Experimental Study on Thermal Breakage of Four-Point Fixed Glass Façade

YU WANG[1,3], QINGSONG WANG[1]*, GUANGZHENG SHAO[1], HAODONG CHEN[1], YANFEI SU[1], JINHUA SUN[1], LINGHUI HE[1], JENNIFER X WEN[2], RUOWEN ZONG[1] and K. M. Liew[3]
[1]State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei 230026, P.R. China
[2]Warwick FIRE, School of Engineering, University of Warwick, Coventry CV4 7AL, UK
[3]Department of Civil and Architectural Engineering, City University of Hong Kong, Hong Kong, China
*Corresponding author: Tel.: +86-551-6360-6455; fax: +86-551-6360-1669. E-mail address:pinew@ustc.edu.cn (Q.S. Wang)

ABSTRACT：

As the weakest part of building façades, glass panels can easily break in fires and change the compartment fire dynamics by creating new openings for air to enter. A series of full scale tests were conducted to investigate the thermal breakage and fallout of four-point fixed glass façades, in which glass panes of 1200 × 1200 × 6 (mm^3) were placed at 35, 45, 50 and 70 (cm) away from n-heptane pool fires on a 500 × 500 (mm^2) square pan. Both float and toughened glasses were investigated. The glass surface temperature, gas temperature at the centre of the exposed side and heat release rate were measured and analyzed. The cracking patterns and glass fallout processes were recorded by digital camera. It is found that all the cracks initiated from the fixed point and their intersections formed islands to cause glass pieces fallout when the exposed side reached around 200-300 °C for the float glasses tested. The fallout fractions suggest that once the first crack is initiated, the point-supported glass panes are much more easily to fallout than edge covered glasses. The toughened glass panes were found to be softened by the fire and bent, but they did not crack even when the fire directly impinged on them.

KEYWORDS：Glass façade, thermal breakage, safe distance, fire resistance

INTRODUCTION

Glass façades are used extensively in modern high-rise buildings due to its transparency, energy saving potential and architectural aesthetics [1].The authors conducted a site survey in the Yangtze River Delta region of China and found that many building surfaces are constructed with glass curtain walls instead of concrete or steel. This is even more common in newly constructed buildings. Figure 1 shows some widely used four-point supported glass curtain walls in three Chinese cities.

However, in comparison with concrete or steel structures, glass facades are more prone to breakage and loss of integrity in fire situations. The breakage of glass panels creates openings for fresh air to enter and passages for rapid fire spread to adjacent rooms/floors. Following Emmons's pioneering work [2], numerous experimental [3-8] and theoretical investigations [9-12] were conducted to study the thermal breakage mechanism of glass panes. The experimental results suggested that the main cause for a single pane of glass exposed to a radiant heat source to break is the thermal gradients between the shaded and exposed regions of the glass. Some numerical simulations have also been carried out to predict the time to the occurrence of the first crack and the probability of failure [13-18]. Almost all the previous investigations were focused on edge covered window glass panes.

(a) The first-tier city Nanjing (b) The second-tier city Hefei (c) The third-tier city Huainan

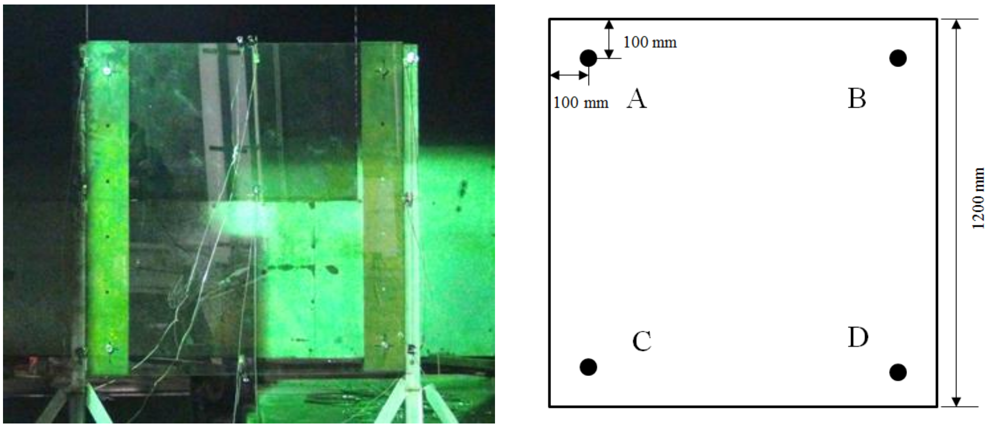
Fig. 1. The glass curtain wall in three typical cities.

It is anticipated that some differences may exist between the breakage behaviour of four-point supported and edge covered glasses. Pagni [19] firstly highlighted the need to study the fallout behavior of glasses in different frames in 2002, especially for four-point supported glass. But relatively little investigations have been conducted in this regard [20]. Some newly constructed buildings with glass façades failed to comply with the requirement of the fire safety codes.

In the present study, a series of full scale tests were conducted to investigate the breakage behavior of four-point supported glass panes of both float and toughened glasses. Measurements were carried out for surface temperatures, heat release rate (HRR) of the fire source, time to the first crack and glass fallout.

THE EXPERIMENTAL SET UP

Figures 2 (a) and (b) display the tested glass which was installed 30 cm over the floor fixed by four screws. The dimension of the glass was chosen as 1.2 m by 1.2 m with 6 mm thickness to mimic the sizes used in practical buildings. All glass panes were edge polished. A 12 mm diameter hole was drilled in each corner. Four screws, which were 10 cm from the edge, were used to support the glass pane and ensure it was vertical to the ground. During the tests, the distance between the float glass pane and fire was set as 35, 45, 50 and 75 cm as shown in Fig. 3. The toughened glass panes were tested at a distance of 35 cm from the fire in all the tests.



(a) (b)

Fig. 2. The tested four-point supported glass.

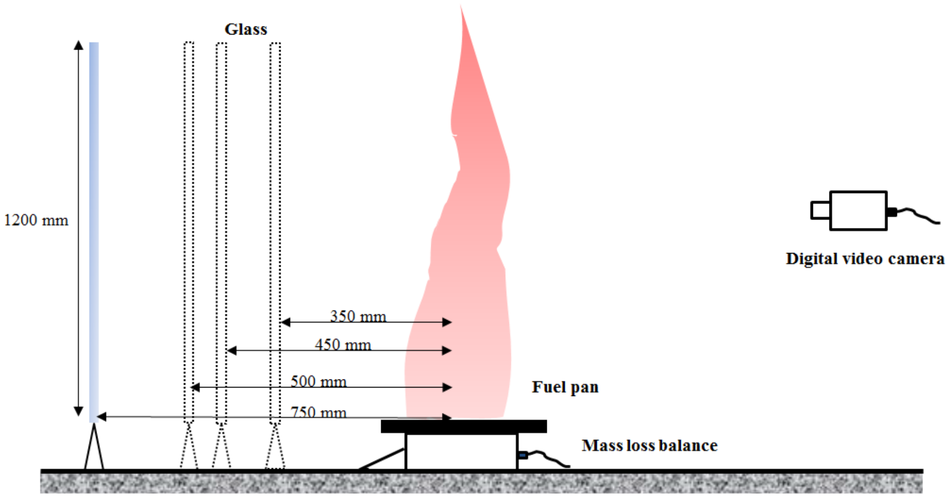
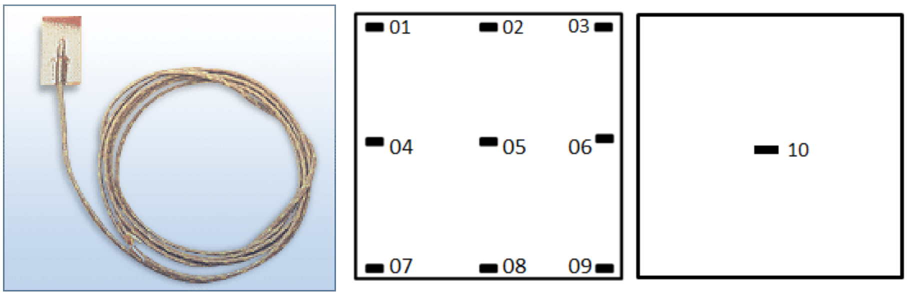
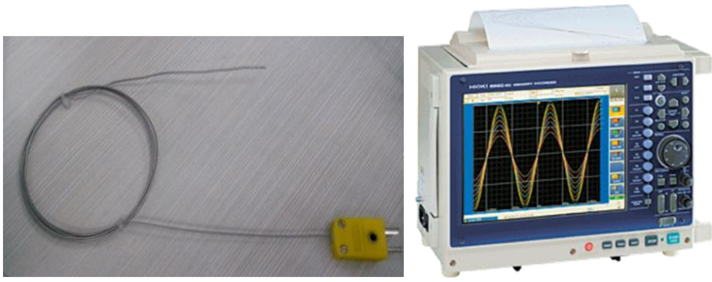


Fig. 3. The schematic of the experiments.

Both sheet and bare K-type thermocouples were used at different positions for temperature measurements. The surface temperatures were obtained using ten type K sheet thermocouples, which were attached to the glass. These thermocouples have high heat-conducting sheets to increase the contact areas between the detected objects and temperature-sensing element within the measuring range of 0-800 °C. Temperatures of the exposed side and ambient side were measured by sheet TC1-TC10 and the locations are displayed in Fig. 4. The bare thermocouple with 1 mm diameter and a measuring range of 0-1300 °C was positioned 5 mm away from the center of the exposed face to record the air temperature variance. Because of direct radiation heating on these thermocouples, uncertainties in temperature measurement are estimated to be 5%. The data acquisition system with 16 channels for thermocouples as shown in Fig. 4 (e) was used with the sampling time adjusted to 0.5 s.



(a) Sheet thermocouple (b) Exposed side (c) Back side



(d) Bare thermocouple (e) Data acquisition system

Fig. 4. The thermocouples and data acquisition system.

The exposed side of the glass pane was monitored by standard video cameras with a framing rate of 25 frame/s. Prior to and upon completion of every test, photographs were taken at 1920 × 1080 pixel resolution of both the exposed and unexposed sides. To explore the relationship between glass breakage and fire development, the HRR of n-heptane pool fire was calculated by the mass loss rate recorded using the electrical balance with a sampling time of 0.5 s. In each test, 2 kg n-heptane fuel on a 500 × 500 mm^2 in a square tray was used to provide a pool fire lasting around 6 minutes.

RESULTS AND DISCUSSION

Seven experiments were conducted with four different distances from fire source to glass pane as shown in Table 1. Case 7 is a verification test for toughened glasses. The measurements of the weighing device were used to calculate the heat release rate :

$$\dot{Q} = \alpha \times \dot{m}_{EXP} \times \Delta H \quad (1)$$

where the burning rate of the fuel varied with time. The combustion efficiency factor α was taken as 0.75 following ISO 9705 [21]. The heat of combustion of n-heptane ΔH is 48066 kJ/kg. The heat release rate versus time in Case 1 is shown in Fig. 5. At 361 s, the maximum HRR of 324 kW was observed. The glass broke at 89 s with a HRR of 198 kW. The time to the first crack in other cases are summarized in Table 2. It was found that the tested glass pane broke and fell out before the HRR reached the maximum value while the fire was still in the development stage.

For float glass panes, the crack and fallout occurred only when the distance were 35 cm, 45 cm and 50 cm. When the distance increased to 75 cm, the glass remained completely intact without any crack until the fire died out. For the float glass located 35 cm from the fire, the crack initiated at 89 s after ignition and middle part of the glass fell out at the same time. At 249 s, the bottom left part of the glass pane also fell out. With further growth of the fire, some new cracks formed and spread to intersect with the previously generated cracks, resulting in the third fell out. There was no further glass fall out until the fire died out and the test completed. When the distances between the glass pane and the fire were 45 cm and 50 cm, the first crack occurred at 144 s and 208 s, respectively. These are much longer than that in Case 1, indicating that the time to first crack increases with the distance between the fire and the glass pane. For Case 2 and 3, the majority of the glass fell out soon after the first crack and no more fallout occurred afterwards. For case 4, the glass pane did not crack despite that the maximum temperature at the centre of the

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exposed side reached 160°C.

Table 1. The summary of experimental cases

Case number	Glass type	Distance (cm)
1	Float	35
2	Float	45
3	Float	50
4	Float	75
5	Toughened	35
6	Toughened	35
7	Toughened	—

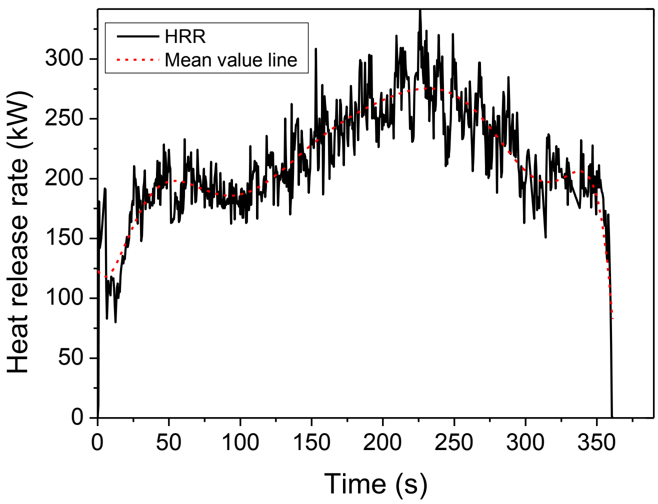

Fig. 5. Typical heat release rate *vs* time.

Table 2. The parameters at first breaking time

Case number	Time of first breaking (s)	Central temperature on exposed side (°C)	Central temperature on back side (°C)	Temperature difference on exposed side (T_{max}-T_{min}, °C)	Heat release rate (kW)	Final Fallout fraction (%)
1	89	219	112	168	198	38.4
2	144	278	103	213	230	35.4
3	208	254	162	225	234	93.2

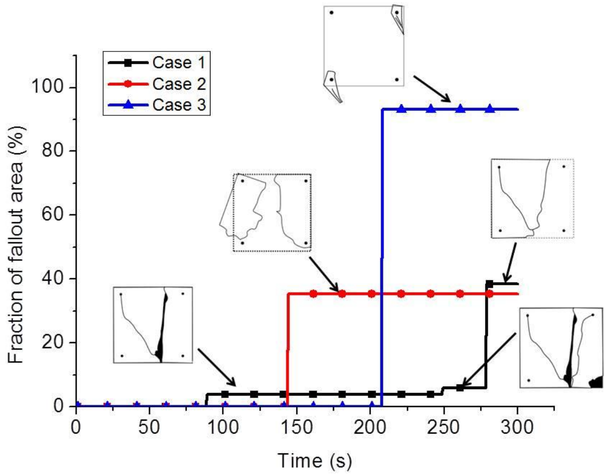

Fig. 6. The time histories of glass fallout.

The processes of crack formation and glass fallout were recorded by digital camera. Figure 6 shows the increase of the fraction of the fallout area with time. The fallout progress shows some differences in the three cases. Case 1 had three steps to the final fallout fraction of 38.4%. The glass panels in Cases 2 and 3 broke into several pieces hanging onto the screws and the final fractions were 35.4% and 93.2%. It was found that the fractions were much bigger than that of the edge covered window glass panels in precious studies [6, 7]. With the protection of metal framework, the glass fallout was less than 10% [6, 7]. As a typical example, the crack patterns in Case 3 are shown in Fig. 7, which was sketched using the digital video as reference. It can be seen that three main cracks initiated from the fixed points and the edge of the glass pane. They then spread and bifurcated towards the centre. Finally the cracks terminated at the edges of the glass pane. After forming the islands, large pieces of glasses fell out near the three fixed points within 0.08-0.60 s as illustrated in Fig. 7 leaving 6.8% of the glass pane hanging to the lower left and top right fixed points. The whole progress of cracking and fall out was finished within 1 second. The crack formation and propagation towards fallout process in Case 1 was similar to that in Case 3 but its fallout region was small as shown in Fig. 8. These results suggest that when the imposed heat flux satisfies the breaking criteria, the crack formation and glass fallout fraction are not directly affected by the distance between the fire and the glass pane. This contrasts that of the edge constrained glass panes where the crack formation was found to be dependent on the imposed heat flux [7].

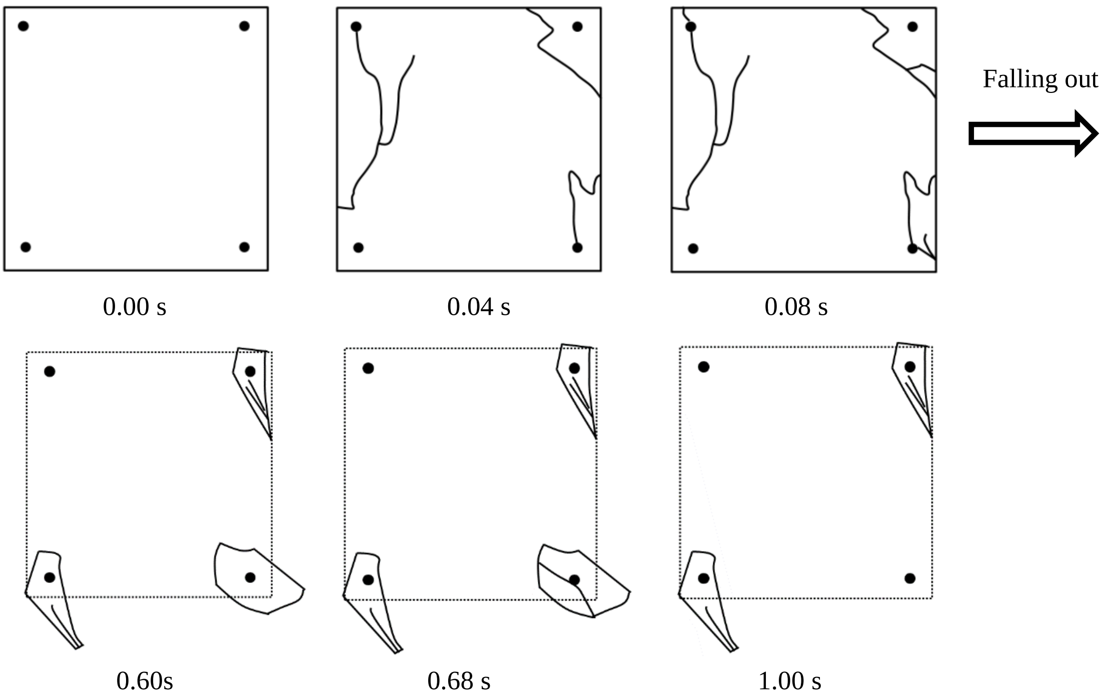

Fig. 7. The breaking progress outlined in Case 3.

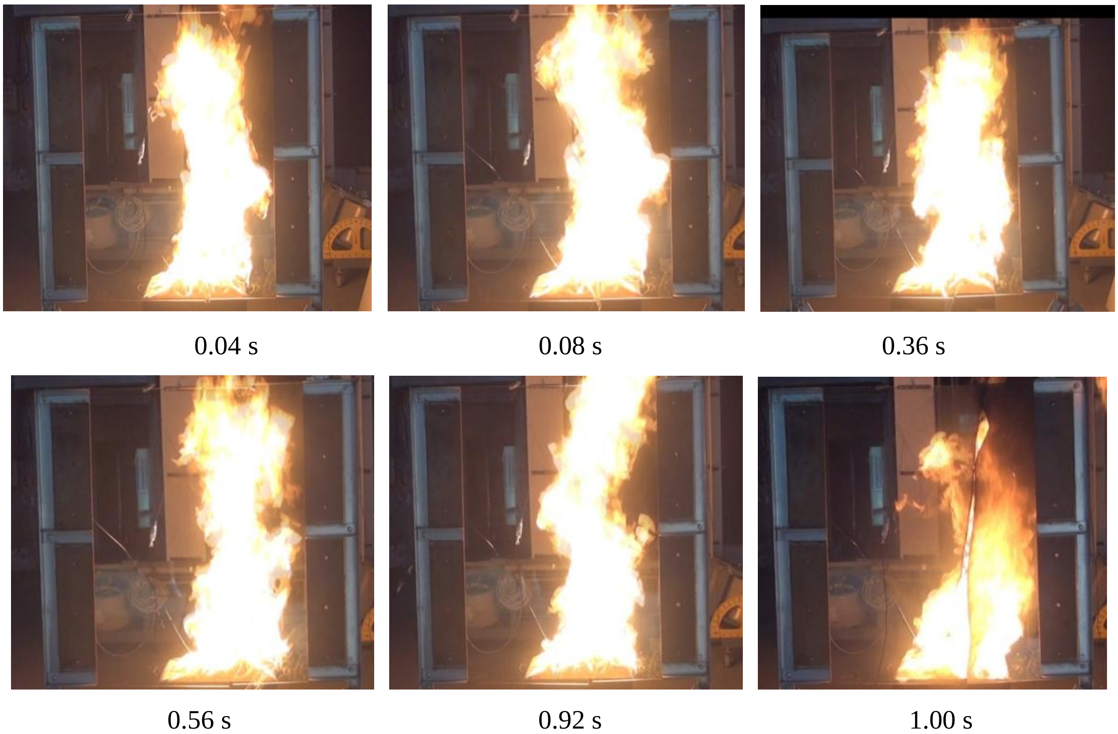

Fig. 8. The recorded images of the breaking progress in Case 1.

As shown in Fig. 2 (b), the locations A, B, C, D represent the upper left, upper right, lower left, lower right supported points. The first crack was initiated in Case 1 at point A, Case 2 at point C and Case 3 at points A and D. These findings indicate that for the four-point supported glass panes, the cracks tend to initiate at the fixed points. This is much different from edge covered glasses in which the initial cracks always form on the edge or the borderline of the shaded areas. When the glass pane is subjected to a fire, it is exposed to non-uniform thermal loading and the temperature differences induce thermal stresses within the glass. Being constrained by the four points, the glass pane could not expand freely resulting in mechanical stresses. The local stress level around the four points is much larger than other parts of the pane. In addition, drilling the four small holes by the manufacturer could also have resulted in small flaws and the existence of the holes also introduces further non-uniform distribution of the thermal stress and could result in the glass to fracture at lower temperature differences [22]. In general, the cracks initiate from the flaws where the stress level is maximum in a glass pane.

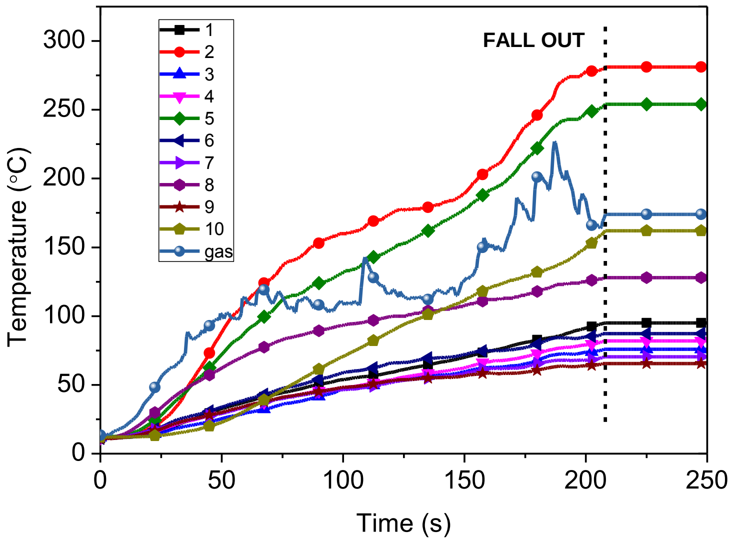

Fig. 9. The temperatures at different monitoring points *vs* time in Case 3.

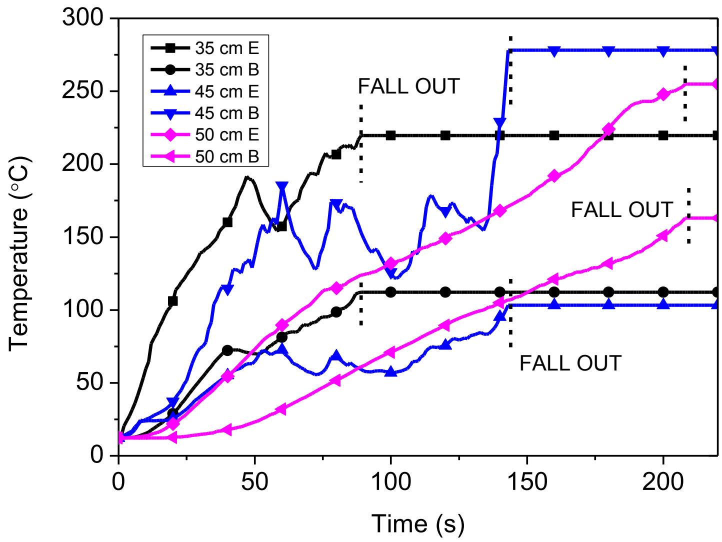

Fig. 10. The glass pane centre temperatures *vs* time in Cases 1-3.

Figure 9 shows the surface and gas temperatures in Case 3. On the exposed side, the measured temperatures of TC02, TC05 and TC08 were much higher than that of the others. TC02 and TC05 showed similar changing patterns and both reached the maximum of about 275°C. T_8 was also relatively higher despite lower than T_2 and T_5. On the ambient side, T_{10} was lower at the beginning, but it increased nearly linearly after 70 s. At the left or right edge, the temperature increased very slowly and had a symmetrical distribution on the two edges. The temperature measured by the thermocouples on both edges even did not exceed 100 °C before cracking. The measured gas temperature increased very fast at the beginning. However, by comparing it with the exposed center temperature T_5, which were measured by two thermocouples located 5 mm apart, it was found that the surface temperature (T_5) was lower only before 75 s and then remained higher than the surrounding air temperature until the glass broke. This is thought to be likely caused by air convection and its low specific heat, indicating that heat exchange at the time of crack formation is mainly radiation between the heated source and the glass pane rather than convection. But during the early stage, convection is also important and responsible for the rapid increase of the air temperature.

Temperature variations in Cases 1 and 2 are similar to Case 3 except that the value being smaller. The central temperature on the glass pane is a representative parameter that can intuitively demonstrate the thermal state. The centre temperatures on the exposed and back sides in Cases 1-3 are shown in Fig. 10. It can be seen that the exposed side temperatures all exceeded 200 °C and back side temperature exceeded 100 °C after glass fallout. Being closer to the fire, the temperature in Case 1 increased more quickly than in the other cases. But the thermocouples were also more easily affected by the fire. As a result, considerable temperature fluctuations were recorded in Cases 1 and 2. For all cases, the variations of temperatures on the exposed and back sides follow similar patterns. The temperature and other parameters at breaking time are summarized in Table 2. The central temperatures on the exposed side at breaking time were all within the range of 200-300 °C. Back side temperatures were within the range of 100-200 °C. These findings are consistent with our previous studies [23] in which different fixing methods were investigated. Considering the randomness of glass breaking [4, 24], the measured temperatures here are relatively steady, indicating that the length of time in which the glass is being continuous heated has limited influence on glass breakage. The temperature distribution has much more influence on glass breakage than the heating period for the point-fixed glass pane subjected to a fire.

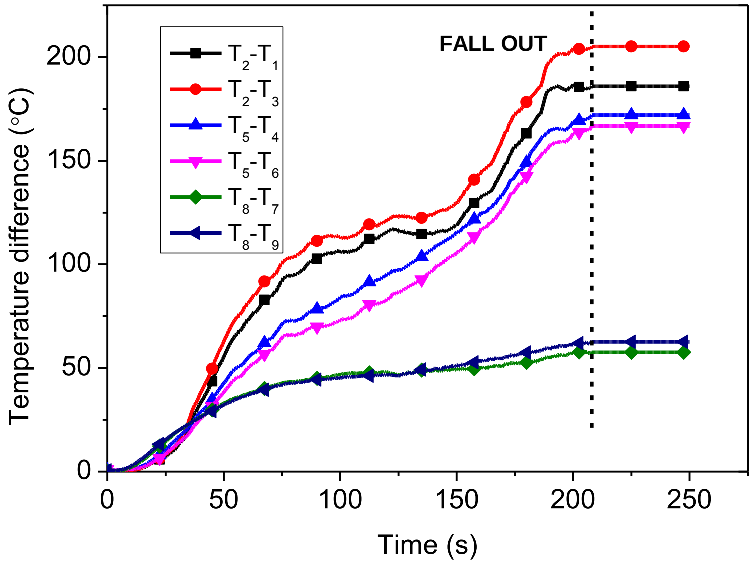

Fig. 11. Temperature differences at different monitoring points *vs* time in Case 3.

These results suggest that ΔT is a significant parameter for determining the breakage of glass, in the Eq. (2) [10]:

$$\sigma_y = E\beta(T_\infty - T_o) \qquad (2)$$

where $_y$ is the normal failure stress, is Young's Modulus, is the coefficient of linear thermal expansion, T_∞ is the heated glass temperature and T_0 is the edge temperature. The parameter and are respectively taken as 72 GPa and 9×10^{-6} K^{-1}[19]. Breaking stress for soda lime float glass was found to be between 10 to 50 MPa [19], which correspond to temperature differences of between 15 to 77 °C according to the above equation. This is much less than the maximum temperature differences in our experiments. As shown in Fig. 11, the first crack occurred when the temperature difference reached about 150 °C. This indicates that the above simplified breaking criteria may not be applicable to four-point fixed glass. In such cases, there is more freedom for expansion when the glass pane is heated; hence the resulting mechanical stresses are smaller in comparison to edge covered glass panes subjected to similar temperature differences. As a result, to reach the overall stress level for crack initiation, the required thermal stress would be larger.

For Cases 4-6, no crack was initiated. When the distance between the glass pane and the fire was 75 cm, the float glass was heated for about 400 s and remained intact until the fire died out. The maximum temperature of the exposed side reached 160 °C but the temperature distribution was much more uniform with the glass pane being placed further away from the fire. Manzello et al. [25] conducted a real-scale compartment fire in which toughened glass panels with a 6.35 mm thickness were fitted in the wall assembly. They reported that the exposed glass surface temperature for fallout of the bottom single-pane toughened glass panel was 400-500 °C. Similar experiments were also conducted by Xie et al. [26] in the ISO 9705 fire room and the breaking temperature was found to be about 600 °C. In our experiments, the glass was positioned only 35 cm away from the fire and occasionally the fire impinged on the glass subjecting the test sample to even bigger thermal shock. The maximum temperatures in Cases 5 and 6 were 633 °C and 623 °C; both exceeded the highest temperatures reached in previous studies. Despite the toughened glass being at such high temperature for a relatively long period, no crack or fallout occurred, suggesting that the point fixed glasses have better fire resistance characteristics than edge covered glasses. This is thought to be because the relatively larger temperature gradients and hence thermal stresses between the central and shaded portion of the glass shaded by the edge in edge covered glass assembly. The use of toughened glasses further increases the fire resistance characteristics. It can hence be concluded that point fixed façade constructed of toughened glass panels have reasonably good fire resistance.

To further examine the fire resistance of toughened glasses, Case 7 was specially designed with the glass being horizontally placed

30 cm above the ground. It was fixed onto two supporting metal cube to ensure that the fire could impinge directly on it. The same pool fire lasting more than 5 minutes was used to impose thermal loading. It can be seen from Fig. 11 that the glass was softened and bent in the middle but no crack was observed, demonstrating its relatively good fire resistance performance.

Fig. 12. Image showing the 6 mm toughened glass subjected to fire.

CONCLUSIONS

Seven full-scale tests were conducted to investigate the thermal breaking and fallout of four-point fixed glass panes. Four tests were conducted with float glass panes fixed at different distances from the fire source while three tests were conducted with toughened glass panels. The results indicate that distance to the fire source has significant effect on the time to the first crack, which are 89 s, 144 s and 208 s, respectively for float glass panes fixed at 35, 45 and 50 cm from the fire. When the distance increased to 75 cm, no crack was observed in the float glass pane. Once the first crack was initiated, more cracks followed almost immediately from the supported points and the glass fell out within 1 s. The fallout fractions suggest that point-supported glass panels are much more easily to fall out than edge covered glass panes. Glass breaking occurs only when the temperature gradients are sufficient to introduce the thermal stresses that meet the breaking criteria. In the particular cases tested, a temperature on the exposed side of 200-300 °C and temperature difference of 150-200 °C seemed to be sufficient. For toughened glasses, cracks did not occur when exposed to the same size pool fire 35 cm away. It was believed the fire also occasionally impinged on the glass pane. The tested point fixed toughened glass was found to have withstood a central temperature of 633 °C on the exposed side without cracking. Such temperature was found sufficient to induce crack and fallout in edge covered toughened glass [25, 26]. A further test demonstrated the good fire resistance of toughened glass even when fire directly impinged on it.

It can be concluded that the four point fixed glass façade has better fire resistance performance than edge covered glasses; and this can be further improved by the use of toughened glasses.

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