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Study of point-supported glass breakage behavior with varying
 point-covered areas under thermal loading

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#### 9 Abstract

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10 Point-supported glazing assemblies are widely used in modern buildings for aesthetic elegance, as well as for economic reasons. However, the formation of vents 11 12 caused by glass breakage could aggravate ventilation controlled compartment fires. The 13 point-covered area generally varies and may constitute potential fire hazards. 14 Accordingly, it is necessary to investigate the fire performance and breakage 15 mechanisms in various point-covered areas. In this study, a total of 12 tests, including three various point-covered area glazing, were heated by a  $200 \times 200 \text{ mm}^2$  pool fire. 16 The breakage time, glass surface and air temperatures, incident heat flux, and crack 17 initiation and final fall out ratio were obtained. The critical conditions for the three 18 19 aforementioned various point-covered area glazing were determined. The reference 20 breakage times,  $t_r$ , which were calculated by assigning a failure probability of 0.1 to the 21 two-parameter Weibull distribution were 119, 140, and 166 s. It was established that a 22 relatively small point-covered area glazing can survive longer; the smaller the point-23 covered area was, the larger the final fallout ratio of glazing assemblies will be. 24 Numerical simulations were performed to investigate the stress distribution on the glass 25 pane, with breakage times well predicted. Accordingly, these results have implications 26 on the fire resistance design for point-supported glazing assemblies.

Key words: point-supported glazing; fire; point-covered area; first breakage time;
stress field distribution.

#### 29 **1. Introduction**

In recent years, with the rapid development of glass production technology, various types of functional glass have been developed, further increasing their applications in the building industry sector. Glass curtain walls have become essential parts of building functionalization and diversification [1]. Thus, instead of four-edge covered glass facades, point-supported glass curtain walls are increasingly being employed in highrise building envelopes for their aesthetic and flexible characteristics [2][3]. Although glass is not a type of combustible material under a fire environment, as it is a relatively

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37 fragile material compared with concrete or steel, it may easily crack and even fall out 38 when subjected to fire, which would unavoidably detrimentally influence building structure stability and integrity [4][5]. Newly formed vents, which would supply more 39 oxygen from the outside fresh air, could increase the growth of ventilation controlled 40 41 enclosure fire and have a crucial contribution to the interactive-external tridimensional 42 fire development. The extensive employ of point-supported installation of glass facades 43 would inevitably introduce with it, not only aesthetics, but also risks associated with 44 fire. Accordingly, it is essential to explore its specific fire performance.

45 In the 1<sup>st</sup> International Symposium on Fire Safety Science, Emmons highlighted that "glass breakage is an important fire structure problem" [6]. Thereby, Keski-Rahkonen 46 47 [7][8] established a classic physical model to analyze its fracture mechanism when 48 subjected to uneven thermal loads. Through an analytical method, it was determined 49 that the covered edges were the most prone to cracking. Skelly et al., Pagni et al., and, 50 Shield et al. [9][10][11][12] performed a series of experiments to validate a previous 51 theoretical model and concluded that the critical temperature difference among edgecovered glazing was approximately 90 °C. Manzello [13] and Klassen et al. [14][15] 52 53 investigated the fire performance of large-scale glazing under a real fire. Chow et al. 54 [16] conducted fire tests concerning the heat transfer and smoke movement in a model 55 box on part of a glass system with two panels. Recently, Debuyser et al.[17] heated monolithic and laminated glazing with a special focus on the heat transfer and 56 57 developed a 1D heat transfer model to determine the evolution of the temperature 58 profile as a result of a given incident heat flux. BREAK1 [18] and EASY [19] were 59 developed to predict the cracking time. Through previous studies, several consensuses 60 have been reached, such as the following: although various types of glass, installation 61 forms, and external heat sources have remarkable influence on the fire performance of 62 glazing, the major cause of glass rupture is the excessive tensile stress caused by 63 inhomogeneous temperature distributions resulting from the presence of shaded areas, 64 including the location of heat source relative to the glazing.

65 Nevertheless, previous studies concerning the fire performance of point-supported glass façade, which are typically supported by four points and extensively used as 66 67 external facades of core wall structured buildings or partition walls, as shown in Fig. 1, were limited. Recently, Wang et al. [2][20] conducted experiments and numerical 68 69 simulations concerning the fire response of point-supported glazing. In relation to the 70 investigation of the influence of various point-covered areas, a geometric factor was 71 introduced as a function of covered width, as proposed by Pagni et al. and Joshi et al. 72 [21][22], to investigate the edge-covered width effect. Tofilo et al. [23] conducted an 73 investigation to theoretically determine the influence of various covered widths on 74 thermal stress by establishing an approximate solution for a long strip of glass pane. 75 Chen et al. [24] conducted experiments concerning different shaded widths, ranging 76 from 10 to 50 mm under radiant heat. It was established that various shaded widths of 77 glass panes have a vital influence on breakage behavior, whereas previous studies 78 discussed above, solely concentrated on the framed edge-covered glass facades, which 79 were generally covered by a nontransparent frame or gasket. To the best of our 80 knowledge, there is no open literature concerning the influence of varying point-81 covered areas on point-supported glazing assemblies. In engineering practice, the 82 supporting point-covered area typically varies, which may introduce a potential fire 83 hazard. Thus, it is insufficient with respect to practical guidance and national fire codes 84 on the fire performance of various point-supported areas. In consideration of the 85 increasing adoption of point-supported glazing with different point-covered areas in 86 modern buildings, it is essential to investigate the thermal breakage behavior and 87 underlying heat transfer mechanism, which could enhance our comprehension of the 88 breakage process and criteria.



89

90

Fig. 1. Point-supported glass curtain wall, USTC campus, Hefei.

### 91 **2. Experimental setup**

92 As shown in Fig. 2(a), the test equipment primarily consisted of four sections: heat 93 source, cabinet for glass installation, temperature and incident heat flux measurement 94 system, and mass-loss balance system. The cabinet had a vent in front of the glass 95 installation, which could support combustion in a compartment space. The edge-96 polished float glass pane was mounted on a frame with four screws. To investigate the 97 influence of different supporting point-covered areas, three different sizes of screw nuts, 98 as illustrated in Fig. 2(b), made of 304 stainless steel with a heat conductivity of 16.2 99  $W/(m \cdot K)$  at 373 K, and with the same inner diameter and thickness, were adopted. The inner diameter and thickness were 10 and 4 mm, respectively, and were not changed in 100 101 the course of the experiments. The outer diameters were 15, 30, and 45 mm. In order to 102 make the experiment comparable to a real fire environment, four 10-mm diameter 103 circular holes were drilled in each corner at a distance of 35 mm from the edge of the 104 glazing. The glazing was located 300 mm above the ground and 300 mm away from the n-heptane pool fire in a 200×200-mm<sup>2</sup> pan, which was determined by a pre-105 experiment. Twelve 600×600×6-mm<sup>3</sup> float glasses made of identical materials by the 106 107 same local manufacturer were selected. As shown in Fig. 2(c), the glass surface 108 temperatures were determined by 15 1-mm diameter K-type sheathed thermocouples 109 (TCi), which were attached to the glass panes with high-temperature adhesive. The 110 thermocouples were numbered TC1-TC10 (attached to the fire side surface), TC12-111 TC16, and TC1–TC10 (attached to the ambient side surface). In addition, a sheathed thermocouple, numbered TC 11, was set 5 mm in front of the glass to measure the air 112 temperature. It should be noted that TC01, 03, 05, 07, 12, and 14 were attached to the 113 114 point-covered areas to measure temperature variations in the experiments. Because of 115 the effect of hot air disturbance and radiation, the uncertainty of temperature measurement was evaluated at  $\pm 5\%$ , which was considerably less than that in 116 117 compartment fire experiments (uncertainty 10-30%) [13][25]. To elaborate on the location of crack initiation, A, B, C, and D represent the hole edge on the top left corner, 118 119 top right corner, bottom left corner, and bottom right corner, respectively, as the 120 locations where the cracks initiated. The heat release rate (HRR) of n-heptane pool fire was calculated based on the mass-loss rate recorded using a 404×360-mm<sup>2</sup> METTLER 121 122 TOLEDO XA32001L model of an electric balance with an accuracy of 0.1 g. 123 Furthermore, a GTT-25-50-WF/R model of a Gordon total heat flux gauge with a measurement range of  $0-50 \text{ kW/m}^2$  was used to determine the total incident heat flux. 124 including the full-band radiation and convective heat at the exposed side. The gauge 125 126 was set 10 mm from the right side of the glass pane (viewed from a digital video camera) and mounted flush to the surface of the glass. By this means, the gauge would be located 127 as close as possible to the measurement location. This method had been used 128 129 extensively in measuring the incident heat flux on the glass pane. An n-heptane pool with a 99% purity and 1-kg mass was used to simulate the real fire scene and to ensure 130 the consistency of all experimental fire sources. During the stable combustion stage, 131 132 the heat release rate reached 100–200 kW. Furthermore, a video camera with a framing rate of 50 frame/sec was employed to record glass breakage and fire development. 133 134







(b) Point-supported frame.

142 143 144

The distribution of thermocouples and heat flux gau **Fig. 2.** The schematic of the experimental setup.

145

### 146 . 3. Numerical methods

In a previous work [20], experiments were conducted to determine the stress on specific monitoring points on the glazing surface under fire-heated conditions. However, the measurement results were not able to show the overall stress distribution on the glass pane. Thus, for the purpose of revealing the stress distribution, an FEM software,

151 COMSOL Multiphysics, was employed to predict it. In this model, temperatures 152 extracted from experimental data were loaded on the exposed side surface. It was supposed that the temperature variance at the ambient side was only caused by heat 153 conduction from the exposed side surface. The dimensions and properties of the glass 154 were identical with the glass pane used in the experiments, as summarized in Table 1. 155 156 Grid independence tests were conducted to ensure the reliability and accuracy of 157 simulation results. Consider Test 2 of Case 1 as an example. A total of 72 060 hexahedral elements, 19972 quadrilateral elements, 1472 edge elements, and 72 vertex 158 elements were adopted based on the principle of time saving and accuracy, as shown in 159 Fig. 3. The time interval was set to 1 s to guarantee the reliability and accuracy of results. 160

161

162 **Table 1** 

163	Glass	properties	used	in	the	simul	latior
-----	-------	------------	------	----	-----	-------	--------

Properties	Symbol	Value
Density (kg/m <sup>3</sup> )	ρ	2500
Modulus of elasticity (Pa)	E	$7.2 \times 10^{10}$
Poisson's ratio	v	0.20
Thermal expansion coefficient (1/K)	β	8.75×10 <sup>-6</sup>
Reference temperature (K)	$T_R$	293
Specific heat capacity $(J/(kg \cdot K))$	$C_p$	703
Thermal conductivity $(W/(m \cdot K))$	k	1.38
Ultimate tensile strength (Pa)	S <sub>ut</sub>	5×10 <sup>7</sup>
Ultimate compressive strength (Pa)	$S_{_{uc}}$	5×10 <sup>8</sup>



164 165

Fig. 3. Mesh grids in Test 1 of Case 3.

166

### 167 **3.1. Heat transfer model**

168 In this finite model, the temperature increase was mainly caused by the total incident

169 heat flux, including the fire source radiation and air convection, which can be expressed

170 by the heat transfer equation [22]:

171 
$$\rho c \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial z^2} + Q$$
(1)

172 where,  $\rho$ , c, and k are the density, specific heat, and thermal conductivity of the glazing, respectively, and O represents the total incident heat flux. The heat transfer progress of 173 174 this finite model can be expressed by the total incident heat flux received by the exposed side of the glass pane. Furthermore, heat is radiated to the surroundings, convected with 175 air, and conducted to the glass pane. Test 2 of Case 1, Test 2 of Case 2, and Test 1 of 176 177 Case 3 were selected to predict the stress distribution and crack initiation. The 178 experimental temperatures obtained by thermocouples were used in the simulation. 179 Because of the limitation of thermocouples, which were arranged during the 180 experiments according to the temperature distribution, a total of five regions were divided to load the temperature extracted from experiments, as shown in Fig. 2(c). For 181 182 region 5, the average temperature measured by six thermocouples (TC 2, 4, 6, 8, 9, and 183 10) in this region was considered as the input temperature. For regions 1, 2, 3, and 4, 184 the temperatures measured by TC1, 3, 5, and 07 were regarded as input temperatures, 185 respectively.

186

#### 187 **3.2. Thermal stress model**

The experimental results suggested that the glass pane was constrained in the zdirection at the edge of the support point. Consequently, it was assumed that the displacement in the z direction was zero. To avoid rigid body displacement during the numerical simulation process, it was necessary to add simple constraints on two sides at the bottom of the glass pane. Generally, constraints cause stresses near the constrained boundaries when the structure undergoes temperature changes. Typically, thermal stress has a spatial distribution, as given by the following:

195

$$(\lambda + 2G)\nabla^2 e - \alpha \nabla^2 T = 0 \tag{2}$$

196 where,  $\lambda$ , *G*, and *e* denote Lame coefficient, shear modulus of elasticity, and volumetric 197 strain, respectively;  $\alpha$  represents the thermal expansion coefficient. The quantities  $\lambda$ , *G*, 198 and *e* are expressed as follows:

199 
$$\lambda = \frac{E\nu}{(1+\nu)(1-2\nu)}, \ G = \frac{E}{2(1+\nu)}, \ e = \varepsilon_x + \varepsilon_y + \varepsilon_z \tag{3}$$

200 where, v is Poisson's ratio, and  $\varepsilon_x$ ,  $\varepsilon_y$ , and  $\varepsilon_z$  are the strains in the x, y, and z directions. 201 If the strain field satisfies the general compatibility relations, then, in principle, it is 202 possible to integrate the above relationships. The procedure is outlined as follows [26]:

203 
$$\varepsilon_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial X_j} + \frac{\partial u_j}{\partial x_i} \right)$$
(4)

204 
$$u_{i}(\mathbf{X}) = u_{i}(\mathbf{X}_{0}) + \int_{\mathbf{X}_{0}}^{\mathbf{X}} (\varepsilon_{il} + (\mathbf{X}_{k} - \mathbf{X}_{k}^{'}) (\frac{\partial \varepsilon_{il}}{\partial \mathbf{X}_{k}} - \frac{\partial \varepsilon_{kl}}{\partial \mathbf{X}_{i}})) d\mathbf{X}_{l}^{'}$$
(5)

The distance along the integration path can be parameterized by s, ranging from 0 to 1. This integral can be calculated as long as the strain field is an explicit function of the material frame coordinate, X.

$$\mathbf{X}' = \mathbf{X}_{\mathbf{b}} + s \mathbf{1} \tag{6}$$

$$u_{i}(\mathbf{X}) = \int_{0}^{1} \left(\varepsilon_{i} + (1-s)p \left(\frac{\partial \varepsilon_{i}}{\partial X_{k}} - \frac{\partial \varepsilon_{k}}{\partial X_{i}}\right)\right) p \, ds_{l}$$

$$\tag{7}$$

#### **3.3. Crack model**

The crack initiation of the glass pane is random and uncertain. Generally, the larger the thermal stress is, the greater the possibility of cracking would be. In addition, glass has critical tensile and compressive strengths. Therefore, it is feasible to determine the glass crack initiation behavior by comparing the thermal stress with the critical tensile strength. Accordingly, the Coulomb–Mohr criterion was applied to determine crack initiation [19]. Crack occurs when the maximum and minimum principal stresses combine for a condition that satisfies the following equation:

218 
$$\frac{S_1}{S_{ut}} - \frac{S_3}{S_{uc}} \ge 1$$
 (8)

where,  $S_{ut}$  and  $S_{uc}$  are the ultimate tensile and compressive strengths, respectively. Both  $S_3$  and  $S_{uc}$  remain in compression (negative).

221

#### 222 4. Experimental results and discussion

#### **4.1. Total incident heat flux**

224 The total incident heat flux is a significant parameter for analyzing the glass breakage 225 behavior. Table 2 summarizes the incident heat fluxes at the exposed side at the time of 226 the first breakage. Because the heat flux gauge was located 10 mm off the glazing, the 227 measured values may have been slightly smaller than that at the center of the glazing. 228 Nevertheless, this method was widely utilized to obtain this parameter in a previous 229 study [13]. The present experimental results suggested that the values were distributed in the range of 11.48–24.01 kW/m<sup>2</sup> among the different cases. The critical heat flux for 230 glass breakage varied significantly when the area of the point-covered changed. It could 231 232 be concluded that when subjected to the same incident heat flux, the smaller point-233 covered glazing had better fire resistance, and thus, required a relatively longer time to 234 reach the critical heat flux. In addition, it should be noted that the average heat flux was 235 similar between Cases 2 and 3, mainly because the breakage of these two forms 236 occurred when the n-heptane pool fire grew under a relatively stable state.

- 237
- 238 Table 2

Case no.	Test no.	Heat flux at the first breakage time $(kW/m^2)$	Average (kW/m <sup>2</sup> )
	1	11.48	
	2	12.79	10.05
1	3	13.46	12.95
	4	14.07	
	1	21.75	21.12
2	2	23.26	21.13

239 The incident heat fluxes at the first breakage time.

	3	19.34	
	4	20.15	
	1	20.34	
2	2	24.01	22.47
3	3	24.89	22.47
	4	20.63	

The increase in glass temperature was primarily attributed to the fire source radiation and convection on the exposed side, which can be expressed as follows [27]:

243 
$$\rho cL \frac{dT(0t,)}{dt} = q_{con} + q_{rad}$$
(9)

244 
$$q_{c \circ n} \equiv h( \oint T_{c \circ n} - T( \oint (10))$$

where  $\rho$ , *c*, and *L* are the density, specific heat capacity, and thickness of the glass pane, respectively;  $q_{conv}$  and  $q_{rad}$  represent the convection heat flux and radiation heat flux, respectively;  $h_0$ ,  $T_{0\infty}$ , and T(0, t) denote the convective heat transfer coefficient, ambient air temperature, and glazing temperature at the exposed (fire) side, respectively.

Assuming a constant radiation heat flux,  $q_{rad}$ , and convective heat transfer coefficient,  $h_0$ , the glazing temperature rise may follow an exponential growth according to the following equation calculated by solving the above differential equations:

252 
$$T(0t, \Rightarrow -\frac{q_{rad}}{h_0} e^{-\frac{h_0}{p^{Lc}t}} - +1\mathcal{T}_{0\infty}$$
(11)

253 where  $T_{0\infty}$  is the initial glass pane temperature.

In this heat transfer model, the convection heat flux can be calculated from the ambient air temperature at the center of the exposed side. Because of the action of high temperature gas, the convective heat transfer coefficient of the exposed side,  $h_0$ , would vary during the experiments. In this study, we adopted the equation proposed by Pagni and Emmons, expressed as follows [28]:

259 
$$h_0(t) = 5 + 45 \left[ T_{0\infty}(t) - T(0, t) \right] / 100$$
(12)

Note that when  $h_0$  is equal to 50 W/(m·K), this value will be retained and remain unchanged.





263 264

Fig. 4. Proportion of convective heat flux.

265 Consider Test 2 of Case 2 as an example. Figure 4 illustrates the variance of the 266 incident heat flux on the glass panes. It was found that the first breakage occurred at 267 135 s, and the total incident heat flux fluctuated in the range  $0-23 \text{ kW/m}^2$  before the occurrence of this first breakage. The air temperature at the exposed (fire) side was 268 269 higher than the temperature of the glass surface and rapidly rose after ignition. In the 270 figure, the proportion of the heat convection is represented with a red curve. The results 271 suggested that before 50 s, the glazing temperature gradually rose, whereas the air 272 temperature rapidly increased because of the direct heat radiation and convection from 273 the fire source, which resulted in the corresponding rapid increase in the proportion of 274 heat convection. Thereby, under the combined action of the fire source radiation and 275 heat convection, the temperature of the glazing rapidly increased. However, because a 276 considerable amount of hot gas accumulated in the confined space, it was apparent that 277 convective heat transfer had a significant influence on the temperature increase of the 278 glass pane. This phenomenon further confirmed that convective heat transfer had a 279 more significant function under such a condition than that in an open space fire because 280 hot gas in open space would rapidly release heat to the external space. In a previous 281 experiment [27] conducted with an open space fire, the convective heat transfer had no 282 contribution to the temperature rise of the glass pane after 90 s because the gas 283 temperature was lower than the glazing at the surface of the exposed side.

**4.2. Heat release rate** 

The heat release rate is also a significant parameter for analyzing glass breakage. The change in the fuel mass was measured during the experiments, and HRR  $\dot{Q}$  of the heat source in the 200×200 mm<sup>2</sup> square fuel pan was calculated using the following:

- $\dot{Q} = \alpha \times \dot{m} \times \Delta H \tag{13}$
- where,  $\alpha$  is the combustion efficiency factor taken as 0.75 [29];  $\dot{m}$  is the mass-loss rate

290 of n-heptane, in kg/s;  $\Delta H$  is the fuel combustion heat of n-heptane at 48 066 kJ/kg. The 291 mass of n-heptane was approximately 1000 g, which could maintain combustion for more than 6 min. Consider Test 3 of Case 3 as an example, as shown in Fig. 5. It should 292 293 be noted that the blue broken line, obtained by data fitting experimental results, would be a better representation of the heat release rate. The results suggested that the heat 294 295 release rapidly rose after ignition, reached a relatively steady state, and finally, 296 decreased. Thus, the whole combustion process could be divided into three stages: the 297 rapid growth stage, relatively steady stage (75-145 kW), and decay stage. After ignition, 298 the heat release rate reached a relatively steady stage within 37 s and remained at that stage for about 250 s, attaining a maximum value of 145 kW at 190 s. The first breakage 299 occurred at 204 s, which was under a relatively stable combustion stage with a heat 300 301 release rate of 121 kW. Based on 12 experimental results, it was concluded that the first 302 breakage usually occurred when the combustion was in a relatively steady stage. 303



304

305

#### Fig. 5. Heat release rate in Test 3 of Case 3.

### **4.3. Time to the first breakage and fall out**

307 The first breakage time is a particularly critical parameter for the analysis of glass 308 breakage and fall out. After the glass pane cracked for the first time, "islands" were swiftly formed and the pane was considerably prone to fall out. On the one hand, glass 309 310 fall out could result to the loss of glazing integrity, which would have a detrimental influence on the stability of the building structure. On the other hand, newly formed 311 vents caused by glass breakage could provide a route for the entry of outside fresh air 312 313 into the interior space and fuel the growth of ventilation-controlled enclosure fire. Accordingly, such vents have a crucial function in the development of an interactive-314 315 external tridimensional fire. As listed in Table 3, the first glass breakage times in four 316 repeated experiments of the same case were similar. However, there was a significant

distinction among various point-covered areas, which indicated that such areas had an
instantaneous influence on breakage times. It was found that the larger the pointcovered area was, the shorter the breakage time will be. Thus, it can be concluded that
a relatively smaller point-covered area has better fire resistance.

322	Table 3
323	The time to the first breakage.

Casa na	-	Tł	ne first breakage	time (s)	
Case no.	Test-1	Test-2	Test-3	Test-4	Average
1	122	130	127	135	129
2	159	150	165	146	155
3	185	173	204	196	190



325 326 327

328 Because initial minor imperfections or defects distributed along the edges of glazing and drilled holes are generally unavoidable because of the drilling process during 329 330 fabrication [30], the edges were polished before the experiments were conducted to minimize the impact of these imperfections and defects on glass breakage to the extent 331 332 possible. Despite all these, the breakage and fall out of glazing during fires remain 333 stochastic [31]. Compared with theoretical and numerical studies, the repetition of 334 experiments conducted under the same conditions for each case is a relatively accurate 335 method to investigate the glass breakage phenomenon. In addition, the quantification of these impacts were performed using Weibull distribution functions by fitting the 336 337 experimental data [11]. It is assumed that the first breakage time, t, satisfies this 338 distribution, as follows [32]:

$$\varphi(t) = \left(\frac{t - t_u}{t_0}\right)$$

$$p(t) = \left(\frac{t - t_u}{t_0}\right)^m \tag{14}$$

where,  $t_u$  and  $t_0$  denote the failure-free period and characteristic life, respectively, and *m* is the shape factor. Thus, the foregoing described the lifetime distribution of the material. The Weibull ++ 7.0 software, based on the linear least squares fitting method, was employed to determine the characteristic life,  $t_0$ , and shape factor, *m*, of the Weibull distribution, as listed in Table 4. Furthermore, the failure probability function, F(t), is given by the following expression:

$$\mathbf{F}(t) = 1 - \exp\left[-\left(\frac{t - t_u}{t_0}\right)^m\right] \tag{15}$$

The probability density function, f(t), which is the derivative of F(t), can be expressed as follows:

349 
$$\mathbf{f}(t) = \frac{m}{t_0} \left(\frac{t - t_u}{t_0}\right)^{m-1} \exp\left[-\left(\frac{t - t_u}{t_0}\right)^m\right]$$
(16)

#### 350 Table 4

351	Parameters for the two	-parameter Weibull	distribution	function	of the	first br	eakage	time.
							<u> </u>	

Case no.	m	$t_0(s)$	$t_u(s)$	$t_r(s)$
1	23.61	131.05	0	119
2	17.69	159.07	0	140
3	14.02	195.71	0	166

352

346

353 The calculated values of  $t_u$ ,  $t_0$ , and *m* were substituted in Eqs. (15) and (16) to obtain 354 the failure probability and probability density functions plotted in Fig. 7. It was found 355 that the failure probability sharply increased at a certain point when the breakage times were more than approximately125, 150, and 175 s for Cases 1–3, respectively. It was 356 357 noteworthy that the failure probability rose from approximately 0.1 to 1 with the smallest range 117–127 s for Case 1. The reference breakage times,  $t_r$ , which were 358 359 calculated by setting the failure probability to 0.1, were essential to the fire-resistance design of glazing assemblies. For Cases 1–3, the breakage times,  $t_r$ , were 119, 140, and 360 361 166 s, respectively. The results further confirmed that glazing with relatively smaller point-covered areas had better fire-resistance when subjected to the same fire 362 363 environment. The probability density function is plotted in Fig. 7(b). In addition, in a previous study pertaining to the influence of the edge-covered width for framing edge-364 covered glazing on fire performance [22], it was found that the first breakage times 365 decreased as the edge-covered width increased. Thus, from the perspective of breakage 366 367 time, a relatively smaller point-covered area and edge-covered width are recommended 368 for point-supported and edge-covered glass curtain walls, respectively, under the 369 premise of structural strength in engineering practice.





(a) Variation of the Weibull failure probability with the first breakage time.



375

376

(b) Variation of the Weibull probability density function with the first breakage time. **Fig. 7.** Weibull distribution results of the first breakage time.

It was found from experimental results that all cracks were initiated from the 377 supported points; remarkably different from edge-covered framed glazing whose cracks 378 379 consistently started from the edges of the glass pane [8]. The locations of the crack 380 initiations and fall out ratios are summarized in Table 5. The crack initiation locations 381 A, B, C, and D represent the hole edge at the top left corner, top right corner, bottom 382 left corner, and bottom right corner, respectively. The locations of crack initiations were 383 as follows: two tests at A, two tests at B, three tests at C, and eight tests at D. The excessive thermal stress caused by the temperature difference between the exposed and 384 385 covered areas was the main reason for glazing cracking. Thus, the phenomenon may be 386 attributed to a relatively high temperature difference at the bottom right corner (D). It 387 is noteworthy that not all cracks initiated from a single supported point. The crack 388 initiation locations under Test 1 of Case 2, Test 2 of Case 2, and Test 4 of Case 3 were 389 at (A, C, D), (C, D) and (C, D), respectively. Figure 8 shows the fall out area ratio of 390 glass panes over time. It was found that there were significant differences in the process of glass fall out among the three cases. It should be noted that the final fall out ratio of 391 392 four repeated experiments in Case 1, with the maximum point-covered area, were all 393 0%, which indicated that fall out had the least possibility of occurring under this 394 condition. Test 4 of Case 3 had the largest final fall out ratio at 11.2%, along with two 395 main fracture processes. It was found that as the times of the main fracture process 396 increased, the number of cracks would increase, forming more crack 'islands' because 397 of crisscrossed cracks. Consequently, the probability of a fall out was increased. The 398 primary reason for the fall out of the glazing when subjected to a confined space fire 399 was the reduction in the constraint among the crack 'islands' and the impact of external 400 disturbances, such as ambient wind load and flame entrainment. Nevertheless, the 401 influence of the impact of external disturbances could be ignored because the cases had 402 the same boundary conditions, except for different point-covered areas. Therefore, the various final fall out ratios were attributed to the decrease in constraints among the 403 404 crack 'islands'. In the experiments, all crack initiations occurred at the supporting point 405 edge After the cracks were initiated, they rapidly propagated and soon formed crack 'islands' near the supporting point edge and other locations because of crisscrossed 406 407 cracks. If the crack 'islands' near the supporting point edge led to a fall out, then, the 408 other crack 'islands' supported by the reactive forces provided by the former 'islands' would cause the glass pane to become considerably prone to a fall out [33]. Thus, a 409 relatively large point-covered area would provide more restraint near the supporting 410 411 point edge, which would further reduce the possibility of a fall out.

412

4

#### 413 **Table 5**

14	The first	breakage	position	and	final	fallout	ratio.
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Case no.	Test no.	First breakage position	Final fallout ratio (%)
	1	А	0
1	2	D	0
1	3	D	0
	4	D	0
	1	A, C, D	1.4
2	2	C, D	2.1
	3	D	0
	4	В	0
	1	С	5.4
2	2	D	0.4
3	3	В	9.7
	4	C, D	11.2





Fig. 8. Time histories of glass fall out.

### 419 **4.4 Glass surface and ambient air temperatures**

420 Sixteen K-type sheathed thermocouples were utilized to measure the temperatures 421 of the ambient air and glass pane surface both on the exposed and ambient sides. This 422 method had been used extensively to investigate the temperature distribution in glazing 423 [2]. Consider Test 2 of Case 2 as an example. The temperature variation in the 424 experiment is shown in Fig. 9(b). The first breakage occurred at 150 s and ambient air 425 temperature at the exposed side was measured by TC11. After ignition, the ambient air 426 temperature rapidly rose, and it was observed that the heating rate was higher than that 427 at the glazing surface. It was found that the ambient air temperature was consistently at 428 its highest because of the smoke aggregation in the confined space. Thus, the influence 429 of thermal convection on the increase of glazing temperature was considerably 430 significant than that in open space fire. Furthermore, the width of the fire plume was slightly smaller than that of the glazing, which resulted to a relatively substantial 431 432 thermal gradient along the horizontal direction. Therefore, the temperatures measured 433 by TC09 and 10, both located at the middle line of the glazing surface at the exposed 434 side, were higher than those of other monitoring points. In addition, because of the hot gas that accumulated on the upper part of the cabinet under the action of buoyancy, the 435 heat convection intensity at the upper part of the glass pane was relatively larger than 436 437 that at the lower part. Consequently, the temperature measured by TC10 was higher 438 than that measured by TC09. Although the center of the ambient side surface temperature (TC16) was relatively lower after ignition, because glass is a poor heat 439 440 conductor, after 40 s, the temperature rapidly rose to a level considerably higher than 441 those of other monitoring points at the ambient side. From an overall perspective, the 442 temperature measured at the exposed side surface was relatively higher than that at the 443 ambient side surface, mainly because the radiant heat from the fire source was blocked 444 by the glass frame. Thus, the ambient side surface was primarily heated through heat conduction from the exposed side surface. As for the comparison among the 445 446 experimental results of the various cases that were conducted under the same fire 447 condition, it was found that the most evident difference among them was the 448 temperature variance of covered areas at the exposed and ambient side because of the 449 different point-covered areas. The exposed area of the glass pane at the fire side was 450 directly heated by the radiation and convection from the flames and hot gas, respectively. 451 Thus, the rate of temperature increase at the exposed area was faster than that at the 452 covered area. With the increased temperature at the point-covered area, the heating rate 453 at that area significantly decreased. Therefore, breakage conditions are determined by 454 the temperature difference between the exposed and point-covered areas. The 455 temperature difference on the glazing surface is defined as follows:

456 
$$T_h = \frac{T_2 + T_4 + T_6 + T_8 + T_9 + T_{10}}{6}$$
(17)

457 
$$T_c = \frac{T_1 + T_3 + T_5 + T_7}{4}$$
(18)

$$\Delta T_{h-c} = T_h - T_c \tag{19}$$

459 where,  $T_i$  is the temperature measured by TCi;  $T_h$  is the average temperature of the exposed area on the exposed side;  $T_c$  is the average temperature of the supporting point-460 461 covered area on the exposed side;  $\Delta T_{h-c}$  is the temperature difference between these two regions. All critical values at the time of the first breakage are summarized in Table 6. 462 463 It was found that for Case 1, temperature differences at breakage time were distributed 464 in the range 117-126 °C, which is considerably lower than the range 122-142 °C 465 calculated in Case 2 and 139-150 °C calculated in Case 3. These results further 466 suggested that a relatively lager point-covered area had better fire resistance. 467



468 469

(a) Temperature variance in Test 2 of Case 1



(b) Temperature variance in Test 2 of Case 2 (c) Temperature variance in Test 1 of Case 471 472 3 473

Fig. 9. Temperatures at different monitoring points.

470

#### 475 Table 6

476	The temperatures a	t the time	of the	first breakage
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		Exposed	Ambient	Gas	Temperature	Average
Case	Test	center $T_0$ (°C)	center,	temperature,	difference $\Delta T$ (°C)	(°C)
no.	no.	contor, 19 ( C)	<i>T</i> <sub>16</sub> (°C)	<i>T</i> <sub>11</sub> (°C)	aniformed, $\Delta I_{h-c}$ (C)	( C)
1	1	222	105	388	117	
	2	185	76	319	122	
	3	207	94	311	126	122
	4	198	102	314	121	
2	1	245	127	327	133	
	2	250	118	322	142	
	3	267	120	328	137	134
	4	242	114	339	122	
3	1	378	190	485	150	
	2	348	145	453	141	
	3	376	182	494	154	146
	4	364	177	464	139	

477

#### 478 5. Numerical results and comparison with experimental results

479 As summarized in Table 7, the maxima of the first principal stresses before the time 480 of the first breakage were all around 50 MPa. These results suggested that the ultimate 481 tensile strength was an essential parameter for predicting glass breakage. The first 482 breakage times predicted by the simulation of Test 2 of Case 1, Test 2 of Case 2, and Test 1 of Case 3 were 131, 155, and 200 s, respectively, which agreed well with 483 484 experimental results (130, 150, and 185 s, respectively). These results are within the 485 allowable range because of the simplification of the boundary condition. It was found that  $\sigma_{xx}$  was not consistent with  $\sigma_{yy}$  primarily because of the asymmetry of the 486 temperature field. The simulation results further suggested that the larger the point-487 488 covered area is, the shorter the first breakage time will be. Hence, the results of this 489 numerical simulation have implications on the design for point-covered areas of point490 supported glass assemblies under the premise of structural strength.

491

#### 492 **Table 7**

493 Numerical simulation results.

-	-	First breakage time (s)				
Case no.	Test no.	Experiment	Simulation	$S_{1\max}$ (MPa)	<u> <math>\sigma_{xxmax}</math></u> (MPa)	<u><math>\sigma_{\text{vvmax}}</math></u> (MPa)
1	2	130	131	50.97	44.19	44.33
2	2	150	155	50.66	49.11	47.72
3	1	185	200	50.91	48.94	48.79

494

495 To determine the location of crack initiation, the distributions of the first principal 496 stresses in the x and y directions were calculated. Note that a stress greater than zero, 497 represented tensile stress; otherwise, it represented compressive stress. Consider Test 2 498 of Case 1 as an example. Before the first breakage, the maximum stress, which was 499 significantly larger than the stress in other regions, was located at the supporting point edge, as shown in Fig. 10(a). Moreover, the location of crack initiation, which satisfied 500 501 the Coulomb-Mohr criterion, was also the location of the maximum of the first 502 principal stress. The location of the crack initiation was consistent with the stress 503 distribution. The results of other cases were similar to the above, where all cracks were 504 initiated at the supporting point edge. It was observed from Fig. 10(b) that the maximum 505 of the first principal stress appeared at the lower right, at the supporting point edge, 506 which was subjected to the maximum tensile stress. It is noteworthy that the supporting 507 point edge often had a large number of minor flaws or defects because of the drilling 508 process, which made this area more prone to cracking. Furthermore, the glass pane was 509 subjected to compressive stresses with a maximum of -25.27 MPa. However, glass 510 compressive strength is 10 times a strong as tension. Therefore, it was easier to initiate 511 cracks from these locations with the maximum tensile stress, which agreed well with 512 experimental results.

513

514 515



(a) First principal stress



(b) First principal stress at the lower right of support point



520 In order to provide a more intuitive understanding of the distribution of the first 521 principal stress in the experiments, the first principal stress variance is illustrated in Fig. 522 11. Consider Fig. 11(e) as an example. Point 1 is located at the center of the glass pane 523 and Points 2-5 represent the maximum values of the first principal stress in the point-524 covered regions. Because the central area had the same instantaneous temperature, the 525 first principal stress at Point 1 was significantly smaller than those in other regions. As 526 shown in Fig. 11(f), it was found that because of the increased temperature difference 527 between the point-covered and exposed areas, the maximum stresses in the x and y 528 directions, and the maximum principal stress, gradually increased. At the time of the 529 first breakage, the maximum stresses in the x and y directions were 48.94 and 48.79MPa, 530 respectively. The maximum stress in the x direction was not consistent with the ydirection stress because of the asymmetry of the temperature field. The simulation 531 532 results suggested that the trend of the first principal stress variance at Points 2-5 were practically similar to the stress trend shown in Fig. 11(f). 533





537 538

535



#### 547 **6.** Conclusions

To determine the influence of various point-covered areas in a fire environment, 12 experiments were performed. A number of essential parameters, such as the first breakage time, final fall out ratio, incident heat flux, glass surface and ambient air temperatures, and heat release rate, were recorded to analyze the breakage behavior of the glazing assembly. Numerical simulation was employed to reveal the stress distribution, and predict the breakage time and crack initiation. The specific conclusions are as follows:

The experimental results suggested that the larger the supporting point-covered 555 1. area was, the shorter the elapsed time was for the first cracking of the glazing 556 557 assembly to occur. The reference breakage times,  $t_r$ , which were calculated by 558 setting the failure probability to 0.1 of the two-parameter Weibull distribution, 559 were 119, 140, and 166 s for Cases 1-3, respectively. Thus, from the perspective 560 of breakage time, a relatively small point-covered area is recommended for the 561 point-supported glass curtain walls under the premise of structural strength in 562 engineering practice.

- 563
  2. It was established that with the increase in the main fracture process times, the
  564 numbers of cracks would increase, and that the smaller the point-covered area
  565 is, the larger the final fall out ratio of glazing assemblies will be.
- In this study, the first breakage time predicted by FEM analysis in relation to the
  effect of the drilled circular hole and point-covered area, agreed well with
  experimental results. Thus, the numerical model could be used in the fireresistance evaluation of point-supported glazing assemblies.

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- 579
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- 583

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