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Experimental study on fallout behaviour of tempered glass façades with different frame insulation conditions in an enclosure fire

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To the authors' knowledge, no research concerning the effect of frame insulation on tempered glass fallout behavior has been performed in a real compartment fire. The interaction of glass fallout and enclosure fire as a fundamental issue may also need to be understood from the perspective of glass behaviour. This manuscript is proposed to deepen the understanding of above issues through 8 compartment fire tests. **Therefore, this topic is within FIRE RESEARCH.**

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All the Figures in the paper can be printed in white and black color.

Thanks very much.

Abstract

Tempered glass is a safety glass required by fire codes for use in building façade systems. However, as previous studies were primarily focused on the ordinary float glass, little is known about the fire performance of tempered glass panels and the interaction between its fallout and enclosure fire dynamics. In this study, eight small-scale experiments investigated the influence of frame insulation conduction on the fallout behaviour of tempered glass. Tempered single-glazing panels, 815×815 mm^2 and 6 mm thick, were installed in the front wall of a compartment with a dimension of 1000×1000×1000 mm^3. The glass panels were heated by a square pool fire of 200×200 mm^2, positioned at the compartment center. Glass frames were made of either stainless steel or insulated materials, and important parameters, including the fallout time, glass surface temperature, hot gas temperature, incident heat flux and heat release rate of pool fire, were recorded. The experiments showed that the critical temperature difference and heat flux of tempered glass are respectively around 340 °C and 46 kW/m^2, which are significantly larger than those for float glass panels. The frame with higher thermal conductivity can increase the fire resistance of the glazing systems. The occurrence of glass fallout may cause unexpected ejected flame with a height of more than 2 m and has a significant influence on the fire growth, temperature distribution and neutral plane height in the compartment (i.e. the zero pressure plane). The results can deepen the understanding of glass fallout in fire and propose to provide the reference to glass façades fire safety design in practical engineering.

Keywords: tempered glass; compartment fire; breakage and fallout; frame condition

1. Introduction

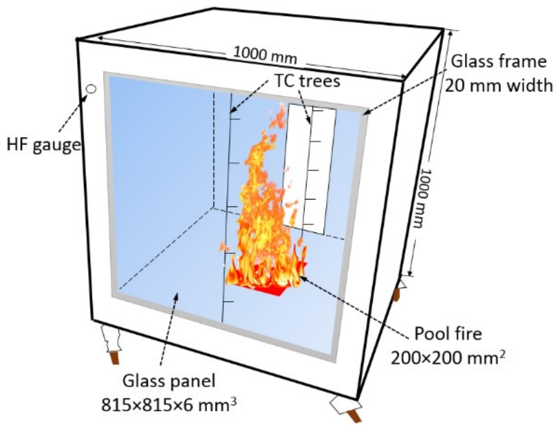
Glass façades are extensively used in high-rise buildings for both architectural and increased energy saving abilities due to recent technology developments [1]. However, unlike steel and concrete, when subject to a fire, glass may break and may fall out when used in façade framed systems due to exceeding thermal stresses; glass façade systems are thus considered as the weakest part of a building envelope [2]. This issue was first highlighted by Emmons [3] as an important structural problem that may dramatically accelerate compartment fire development. Subsequently, a large amount of work has been performed to understand glazing breakage mechanisms and predict the breakage time of ordinary float glass window [4-7]. A consensus has been reached that the thermal gradient across the glass panel is the primary cause for its crack initiation during a fire. Very limited research was performed to predict the fallout of glazing [8-10] which is affected by various factors, such as frame details, window aspect ratio and heating intensity [4].

Glass façades may be installed in different forms and employs various kinds of glass that markedly differs from ordinary window glazing. The research on window glass, with limited consideration of above glass façade characteristics, cannot be directly applied in the glass façade fire performance prediction, which considerably hinders the development of fire performance-based approach and brings potential fire risk to high-rise buildings [11]. Significant efforts in the fire performance of glass façade systems have investigated issues such as: different orientations (e.g. vertical and inclined) [12], fire location [13], smoke movement [14], installation form (e.g. exposed, horizontal hidden and vertical hidden frame) [15], glass types [10] and edge condition (e.g. as-cut, ground, and polished) [16]. Nevertheless, these previous studies focused on float glass rather than tempered glass, with the latter being the predominant glazing type adopted for building envelopes. What is more, some local fire codes require that only safety glass, namely tempered glass or its derivative product, can be used in building façades [17]. The knowledge paucity in tempered glass, coupled with evermore innovative and extensive glass façades systems, makes it difficult for building envelopes to comply with fire safety codes [11, 18]. Thus, it is necessary to study further the fire behaviour of tempered glass façade systems and in particular, as thermal gradients are critical for glass breakage, the properties of the frame, especially its thermal conductivity coefficient is anticipated to be a significant factor for the behaviour of the tempered glass panels. Despite the significance of this issue [5], very limited work concerning the effect of frame insulation has been examined in a compartment fire scenario. Skelly et al. [7] conducted small compartment fire to study the glass behavior with and without a frame, but only float window glazing was investigated. What is more, the interaction of glass fallout and enclosure fire need to be further understood as well [4].

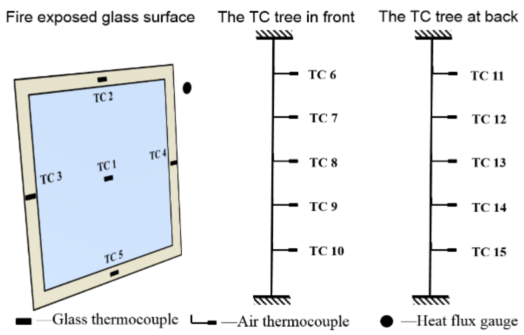
In this work, a model compartment was carefully designed and built to satisfy the experimental requirement and purpose. The exposed framed glass panels were heated by a pool fire located in the center of the compartment. The behaviour of tempered glass in a fire and the effects of frame conduction on the glass panel failure were analyzed.

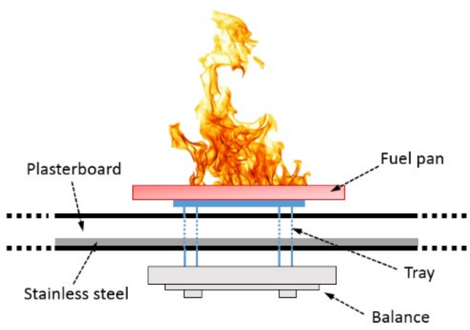
2. Experimental setup and design

A compartment with an external dimension of 1000×1000×1000 mm^3 was built to resemble the fire conditions in glass façade furnished buildings, as shown in Fig. 1(a). In the compartment model, one face of the wall is totally glass and its opposite side is a door which is to resemble the office in the high-rise buildings. The walls of this enclosure were constructed of 5 mm stainless steel lined with 20 mm-thick plasterboards. To the authors' knowledge and survey, an estimated range of glass façade panel dimension is from 300×300 mm^2 to 6000×6000 mm^2, tempered glass panels of 815×815 mm^2, 6 mm thick, were installed into the front wall in the present work. The glass frame was made of 1 mm thick stainless steel and capable of installing glass panels with different thicknesses. Stainless steel was selected due to its relatively stable behavior in fire compare with other frame materials, such as aluminium extrusion, timber or plastic. In each test, the pressure from frame to the glass in the thickness direction was controlled by four screws. Since the maximum expansion, less than 1 mm, is smaller than the normal gap of several mm between the frame and the glass panel [4, 19], no in-plane restraint from the frame existed in the experiments, thus simulating realistic conditions as closely as possible. In addition, a ventilation opening of 200×1000 mm^2 was incorporated into the back wall of the compartment and a pool fire with a dimension of 200×200 mm^2 was positioned at the center of the compartment. The opening factor of the compartment was 0.033 and is representative of an office the size of 3.4×3.4×3.4 m^3 (assumption of the door size of 0.8 x 2.0 m^2). The fuel used in the experiments, whilst not fully representing the mainly cellulosic fuels found in offices, was chosen due to its repeatability in burning behaviour in the pre-glass breakage phase of the experiments. The setup is suitable for the investigation purpose despite its dimension and condition are different from real situations.



(a) The compartment





(b) Distribution of heat flux gauges and thermocouples (c) Fuel mass loss measurement

Fig. 1. The schematic of compartment used for the experimental tests.

The measurement systems included the sheet and sheathed thermocouples (TCs), heat flux (HF) gauge, mass loss balance, digital camera and data acquisition. The sheet thermocouples were attached to the glass panes to detect the surface temperature via their high heat-conducting sheets, which is made of aluminium alloy with a high heat conductivity of 226W/m·K. The dimension of sheets is approximately 25×15 mm^2, thus it can increase the contact areas between detected objects and a temperature-sensing element. Two TC trees, 30 mm away respectively from the glass wall and back wall, were positioned at the center line of the compartment, as shown in Fig. 1(a). In each tree, five sheathed thermocouples were fixed equidistantly (158 mm) to measure the gas temperature. Meanwhile, five sheet thermocouples were employed to record the glass surface temperatures at the fire side: four TCs were attached in covered areas and only one at the center of the fire-exposed surface. It should be noted that both sheathed and sheet TCs were K-Type thermocouples with a measurement range of 0-1200 °C and sensitivity of 41 mV/°C. The uncertainty of TCs was estimated at 10-20% [20].

What is more, a Gardon water-cooled heat flux gauge, which could measure total or radiation heat flux (with sapphire window), was mounted flush to the surface of glass panel. Its measurement range was 0-100 kW/m^2 and located in the upper layer that is assumed to be the location where the maximum incident heat flux occurs. The uncertainty of heat flux in such fire environment was estimated ~±7-16% [21, 22]. The specific distribution of TCs and HF gauge is illustrated in Fig. 1(b). Moreover, an electronic balance, with a measurement range of 0-32100 g and accuracy of 0.01 g, was used to record the fuel mass variance during combustion. Two digital cameras with a framing rate of 50 were employed to monitor the glass and fire behaviour from the front and back views. To avoid the balance working in a high-temperature environment, it was positioned under the compartment and an additional tray was used as a supporter of fuel pan, as shown in Fig. 1(c). The mass loss of fuel (99.9% n-heptane) was recorded to calculate the heat release rate (HRR) the 200×200 mm^2 square pool fire. The combustion efficiency factor was taken as 0.75 [23].

In this work, single tempered glass panels with a dimension of 815×815 mm^2, 6 mm thick, were installed in the exposed framing and the perimeter shading width was 20 mm. In addition, the fuel mass of 1800 mL and ventilation opening of 200×1000 mm^2 were identical. To achieve the investigation purpose, the heat conduction conditions of framing were significantly different. A total of 8 tests were conducted in the compartment: Test 1-4 (Case 1) and Test 5-8 (Case 2) are replicated. In Case 1, namely Tests 1-4, ceramic fibre blanket with a thickness of 5 mm was fixed between the stainless outer frame (1 mm thickness) and glass panel. This gasket with a very low heat conductivity coefficient of 0.035 W/(m·K) could withstand a high temperature of ~1300 °C, which was used to simulate the conservative heat conduction condition of glass façade framing (normally ~0.21W/(m·K)). The lower the framing thermal conductivity is, the more non-uniform the temperature distribution will be. In this work a ceramic fibre gasket was used, which may cause glass breakage more readily than in real conditions, so the results presented can be considered as conservative. In Case 2, namely Tests 5-8, by removal of gasket, the glass panel was directly installed into the stainless framing. The constraint between glass panel and frame was adjusted by the screws to render it identical to that in Case 1. The heat conduction coefficient of stainless framing was 16.0 W/(m·K). All the tests are summarized in Table 1 and all experiments ran until all the fuel was consumed which was approximately 400 s.

Table 1

The summary of experimental tests.

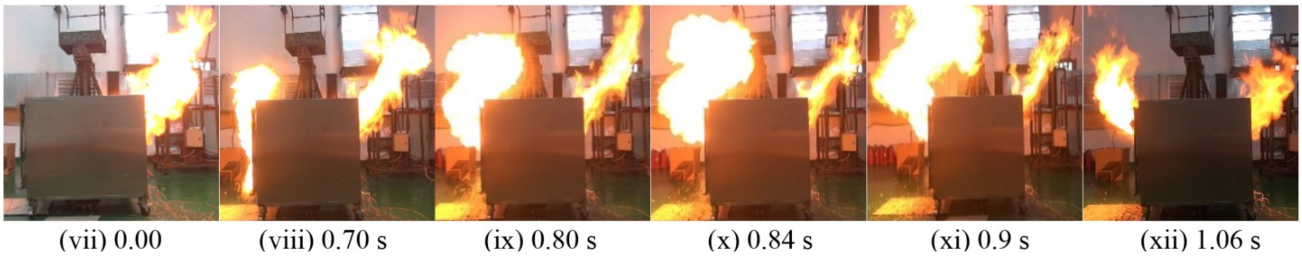
Cases	Test number	Framing condition	Burning duration (s)
Case 1	Test 1	With ceramic fibre gasket	402
	Test 2	With ceramic fibre gasket	423
	Test 3	With ceramic fibre gasket	401
	Test 4	With ceramic fibre gasket	413
Case 2	Test 5	No gasket	435
	Test 6	No gasket	397
	Test 7	No gasket	405
	Test 8	No gasket	387

3. Experimental results

3.1 Fallout behaviour

Fallout of the tempered glass, if critical breakage conditions were satisfied and cracks initiated, occurred very quickly. As an example, the failure of Test 3 is shown in Fig. 2(a). The process only took 0.70 seconds from the crack initiation to complete fallout. It appears that two primary cracks initiated from the top edge of the glass panel and dominated the first 0.2 seconds of breaking. Once the glass had started to fall out, the fallout of the glass allowed a portion of the ejected fuel vapours to ignite outside the compartment. Meanwhile, the whole glass panel broke into a large number of small pieces and started to fall out. This phenomenon occurred in other tests as well. The crack initiation and propagation process at the very beginning were similar to that of float glass, however, more “islands” could be formed in tempered glazing which renders it much easier to fall out.

(a) Breakage and fall out



(b) Side view of window-ejected flame (glass located at left side)

Fig. 2. The process of glass fallout and flame spread in Test 3.

It took less than a second between the initiation of cracking and glass fallout to have finished. As the times of crack initiation and fallout are nearly identical, the fallout time is selected to present the failure of tempered glazing. The fallout time and fraction are listed in Table 2. In Case 1, Tests 1-4, all the glass panels broke due to the temperature difference at the intersection of the exposed and covered glass areas. The fallout times vary in a very small range of 333-369 s.

Table 2

The fallout time and fractions.

Cases	Test number	Fallout fraction (%)	Fallout time (s)	Average (s)
Case 1	Test 1	100	333	351
	Test 2	100	358	
	Test 3	100	343	
	Test 4	100	369	
Case 2	Test 5	0	No crack	387

Test 6	0	No crack
Test 7	100	387
Test 8	100	381 (excluded)

For Case 2 (no ceramic fibre gasket), in Tests 5 and 6, the glass panels remained completely intact without any crack throughout the test. Meanwhile, the glass panel in Test 8 broke only 6 s before the end of burning when the fire suddenly decayed. In the case of Test 8, it seems that the breakage was dominated by the rapid cooling from natural convection rather than the high-temperature environment, so the intra-stress from quenching may be responsible for its cracking [24]. Thus, in Case 2, three of four glass panels effectively withstood the intensive fire heating, and thus the average fallout time of Case 2 is only based on the result of Test 7. The glass fallout time of the remaining Test 7 was 20-50 s longer than tests in Case 1. The results indicate that the heat in steel frame rapidly transferred to the covered areas of glazing significantly reduces the temperature difference in glass and extends the breakage time.

Fig. 2(b) demonstrates the ejected flames after the glass completely fell out. The glass fallout affects the ventilation to the compartment which in turn affects the fire dynamics both to the interior and exterior of the compartment. At the front side, the flame with large momentum spread quickly in both horizontal and vertical directions, with the largest visible flame height of 2.1 m above the glass top edge and the largest horizontal distance of 0.7 m from the glass surface. A scale ruler software was used to measure the visible flame dimension in video and pictures using the compartment size as a reference. In the other tests, the ejected flame heights were all above 2.0 m. After 0.36 s, the burning went back to the new stable status again. The ventilation-controlled fire in the fully developed stage switches to a fuel-controlled fire due to glass fallout. Because of the significant effect of glass fallout, we can define the compartment fire development as pre-fallout and post-fallout stages. The effect of ventilation changes on the critical fallout parameters is discussed in the following section.

3.2 Determination of critical fallout condition

To investigate the influence and proportion of different sources of heat flux, both the imposed radiation heat flux from the flame (in Test 3) and total heat flux from the flame and the smoke (radiation, convection, conduction in the remaining tests) were recorded and compared. The parameters in Test 3 are shown in Fig. 3. According to HRR variance, the flashover occurred at around 250 s. From T_{11}-T_{15}, the height of neutral plane decreased gradually until the glass fallout, which can be explained simply but the ideal gas equation: the gas density decreased with the increase of temperature. In addition, the following equation can directly estimate the phenomenon [25]:

$$h_N = \frac{H_o}{1+(\rho_a/\rho_g)^{1/3}} \tag{1}$$

$$\rho_g = \frac{353}{273+T_g} \tag{2}$$

where h_N and H_o are the neutral plane height and vent height; T_g and ρ_g are enclosure gas temperature and density; ρ_a is the density of air outside the room. Moreover, the exposed glass surface temperature measured by TC1 started to increase much faster than the temperatures in covered areas at around 250 s and the glass fell out at 343 s. At the post-fallout stage, it was found that the T_6-T_{10} were cooled down rapidly from 800 °C to 400 °C. Meanwhile, the T_{13} declined markedly, which indicates the neutral plane moved higher relative to the floor. The similar phenomena occurred in the other tests.

In HRR curve, it indicates a spike just after the flame ejection (291 s) occurs and is also volatile up until about 350 s. However, it did not change the HRR greatly which stabilized between 400-600 kW. With consideration of the noise in the compartment, this HRR is reasonable. Meanwhile, the incident radiation heat flux (front side) decreased by 60%, and then slightly increased due to the glass fallout. This change in heat flux suggests that the flame radiation, rather than the smoke radiation, dominated the imposed radiation received by the glass panel.

The experimental conditions are assumed identical, and the comparison of imposed total and radiation heat fluxes is illustrated in Fig. 4. It was established that convective heat transfer usually accounts for more than 80% of the glass heating, except during the flashover phase where it is approximately 60%. The convective heat transfer is shown to be the primary heat exchange mechanism between the glass panel and the enclosure fire. This is markedly different from the glass heating in open space where convective heat transfer accounts for less than 15% of the total heat exchanged [15]. The difference between free burning tests and compartment fire tests is primarily caused by the smoke or hot gases.

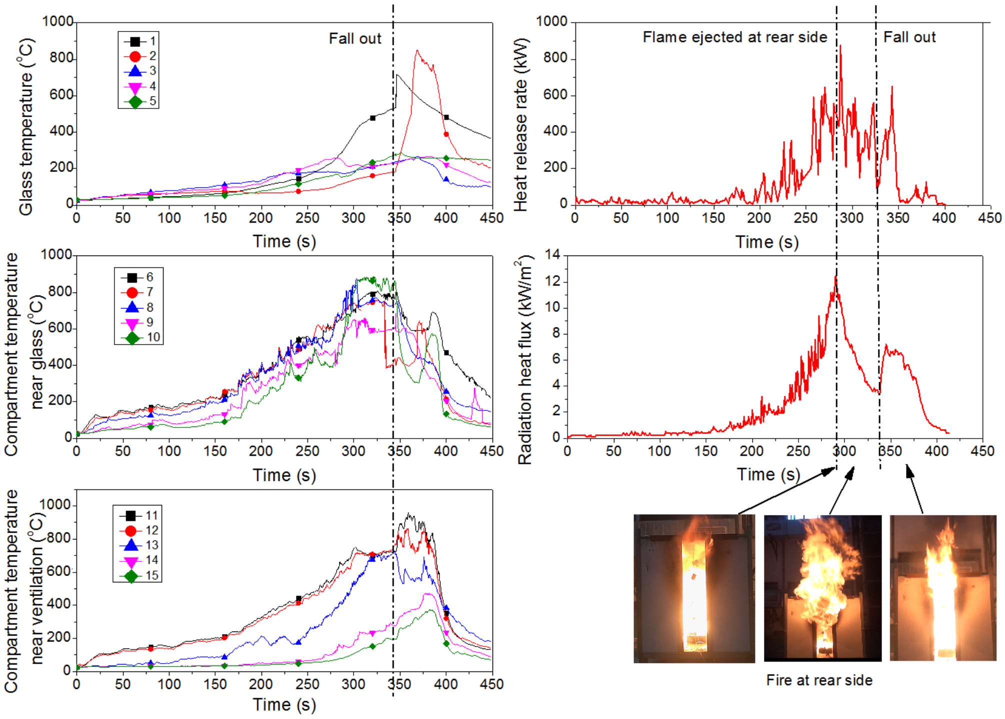


Fig. 3. The temporal evolution of the parameters in Test 3.

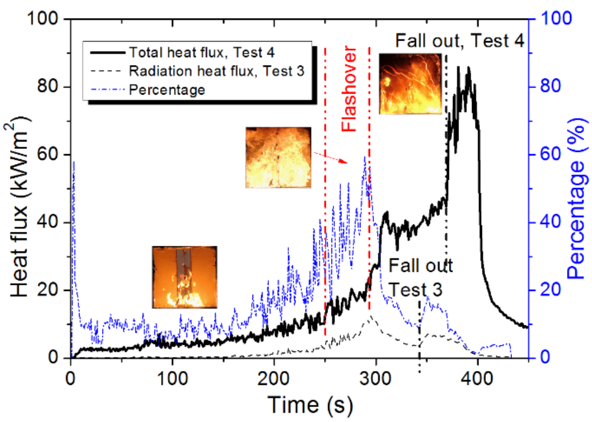


Fig. 4. The comparison of total heat flux and radiation heat flux.

As well as incident heat flux analysis, the temperature difference of the glass panel (center to edge) is also considered as an important parameter for defining glass breakage. In this work, the temperature difference is calculated by the following equation:

$$\Delta T = T_1 - \frac{T_2 + T_3 + T_4 + T_5}{4} \tag{3}$$

in which ΔT is the temperature difference, T_x is the temperature measured by TC_x. The critical temperature difference and total heat flux are summarized in Table 3. In Tests 5 and 6, the maximum temperature differences are 267 °C and 197 °C and the maximum heat fluxes are 80.8 kW/m^2 and 70.9 kW/m^2. In Test 8, the temperature difference at fallout time is 215 °C that is much smaller than other tests, confirming that its breakage reason is the rapid cooling instead of heating. In the tests where fallout occurred (Tests 1-4 and 7), the critical temperature differences are normally between 300-381 °C with an average of 340 °C and a standard deviation of 34 °C. This average value agrees well with the range of 330-380 °C predicted in a previous work [5]. The temperature of glass panel center at breakage time is between 510-565 °C and 704-710 °C for Case 1 and Case 2, respectively. Larger center temperature is required for Case 2, because the temperatures in the covered area increased faster than Case 1 resulting more time needed to achieve the critical temperature difference. Tempered glass may also break when the center temperature is 400-500 °C [20]. The large difference in breakage center temperature observed between Case 1 and Case 2 is directly caused by the heating time, demonstrating that the center temperature alone is not the critical issue for tempered glass breakage. Some theoretical models are based on the incident heat flux as it is easier to predict than the temperature difference during a real fire. Thus, the critical heat flux is discussed although it is not completely independent of the temperature difference. It was established that the critical heat flux normally falls in the range of 40-60 kW/m^2, which is slightly smaller than 50-70 kW/m^2 observed by Manzello et al. [20]. Manzello et al. [20] used thicker glass panels in their work which may contribute to the higher heat fluxes observed. The results suggest that the glass panels with frames with high thermal conductivity require higher heat fluxes and center temperatures to achieve the critical breakage condition. It should be noted that compared with center temperature and heat flux, the temperature difference is relatively critical to tempered glass breakage. In Tests 5, 6 and 8, due to the high thermal conductivity frame, the maximum temperature difference in glazing is below 300 °C, which is smaller than the critical temperature difference (300-380 °C). Thus, no glass breakage occurred despite that the highest center temperature and heat flux reached approximately 700 °C and 80 kW/m^2.

Table 3

The critical parameters at the time of fallout occurrence.

Test number	Center temperature (°C)	Temperature difference (°C)	Heat flux (kW/m^2)
Test 1	531	325	37.1
Test 2	565	381	44.7
Test 3	530	300	6.4 (radiation)
Test 4	510	369	44.8
Test 5	736*	267*	80.8*
Test 6	705*	197*	70.9*
Test 7	710	323	57.9
Test 8	704	215 (excluded)	24.0 (excluded)

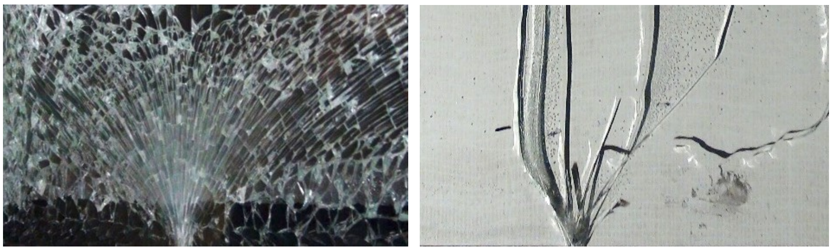
* means the maximum value achieved in the tests without breakage

4. Discussions

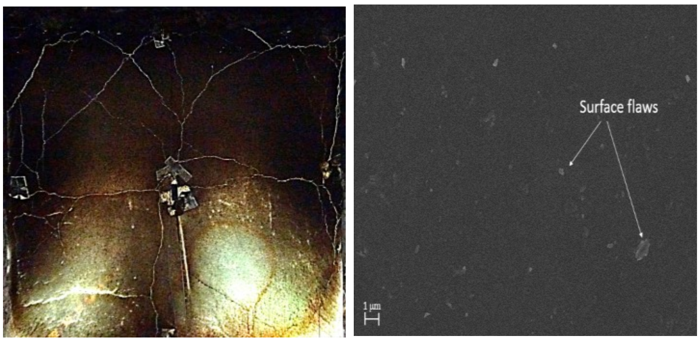
The failure mechanisms of tempered glass in a fire are now discussed. It should be noted that the outer surface of the tempered glass is compressed from the rapid cooling during the manufacturing process and, in general, failure in glass occurs at surface flaws [26]. However, when subject to a fire, the surface compression, caused by tempering, prevents surface flaws from growing and thus can allow greater thermal stress to be withstood.

The fan-shaped cracking pattern at the edge of the tempered glass panel, as shown in Fig. 5(a), exists, similar to that which would be found in float glass (Fig. 5(b)). This implies overloading/overstressing of edge defects in both float and tempered glass can cause failure. The "primary" cracks in tempered glass ran at a very high speed before the whole glass panel disintegrates due to the release of the pre-stress energy [27]. To catch the "primary" cracks, one additional laminated tempered glass panel was tested under the identical condition Fig. 5(c). A scanning electron microscope was used to photograph the glass surface near the panel edge, as shown in Fig. 5(d). The evident crack path and numerous tiny flaws observed confirm that the dominant failure cause of tempered glass in fire is related to the tensile stress concentration near the flaws or defects at the glass panel edges.

The experimental observations, despite the extremely short time of cracking, allow the process of tempered glass failure to be divided into three steps: 1) primary crack initiation at edges caused by thermal gradient; 2) small granular chunks formed by pre-stress release; 3) fallout due to pressure variance in a compartment fire. These three steps occur nearly at the same time, therefore, we can use the classic principle of brittle crack initiation to predict the fallout of tempered glass in a fire.



(a) Crack initiation in Test 2. (b) Crack initiation in float glass.



(c) Crack path in laminated tempered glazing (d) The distribution of tiny flaws on the glass surface

Fig. 5. Post cracks of tempered and float glass panels after heating.

Regardless of the framing thermal properties, however, the fallout of tempered glazing is considered to be determined by the temperature difference between the centre and the edge of the glass panel. Since the tensile strength of 6 mm-thick fully tempered glass is about 5 times larger than corresponding float glass [28], and assuming no plastic deformation exists before breakage, the theoretically critical temperature difference may be obtained according to Hooke's law [4]:

$$\Delta T = \frac{\sigma_b}{E\beta} \tag{4}$$

where E is the elasticity modulus, 67.21 GPa; β is linear expansion coefficient, 8.46×10^{-6} from previous float glass tests [29] (these two parameters are always considered identical to tempered one); σ_b is the breakage stress, 179 MPa of tempered glass. The theoretical critical temperature difference is 315 °C that is relatively conservative compared with the experimental result of 340 °C. It suggests that this simple equation is suitable for tempered glazing fallout prediction.

As the simple equation presented above is suitable for predicting fallout, another simplified mathematical model, BREAK1, has been used to estimate the time for a window to break when exposed to a compartment [30]. No mechanical constant was set in BREAK1 according to [4] and there is heat transfer between the glass and hot layer by setting heat transfer coefficient 40 and 20 $W/m^2 \cdot K$ on exposed and unexposed sides and emissivity of glass and ambient 0.8. Tests 1 and 7, with and without the insulation material in framing, are selected as examples and two input parameters, the total heat flux and hot gas temperature (T_8), are extracted from the experiments. The physical properties mentioned in Eq. (4) are used resulting in calculated breakage times of 308 s (333s in test) and 312 s (387s in test) for Tests 1 and 7, respectively. BREAK1 calculated the exposed temperatures at breakage time are both around 450 °C (531 °C and 710 °C in tests). This demonstrates that BREAK1 may give a reasonable prediction when insulated frames are used, but under-predict the time and temperature for single tempered glazing with uninsulated frames as in Case 2, as observed in [20]. The error in calculation could be due to the temperature variations within the covered areas (approximately 50 °C in Test 1 and 150 °C in Test 7 at 250 s (pre-flashover)), thus the assumption within BREAK1 of constant temperature in such areas should account for the calculated errors.

An in-house finite element software EASY [2], developed by the authors, is used to predict the breakage time and stress field of the tempered glass panels. The glass surface temperature measured in Tests 1 and 7 are implemented. Considering the covered area temperature variance, the thermal loading in exposed and covered areas are respectively the T_1 and the average of T_2, T_3, T_4 and T_5. A total of 7200 (60×60×2) hexahedron elements are used and the time interval is set to 5 s. Coulomb-Mohr criterion was employed to predict the crack initiation. Cracks occur when the maximum and minimum principal stresses combine for a condition which satisfies the following equation [2]:

$$\frac{\sigma_1}{S_{\mathrm{ut}}} - \frac{\sigma_3}{S_{\mathrm{uc}}} \geq 1 \tag{5}$$

where S_{ut} and S_{uc} represent the ultimate tensile and compressive strengths; σ_1 and σ_3 represent the first and third principal stresses. Both σ_3 and S_{uc} are always negative or in compression. More simulation boundary condition about the EASY can be found in [15]. The predicted breakage times are respectively 340 s and 395 s for Tests 1 and 7, which are very close to the experimental results of 333 s and 387 s. Finite element method (FEM) may be suitable for tempered glass breakage prediction in the fire but may need more verifications in the future work.

5. Conclusions

A total of eight glass panels were heated by a pool fire within a model compartment to investigate the effect of frame insulation on tempered glass behaviour and its interaction with compartment fire dynamics. The critical fallout condition of tempered glazing is determined which is used for prediction of the new ventilation in a compartment fire. It has been approved that the frame with high thermal conductivity can give better fire resistance of glazing which is good for further glass façade optimization. The interaction between glass fallout and compartment fire dynamic is preliminarily investigated but may provide references and information for further research. Regardless of glass dimension, the mechanism and critical condition are considered identical. There is no "size effect" for the glass panel in fire and the large panel has a higher possibility for crack initiation which can be well explained by the random distribution of flaws (normally satisfying with the Weibull distribution) [31]. Thus, although the compartment is small, the conclusion concerning glazing should be generic.

The major findings include:

1) Framing systems that do not have a gasket to insulate the glass from the framing material allow increases in temperature in the covered glass areas effectively avoiding the glass fallout and/or providing a delay in failure time.

2) The critical temperature difference and heat flux for tempered glass are respectively 300-380 °C and 40-60 kW/m^2. Once the conditions are satisfied, the whole fallout process may be completed within 1 s.
3) Glass fallout may cause switching from ventilation controlled to fuel controlled fire dynamics. Meanwhile, the neutral plane, compartment temperature and incident heat flux are significantly affected.
4) Convective heat transfer dominates the heating of the glass, particularly in the pre-flashover stage of the fire.
5) Through simplification, a method used for float glass breakage prediction was shown to be suitable for tempered glass fallout prediction. However, more research about tempered glazing fallout in a fire should be conducted for more accurate prediction.

Acknowledgements

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Tables

Table 1

The summary of experimental tests.

Cases	Test number	Framing condition	Heating time (s)
Case 1	Test 1	With ceramic fibre gasket	402
	Test 2	With ceramic fibre gasket	423
	Test 3	With ceramic fibre gasket	401
	Test 4	With ceramic fibre gasket	413
Case 2	Test 5	No gasket	435
	Test 6	No gasket	397
	Test 7	No gasket	405
	Test 8	No gasket	387

Table 2

The fallout time and fractions.

Cases	Test number	Fallout fraction (%)	Fallout time (s)	Average (s)
Case 1	Test 1	100	333	351
	Test 2	100	358	
	Test 3	100	343	
	Test 4	100	369	
Case 2	Test 5	0	No crack	387
	Test 6	0	No crack	
	Test 7	100	387	
	Test 8	100	381 (excluded)	

Table 3

The critical parameters at the time of fallout occurrence.

Test number	Center temperature (°C)	Temperature difference (°C)	Heat flux (kW/m^2)
Test 1	531	325	37.1
Test 2	565	381	44.7
Test 3	530	300	6.4 (radiation)
Test 4	510	369	44.8
Test 5	736*	267*	80.8*
Test 6	705*	197*	70.9*
Test 7	710	323	57.9
Test 8	704	215 (excluded)	24.0 (excluded)

$*$ means the maximum value achieved in the tests without breakage

Figure captions

Fig. 1. The schematic of compartment used for the experimental tests. (a) The compartment; (b) Distribution of heat flux gauges and thermocouples; (c) Fuel mass loss measurement.

Fig. 2. The process of glass fallout and flame spread in Test 3. (a) Breakage and fall out; (b) Side view of window-ejected flame (glass located at left side)

Fig. 3. The temporal evolution of the parameters in Test 3.

Fig. 4. The comparison of total heat flux and radiation heat flux.

Fig. 5. Post cracks of tempered and float glass panels after heating. (a) Crack initiation in Test 2; (b) Crack initiation in float glass; (c) Crack path in laminated tempered glazing; (d) The distribution of tiny flaws on the glass surface.