScienceDirect

Fire Safety Journal

journal homepage: www.elsevier.com/locate/firesaf

Determination of critical fallout condition of tempered glass in an enclosure fire

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ARTICLE INFO

Keywords:
Tempered glass
Fallout
Weibull distribution
Failure probability

ABSTRACT

Tempered glass is extensively used in modern high-rise buildings. However, in some instances the glass will break and fall out when subjected to a fire which will create a new ventilation condition, drastically changing the enclosure fire dynamics. In this work, eleven tempered glass panels with dimensions of $815 \times 815 \times 6\,\text{mm}^3$ were heated by a pool fire placed in the center of a $1000 \times 1000 \times 1000\,\text{mm}^3$ compartment. Parameters such as glass surface temperature, heat flux, failure time and fallout behavior, were all recorded. Weibull distributions were then employed to investigate the probabilistic characteristics of tempered glass fallout. Failure probability functions, survival probability functions, and failure probability density functions of tempered glazing were obtained and compared with those of clear and coated glazing. The critical temperature difference and critical heat flux, with 5% failure possibility for 6 mm-thick tempered glazing, are 301 °C and 36.17 kW/m^2, respectively, which could be used as a conservative estimate for the safe design of glass façades in a fire.

1. Introduction

Glass façades are increasingly used in modern construction for both their architectural and increased saving abilities due to recent technology deveopments [1]. However, the glass is prone to breakage and fallout when exposed to fire, creating new openings, increasing the air entrainment and external fire spread potential, and significantly changing the compartment fire development and dynamics. Emmons first highlighted this issue as an important structural problem [2], and subsequently a large number of studies have been conducted to investigate the glass breakage mechanism. For example, Keski-Rahkonen theoretically determined the breakage condition of float glass in a fire and indicated that exceeding thermal stresses within the glass is the critical reason for crack initiation [3]. Pagni et al. developed a simple model, called BREAK1, to predict the window glass breakage time in a compartment fire [4]. Shields et al. performed full-scale tests in ISO 9705 room to study the breakage and fallout behavior of double glazing [5]. Wang et al. developed finite element method (FEM) software EASY to predict the stress distribution and crack path in glazing [6].

However, almost all the previous work focused on the float glass that is normally used in ordinary windows [7]. With developments within construction, glass technology and architectural aesthetic, tempered glass is more frequently being used instead of float glass, especially in high-rise building glass façades, due to its comparatively good thermal resistance and mechanical performance at ambient and high temperatures [7,8]. It is anticipated that the thermal behavior of tempered glass is very different from float glazing and the limited knowledge about it will inevitably bring potential fire risk and uncertainty during the fire performance-based design [9]. Thus, it is becoming necessary to investigate the breakage and fallout behavior of tempered glass.

Manzello et al. [10] conducted a real scale compartment fire to investigate the behavior of single and double-pane tempered glass. Klassen et al. [11] tested seven different tempered glazing samples. Nevertheless, no repeated tests were performed. To the authors' knowledge, there is no research that systematically determines the critical breakage condition of tempered glass in fire, especially its probabilistic failure characteristics [7,10]. In the present work, eleven experiments were repeated in a model fire compartment and the Weibull distribution was employed to deepen the understanding of its crack probability of a glass bearing certain temperature and heat flux. The specific details of experimental results and analysis are shown in the following sections.

2. Experimental setup and theoretical principles

A total of eleven tempered glass panels, with a dimension of $815 \times 815 \times 6\,\text{mm}^3$, were installed in the front wall of a

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https://doi.org/10.1016/j.firesaf.2018.08.010
Received 29 January 2018; Received in revised form 4 July 2018; Accepted 15 August 2018

Nomenclature

f	Probability density function
F	Failure probability function
q	Heat flux (kW/m^2)
S	Survival probability function
t	Time (s)
T	Temperature (°C)

Greek

β	Shape parameter
η	Scale parameter
γ	Location parameter
Δ	Difference

Subscripts

1–5	Thermocouple number
cf	Clear float
cc	Clear coated

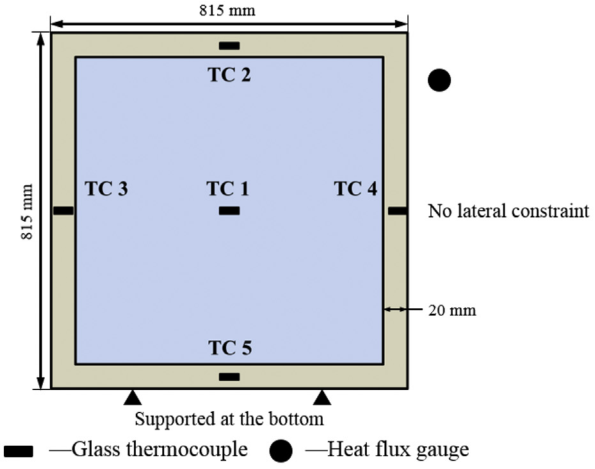
$1000 \times 1000 \times 1000\,\text{mm}^3$ compartment, as shown in Fig. 1(a). The walls of this enclosure were constructed of 5 mm stainless steel lined with 20 mm-thick plasterboards. The glass panel was placed vertically in the square groove which is slightly larger than the dimension of glass ($815 \times 815\,\text{mm}^2$). Then the metal frame was placed on the glass and fixed by the four screws at corners, as shown in Fig. 1(a). A gasket, namely 5 mm thick ceramic fibre blanket, was inserted between the glass and frame to simulate the insulation condition. Thus, there is no constraint from the frame perimeter, but only the constraint in the thickness direction. The pressure in the thickness direction was not measured but the screw was marked during each installation process to make sure the pressure in all tests was identical. The width of covered areas was 20 mm. The glass pane edges were polished. The physical properties of these samples were not measured, but its corresponding float glass (the same raw materials) properties were measured by the authors: the elasticity modulus is 67.21 GPa; linear expansion coefficient is 8.46×10^{-6} [12]. These two parameters are always considered identical to tempered one. The ultimate stress of tempered glazing is 4–5 times of float [13] which should be in the range of 143–179 MPa as per float glass 35.72 MPa [12]. A $200 \times 200\,\text{mm}^2$ square heptane pool fire was placed at the center of the compartment, and a ventilation opening of $200 \times 1000\,\text{mm}^2$ was incorporated into the back wall of the compartment to ensure the continuous burning. In each test, the fuel of 1800 mL kept burning for more than 400 s so that the glass panel would fail before the fire extinction.

Five K-type sheet thermocouples (TC), with a measurement range of 0–1200 °C and sensitivity of 41 μV/°C, were attached on the glass surface using highly thermal conductive adhesives. Among the five thermocouples, four were attached to the covered area and not affected by the flame radiation. The temperatures measured in the covered area are considered relatively accurate. The central sheet TC was covered by high-temperature resistance tape to avoid radiation. What is more, the sheet thermocouples increased the contact area between the glass and thermocouple which ensure the reasonable measurement. Thus, the uncertainty of TCs for glass temperature measurement was estimated at 10–20% under fire conditions [14]. A water-cooled total heat flux (HF) gauge with a measurement range of 0–100 kW/m^2 was placed flush to the glass surface to measure the incident heat flux. The responsivity of the gauge is 0.0906 mV/(kW/m^2) and the uncertainty in a fire environment was ± 8–14% [8]. A data acquisition system with 16 channels for thermocouples and heat flux gauge was used with the sampling frequency of 1.0 Hz. The distribution of thermocouples and heat flux is shown in Fig. 1(b).

Due to the uncertainties involved in glass physical properties, a probabilistic rather than a deterministic approach is needed to determine the critical fallout condition of tempered glass in the fire. The cumulative Weibull function was employed to describe the distribution of the measured parameters. The three-parameter Weibull function is [4,15]:

$$F(x) = 1 - \exp\left[-\left(\frac{x-\gamma}{\eta}\right)^{\beta}\right] \quad x \geq \gamma \tag{1}$$

(a) The compartment model



(b) Distribution of TC and HF on fire-exposed surface

Fig. 1. The experimental setup and measurement instrument distribution. (a) The compartment model; (b) Distribution of TC and HF on fire-exposed surface.