The University of Edinburgh

Thermal breakage of glass façades under fire conditions

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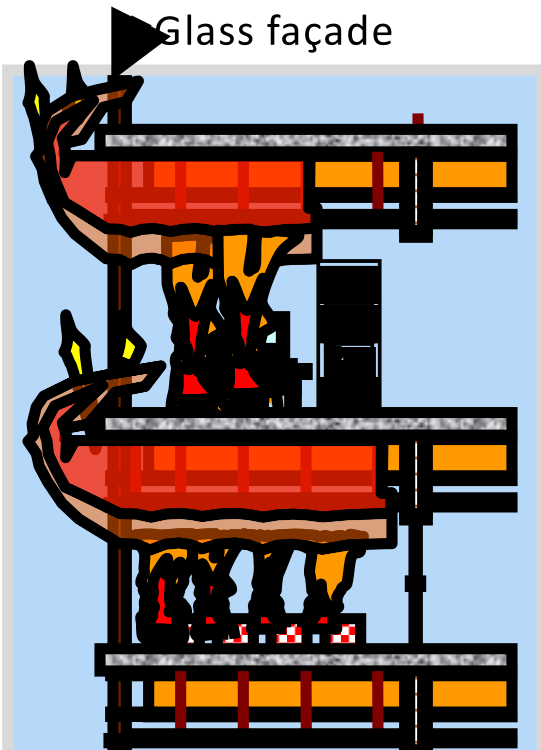
Outline

- Background
- Breakage mechanism
- Different installation
- Different glass type
- Sensitivity analysis of all factors
- Conclusions

Background



Breakage of glass façade:

- plays a key role in compartment fire
- accelerates the fire spread
- needs to be revealed to provide reference for fire safety design of building façades

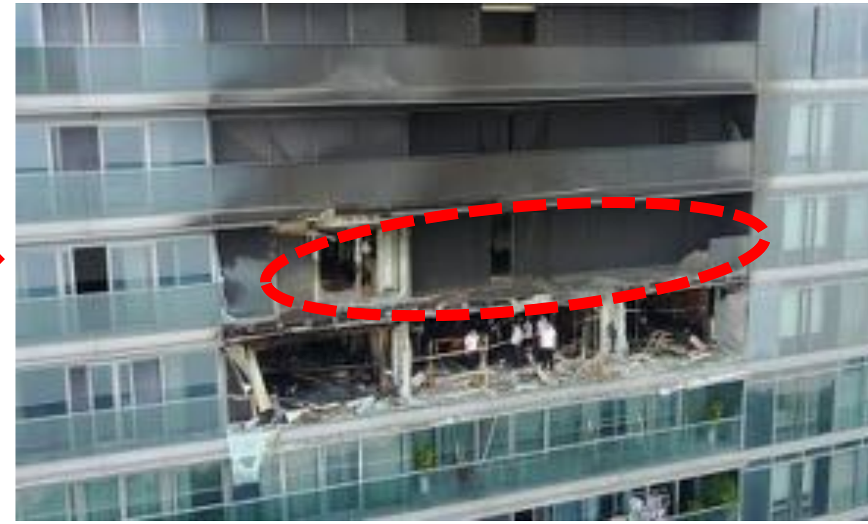
Background

Accident cases:

3.27.2006. **Urumqi city hotel**
Compartment fire broke windows and spread to the upstairs causing the destruction of the whole building and caused 97 died.

2.3.2011. **The Dynasty Wanxin International Hotel**
The fireworks ignited exterior wall and big fire broke the window into the apartment.

Background



Hangzhou China, June 2017, four death

New York USA, April 2018, one death

Background

Fire safety of glass:

1. Firstly proposed by Emmons in 1st IAFSS (1986): one ***structural problem of importance*** to fire growth

2. Pagni, Keski-Rahkonen et al. ***Theoretical model***: heat transfer, stress prediction

3. Skelly, Shields and Harada et al. ***Experimental investigation*** for critical temperature difference

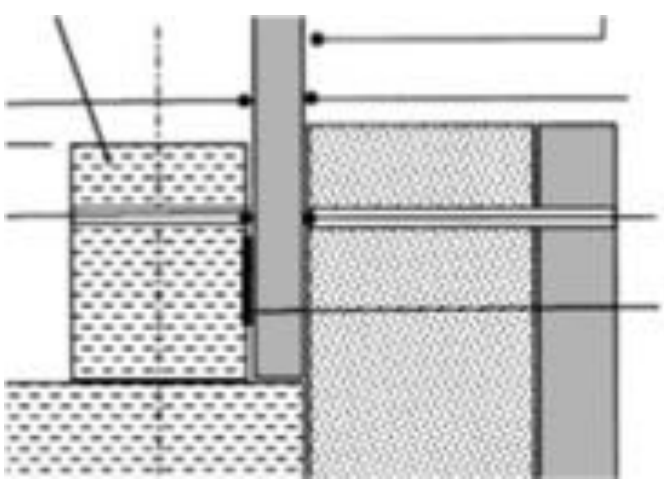
4. Wen, Dembele and Pagni et al. ***Numerical simulation*** for breakage time prediction

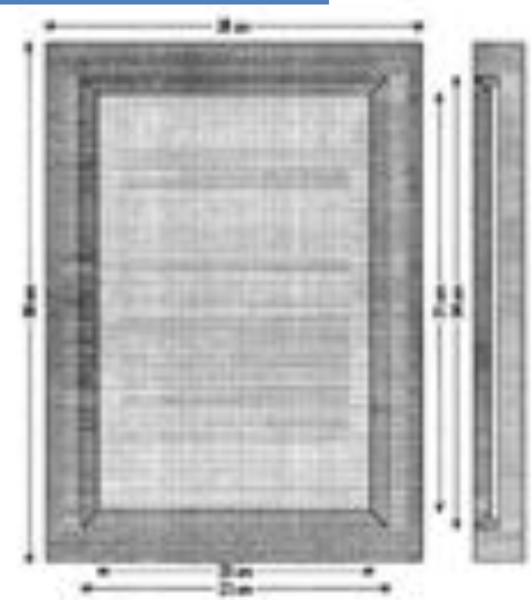
Consensus researched: ***thermal gradient*** between exposed and covered areas

Background

Prior investigations were focused on edge covered window glass pane

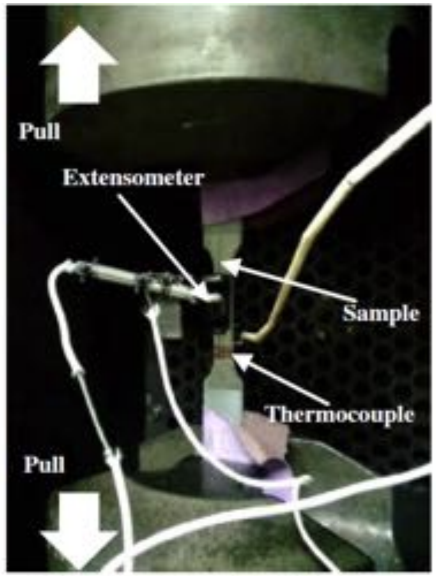
Glass façades
Different installation forms
Different glass type
Mechanism





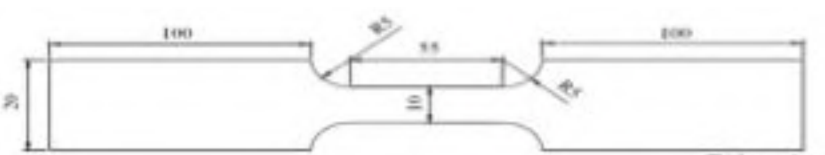
Mechanism

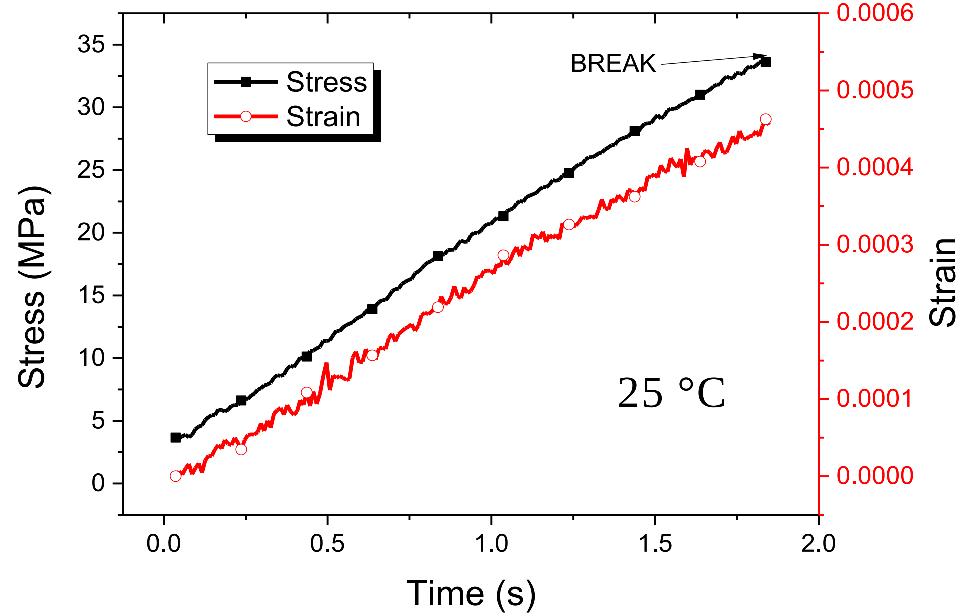
(a) Heating chamber

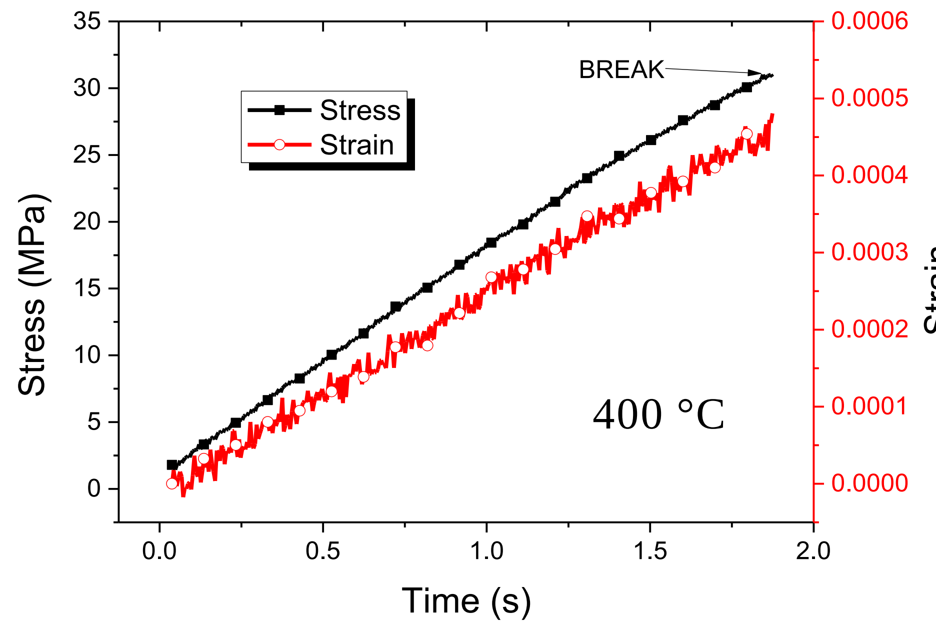


(b) Glass sample during testing

(c) Control system

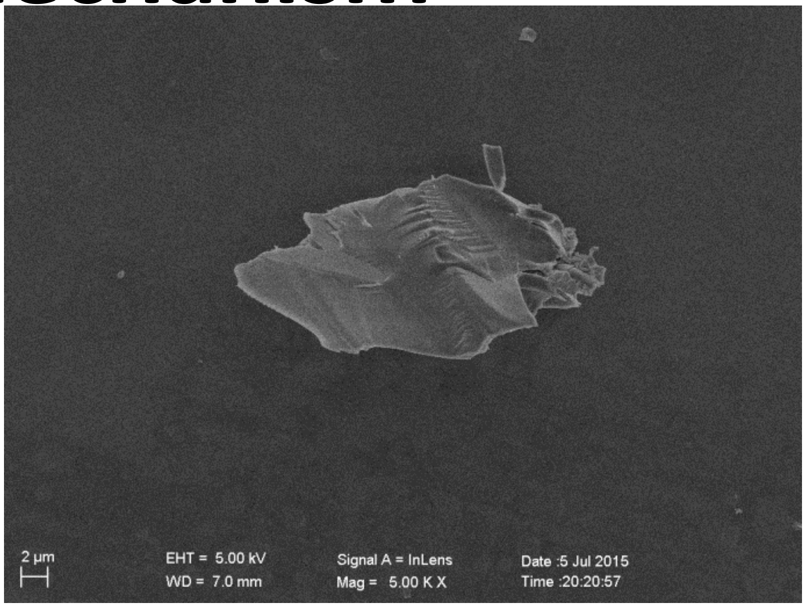


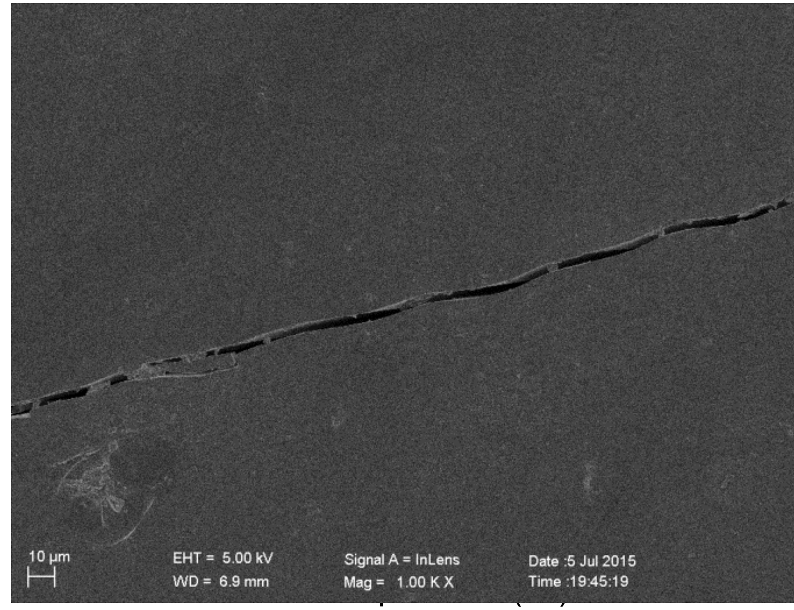




[1] Y. Wang, Q. Wang, G. Shao, H. Chen, J. Sun, L. He, K.M. Liew, Experimental study on critical breaking stress of float glass under elevated temperature, Materials & Design, 60 (2014) 41-49.

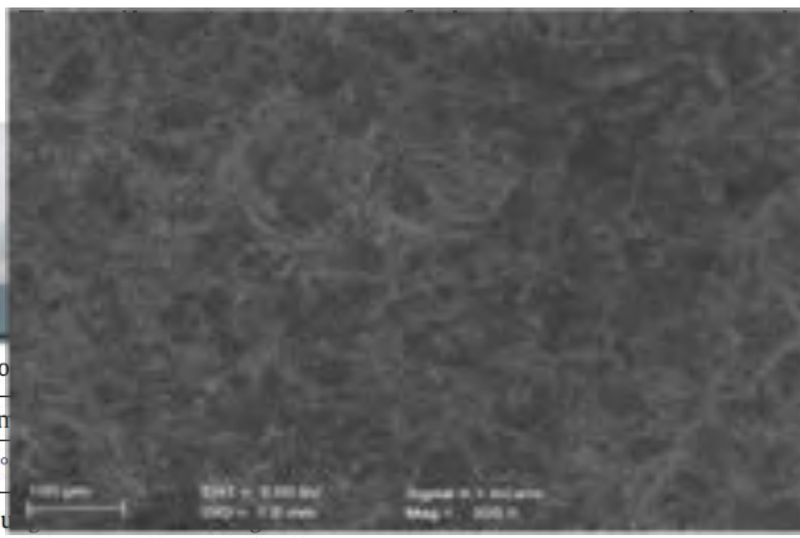
Mechanism





Variance at different temperatures
75-120°C minimum

The flaws caused by manufacturing reduce the strength of the glass significantly



The co

Sam			3	4	5	Average
β (°			8.53 × 10^{-6}	8.35 × 10^{-6}	8.63 × 10^{-6}	8.46 × 10^{-6}

The You

Sample no.	1	2	3	4	5	6	7	Average
E (GPa)	68.73	66.03	67.47	63.78	69.37	68.34	66.76	67.21

[1] Y. Wang, Q. Wang, G. Shao, H. Chen, J. Sun, L. He, K.M. Liew, Experimental study on critical breaking stress of float glass under elevated temperature, Materials & Design, 60 (2014) 41-49.

Mechanism

Stochastic analysis

Weibull distribution:

$$F_X(x) = 1 - \exp\left[-\left(\frac{x-\delta}{\theta}\right)^{\beta}\right]$$

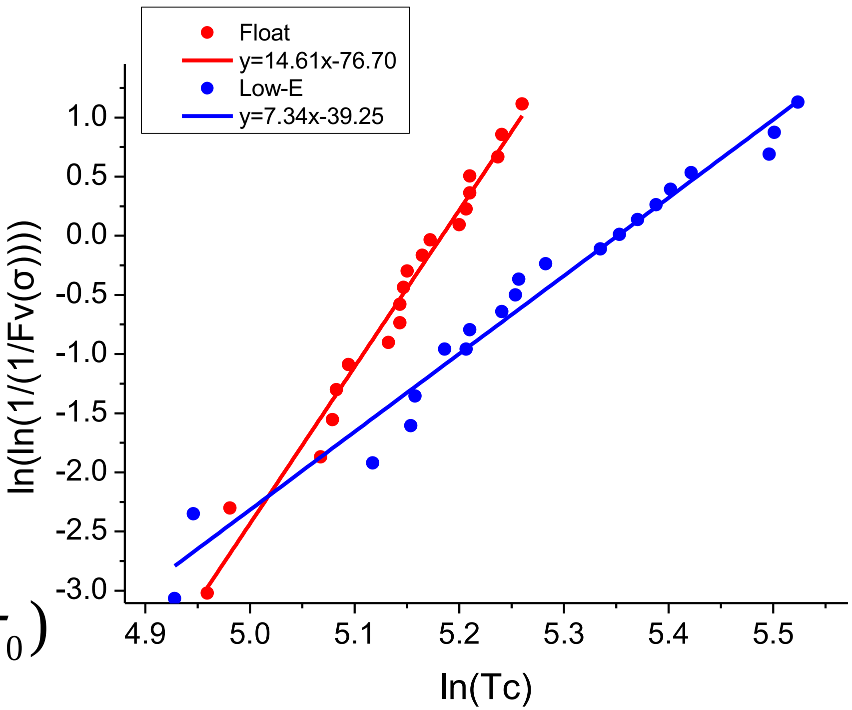
θ scale parameter, β shape parameter, δ location parameter

Weakest-link theory:

$$F_n(\sigma) = 1 - \left[1 - F(\sigma)\right]^n$$

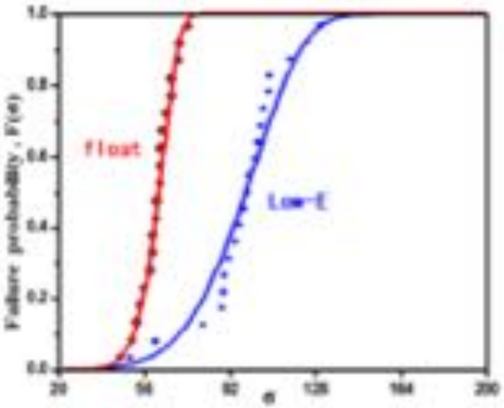
$$\ln\left[\ln\left(\frac{1}{1-F_V(\sigma)}\right)\right] = m\ln(\sigma) - m\ln(\sigma_0)$$

$$F_V(\sigma) = \frac{i-0.3}{N+0.4}$$



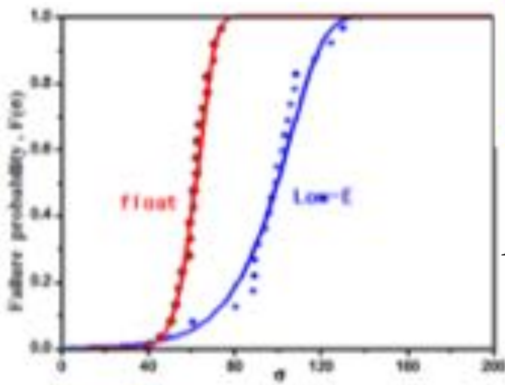
[2] Q. Wang, Y. Wang, Y. Zhang, H. Chen, J. Sun, L. He, A stochastic analysis of glass crack initiation under thermal loading, Appl. Therm. Eng., 67 (2014) 447-457.

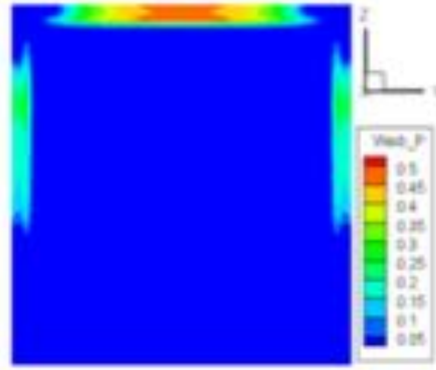
Mechanism



Breaking stress △
T~two parameter Weibull

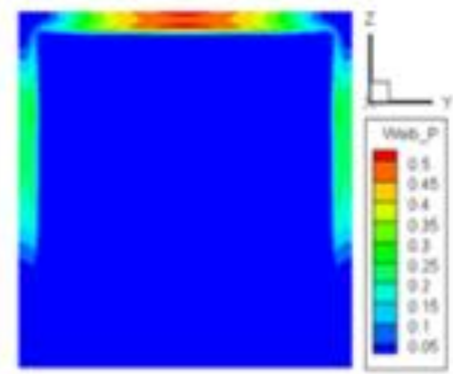
Breaking stress △
T~three parameter Weibull





$$F(\sigma_b) = 1 - exp[(\frac{\sigma_b}{\sigma_0})^m]$$

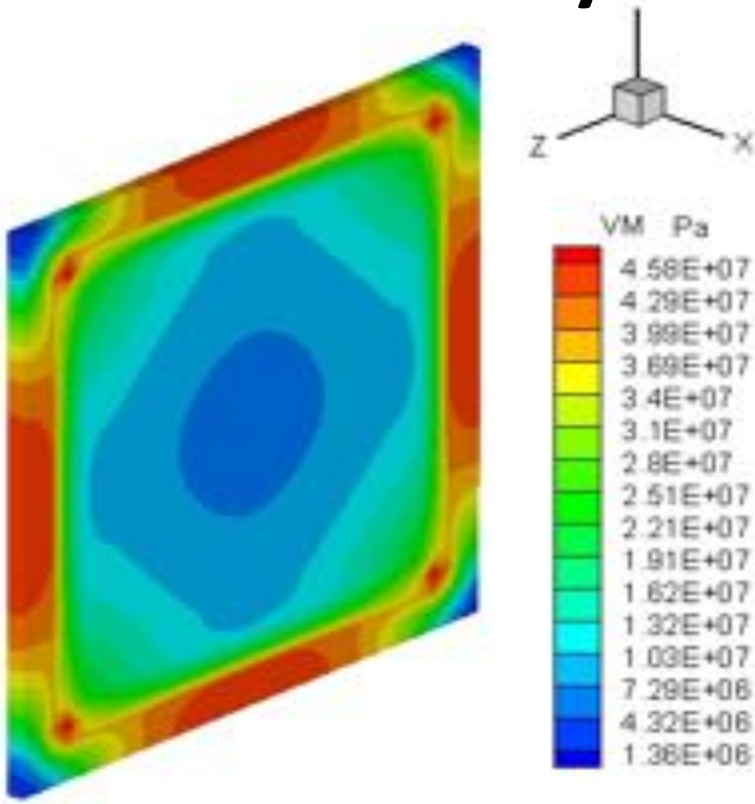
$$F(\sigma_b) = 1 - \exp[(\frac{\sigma_b - \sigma_u}{\sigma_0})^m]$$

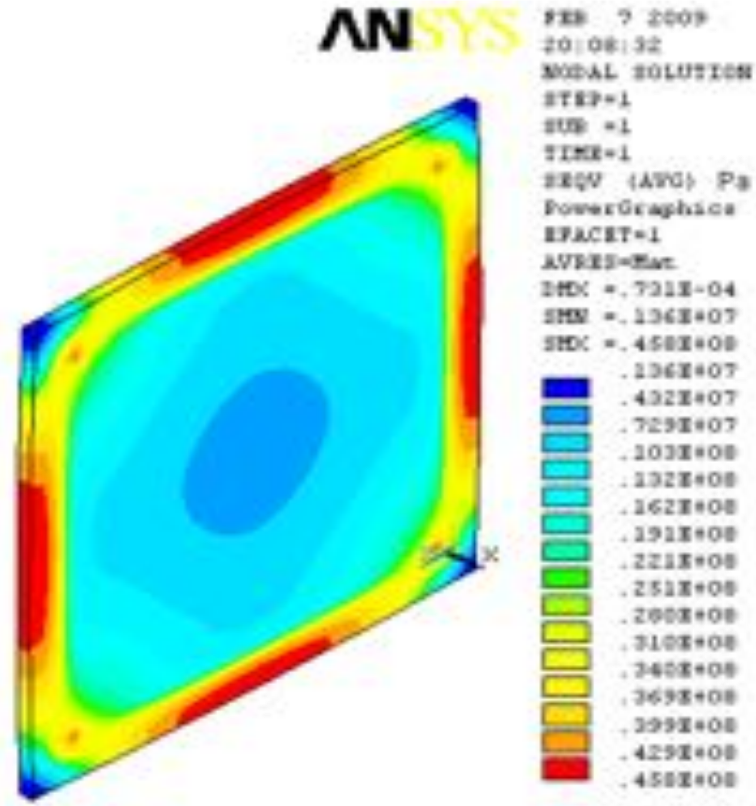


Glass type	Weibull function	*m*	σ_0 (MPa)	σ_u(MPa)	σ_z(MPa)
Float	2 parameter	9.93	63.94	--	50.97
	3 parameter	7.91	52.57	11.36	50.90
Low-E	2 parameter	5.64	104.43	--	70.07
	3 parameter	657.08	10512.00	−10407.00	69.03

[2] Q. Wang, Y. Wang, Y. Zhang, H. Chen, J. Sun, L. He, A stochastic analysis of glass crack initiation under thermal loading, Appl. Therm. Eng., 67 (2014) 447-457.

Mechanism
Deterministic analysis





Thermal stress model

$$(\lambda + 2G)\nabla^2 e - \beta \nabla^2 T = 0$$

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

FEM equation：

$$\left(\sum_{e=1}^{E}[K^{(e)}]\right)\underset{\sim}{\vec{Q}} = \underset{\sim}{\vec{P}}_c + \sum_{e=1}^{E}(\vec{P}_i^{\,e} + \vec{P}_s^{\,e} + \vec{P}_b^{\,e}) = \underset{\sim}{\vec{P}}$$

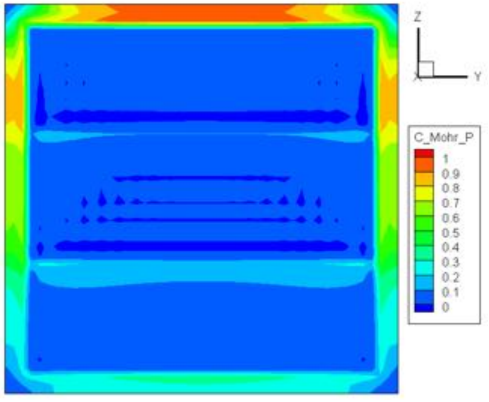
$$\vec{P}_i^{(e)} = \iiint_{V^{(e)}} [B]^T[D]\,\vec{\varepsilon}_0\, dV \qquad [K^{(e)}] = \iiint_{V^{(e)}} [B]^T[D]\,[B]dV$$

$$\vec{P}_b^{(e)} = \iiint_{V^{(e)}} [N]^T\, \vec{\bar{\phi}}\, dV$$

[3] Q.S. Wang, Y. Zhang, Y. Wang, J.H. Sun, L.H. He, Dynamic three-dimensional stress prediction of window glass under thermal loading, Int J Therm Sci, 59 (2012) 152-160.

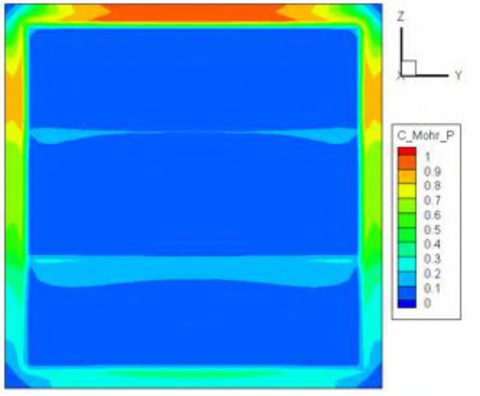
Mechanism

Maximum Principal Stress Criterion



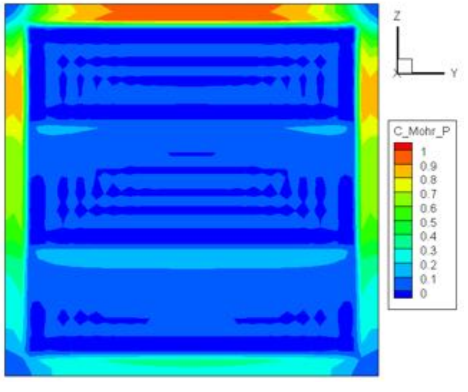
$$\frac{\sigma_1}{S_{\text{ut}}} \geq 1$$

Coulomb-Mohr Criterion



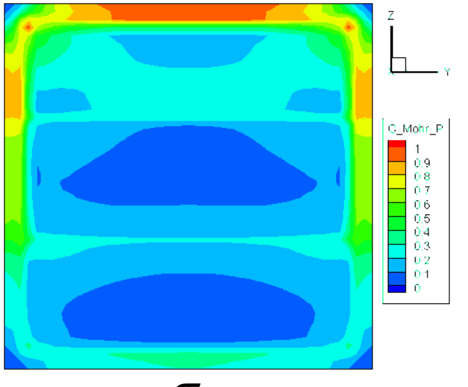
$$\frac{\sigma_1}{S_{\text{ut}}} - \frac{\sigma_3}{S_{\text{uc}}} \geq 1$$

Maximum Normal Stress Criterion



$$\max(\sigma_1, \sigma_2, \sigma_3) \geq S_{\text{ut}}$$

Maximum Mises Stress Criterion

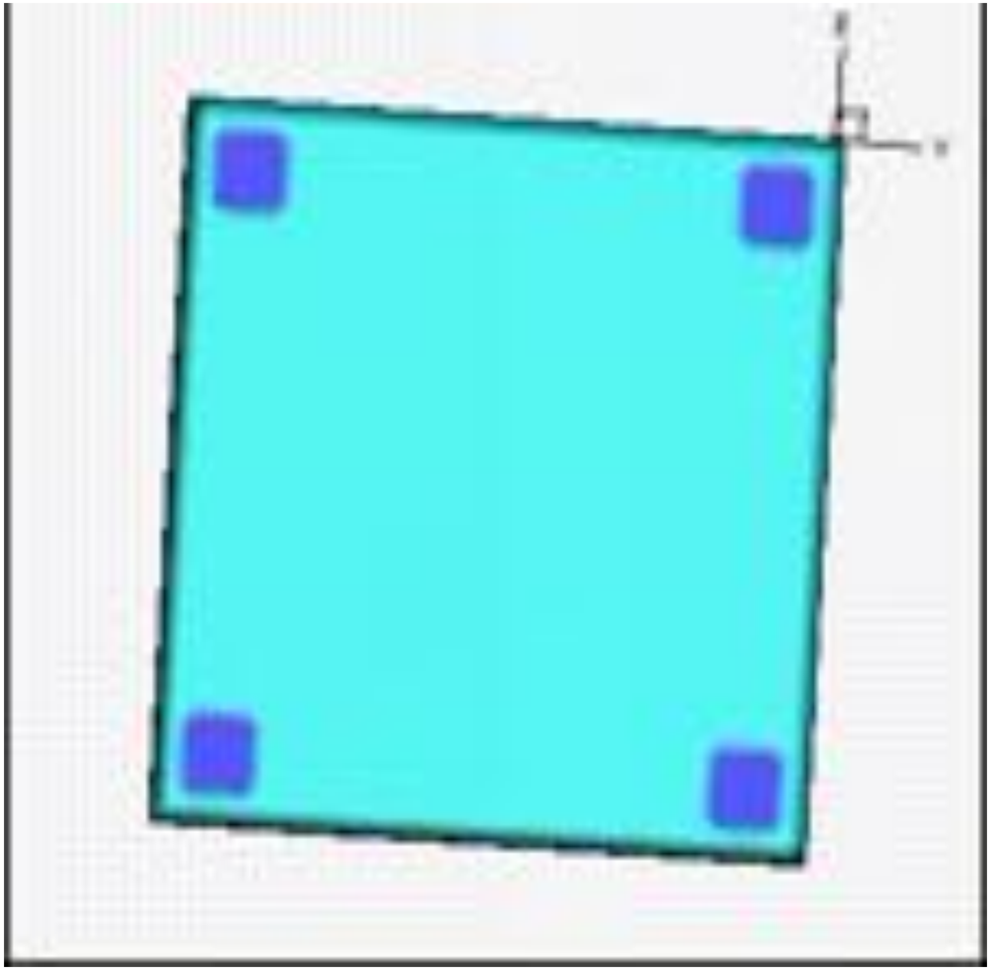


$$\frac{\sigma_{\text{vm}}}{0.577 S_{\text{ut}}} \geq 1$$

[4] Y. Wang, Q. Wang, H. Chen, J. Sun, L. He, Comparative Study on Crack Initiation and Propagation of Glass under Thermal Loading, Materials, 9 (2016) 794.

Mechanism

- Crack propagation criteria



1. Mixed-mode criterion based on SIFs

$$\left(\frac{K_{\mathrm{I}}}{K_{\mathrm{IC}}}\right)^2 + \left(\frac{K_{\mathrm{II}}}{K_{\mathrm{IIC}}}\right)^2 = 1$$

2. Mixed-mode criterion based on energy release rates

$$\left(\frac{G_{\mathrm{I}}}{G_{\mathrm{IC}}}\right)^\alpha + \left(\frac{G_{\mathrm{II}}}{G_{\mathrm{IIC}}}\right)^\beta + \left(\frac{G_{\mathrm{III}}}{G_{\mathrm{IIIC}}}\right)^\eta = 1$$

$G_{\mathrm{IC}} = G_{\mathrm{IIC}} = G_{\mathrm{IIIC}} = G_{\mathrm{C}}$, α, β and η=1

3. SIF-based maximum circumferential stress criterion

$$K_{\mathrm{Ieff}} = K_{\mathrm{I}} + B \mid K_{\mathrm{III}}$$

[4] Y. Wang, Q. Wang, H. Chen, J. Sun, L. He, Comparative Study on Crack Initiation and Propagation of Glass under Thermal Loading, Materials, 9 (2016) 794.

Mechanism revealed,

Then?

Full scale experiments!

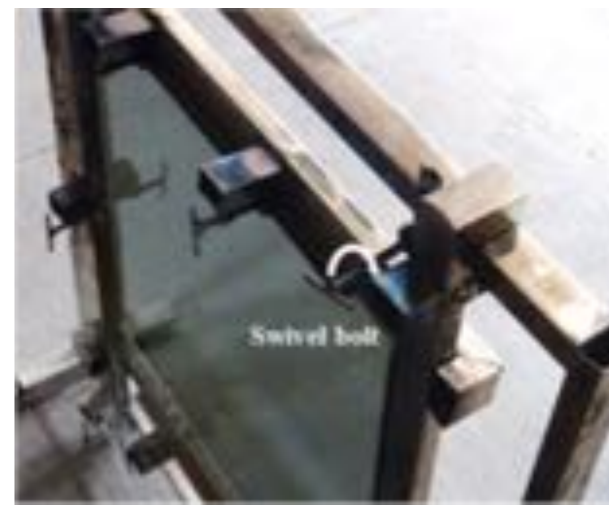
Installation form: frame supported glass

Exposed frame

Horizontal-hidden frame

Vertical-hidden frame

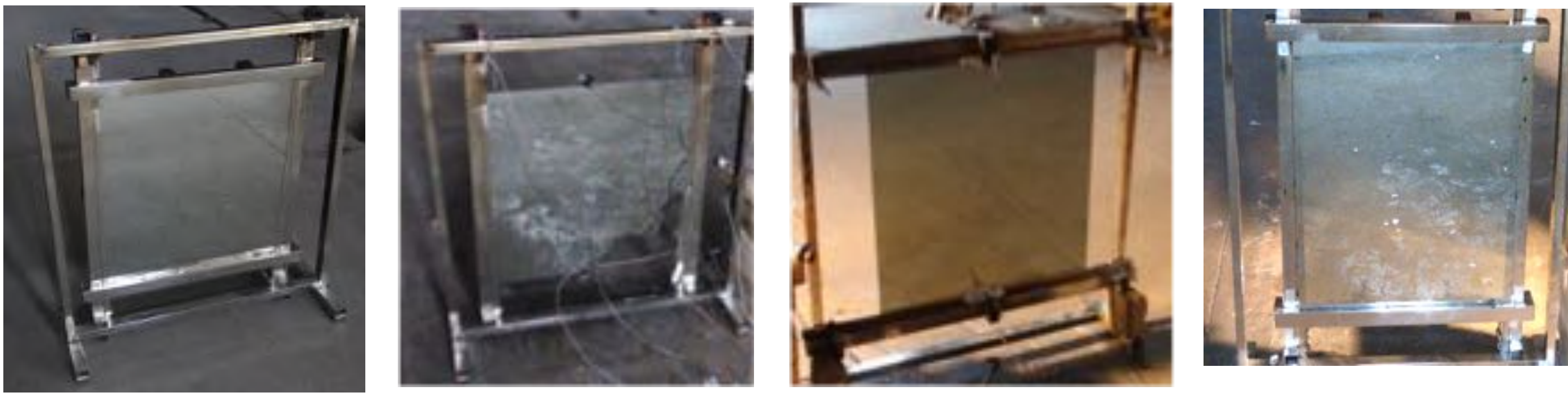
Hidden frame



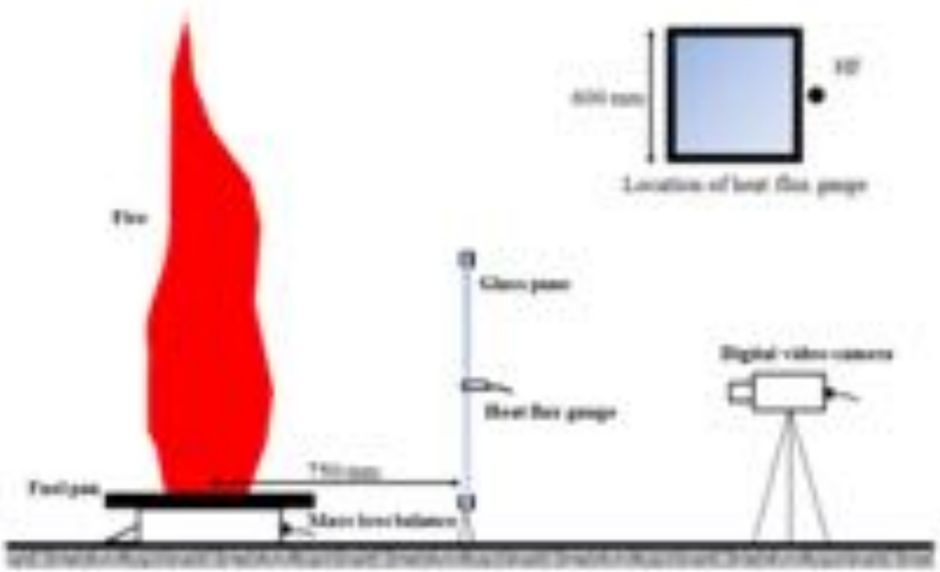
Glass frame setup in the experiment

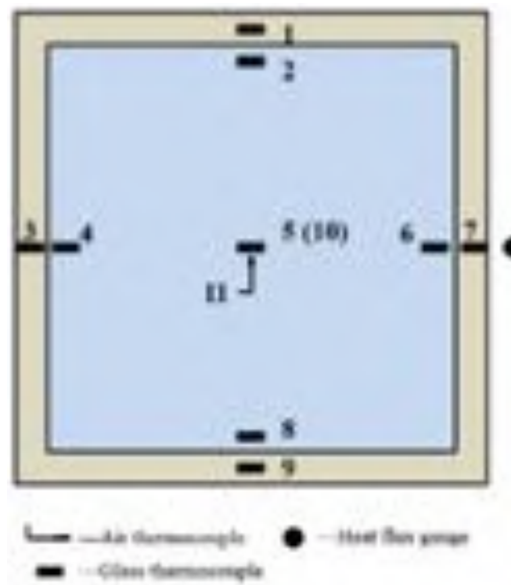
[6] Y. Wang, Q. Wang, Y. Su, J. Sun, L. He, K.M. Liew, Fracture behavior of framing coated glass curtain walls under fire conditions, Fire Saf. J., 75 (2015) 45-58.

Frame supported glass façades



Cases design

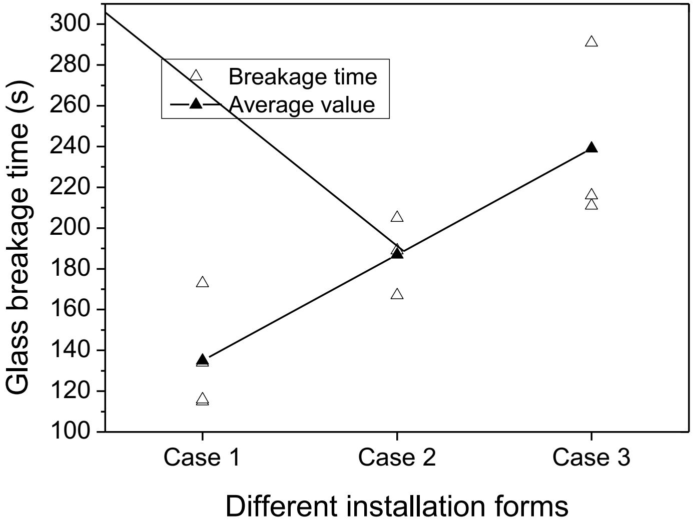


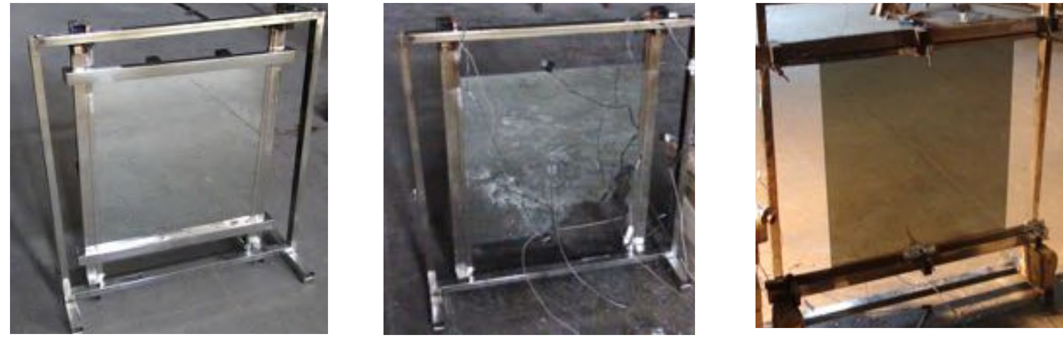


- 16 tests, for four different installation forms of framing glass

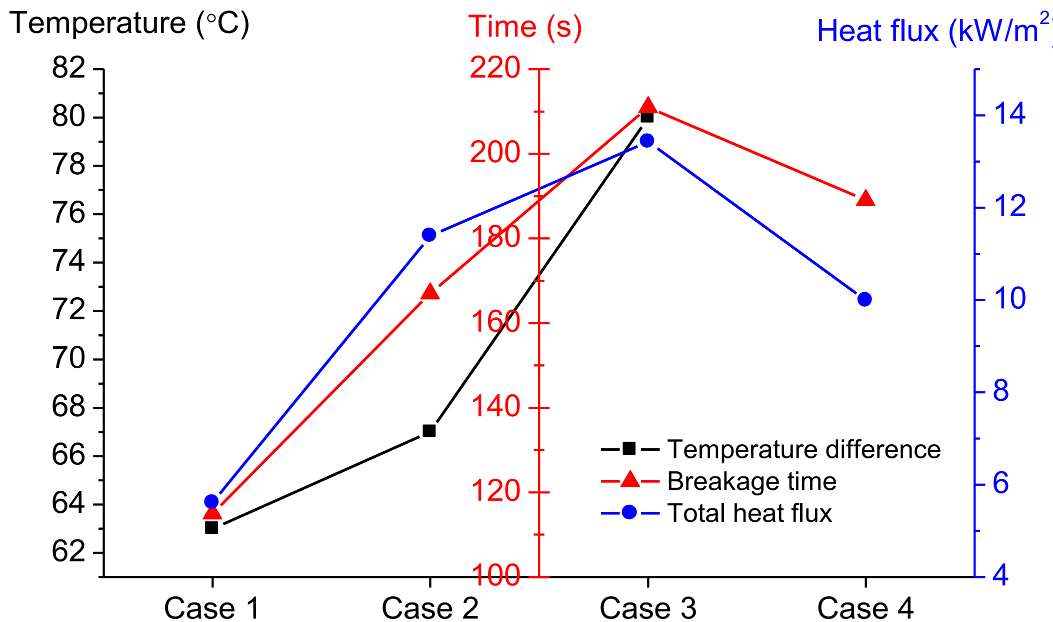
[6] Y. Wang, Q. Wang, Y. Su, J. Sun, L. He, K.M. Liew, Fracture behavior of framing coated glass curtain walls under fire conditions, Fire Saf. J., 75 (2015) 45-58.

Frame supported glass façades





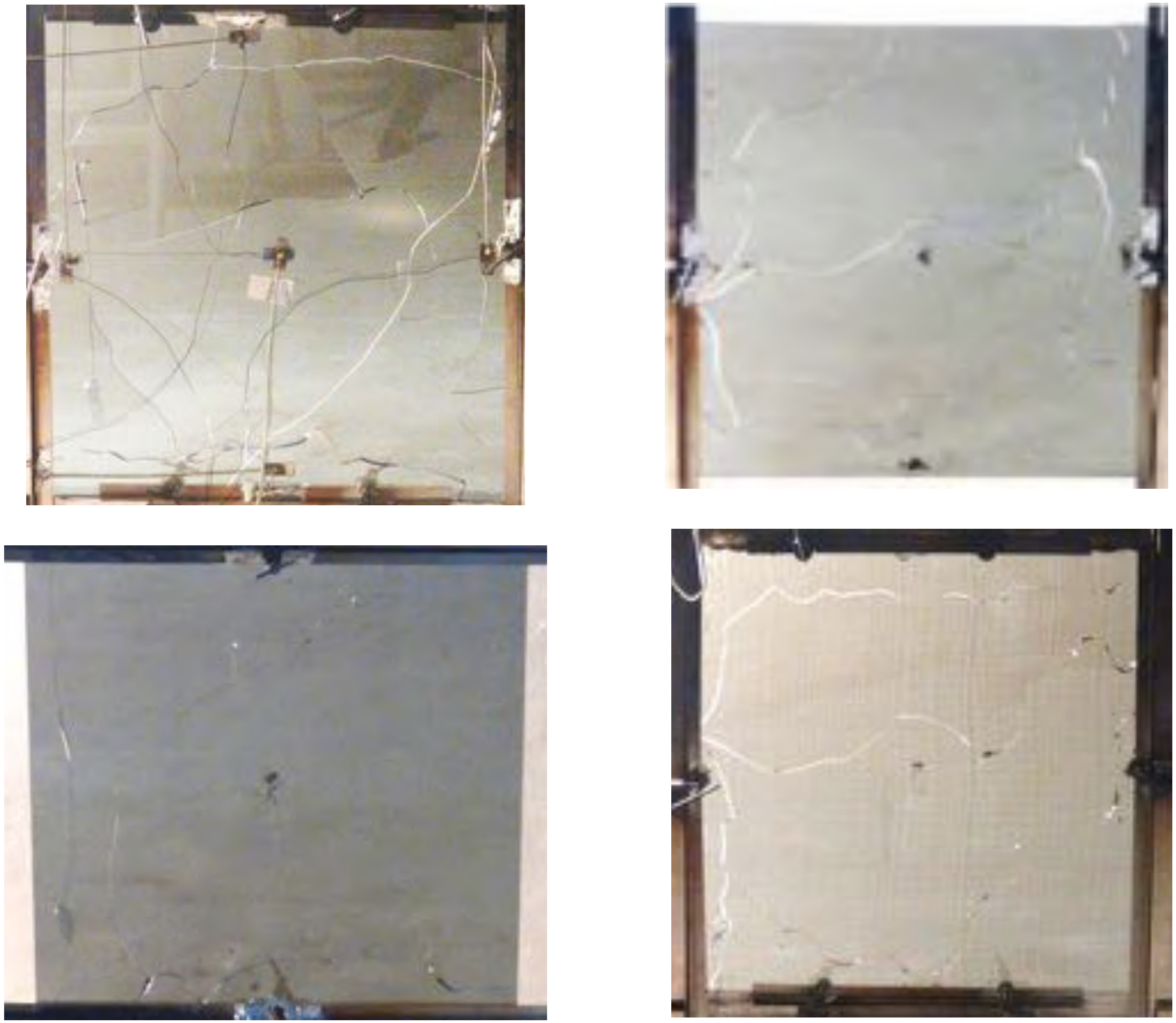
Comparison of breakage time



Comparison of critical parameters

[6] Y. Wang, Q. Wang, Y. Su, J. Sun, L. He, K.M. Liew, Fracture behavior of framing coated glass curtain walls under fire conditions, Fire Saf. J., 75 (2015) 45-58.

Frame supported glass façades



Post crack

[6] Y. Wang, Q. Wang, Y. Su, J. Sun, L. He, K.M. Liew, Fracture behavior of framing coated glass curtain walls under fire conditions, Fire Saf. J., 75 (2015) 45-58.

Frame supported glass façades

Dynamic Equation :

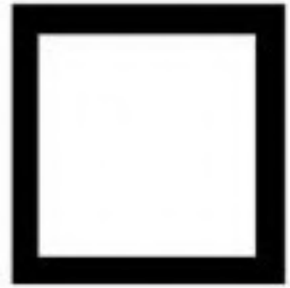
$$\mathbf{M\ddot{U}} + \mathbf{C\dot{U}} + \mathbf{KU} = \mathbf{R}$$

Coulomb-Mohr criterion:

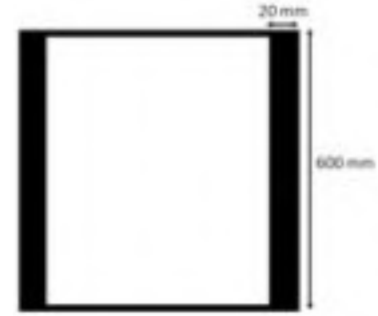
$$\frac{\sigma_1}{S_{ut}} - \frac{\sigma_3}{S_{uc}} \geq 1$$

SIFs based mixed-mode criterion:

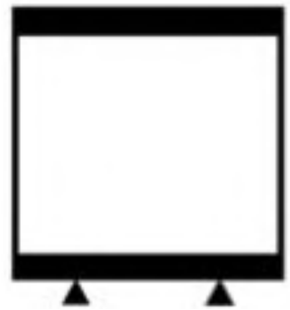
$$\left(\frac{K_{I}}{K_{IC}}\right)^2 + \left(\frac{K_{II}}{K_{IIC}}\right)^2 = 1$$



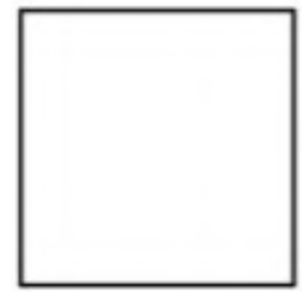
Simulation 1



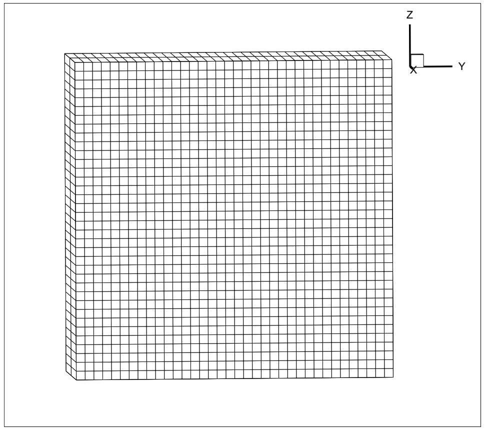
Simulation 2

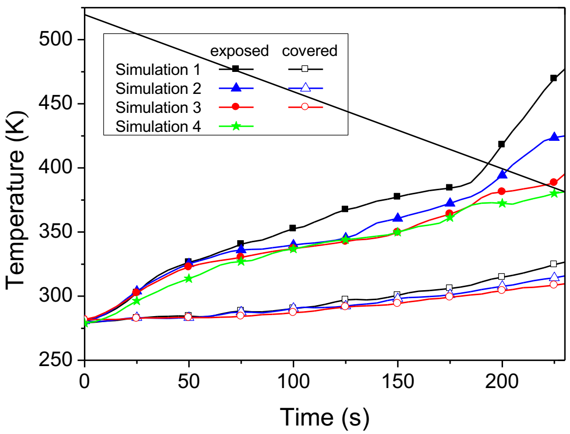


Simulation 3



Simulation 4





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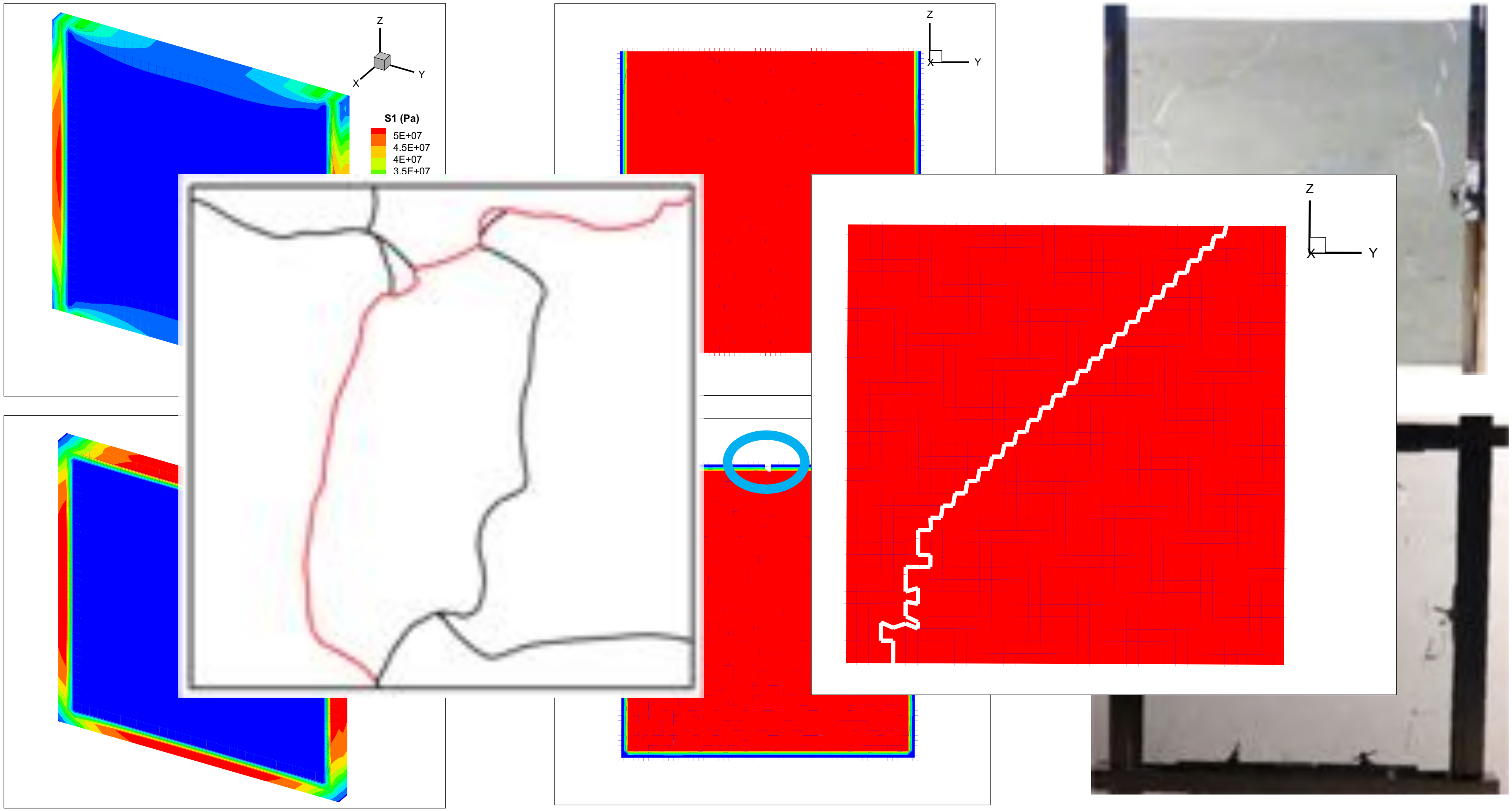
Frame supported glass façades

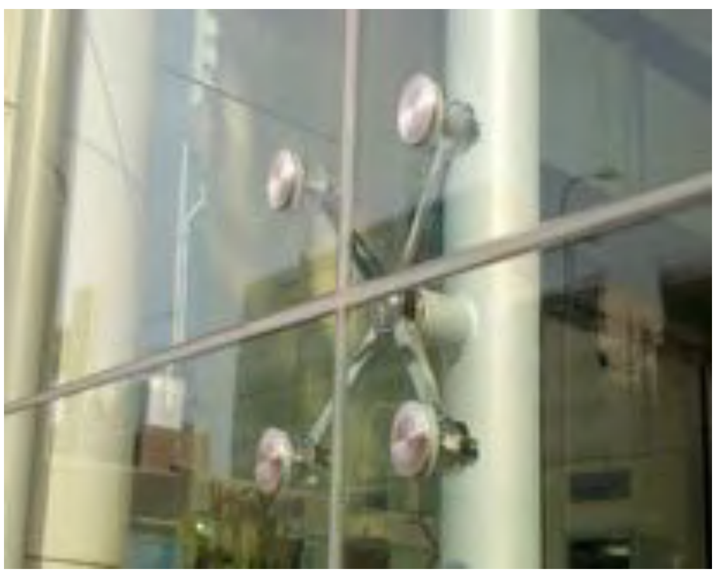


Strss distribution | Crack initiation position | Experimental results

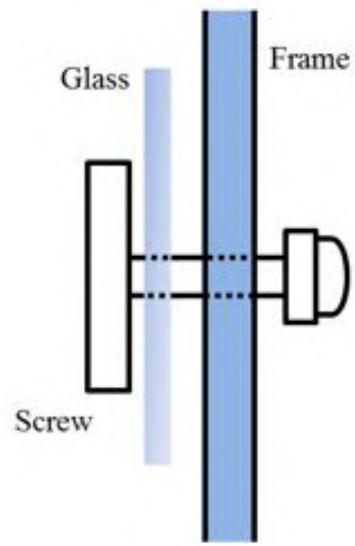
- Experimental Breakage time: 173 s, 205 s, 216 s
- Calculated breakage time: 175 s, 205 s, 225 s

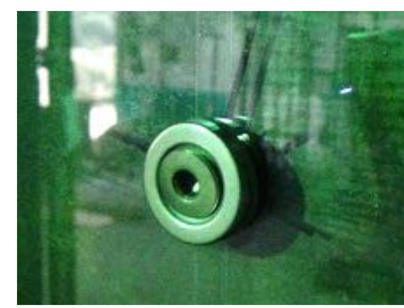
[6] Y. Wang, Q. Wang, Y. Su, J. Sun, L. He, K.M. Liew, Fracture behavior of framing coated glass curtain walls under fire conditions, Fire Saf. J., 75 (2015) 45-58.

Installation form: point supported glass



Point supported glass

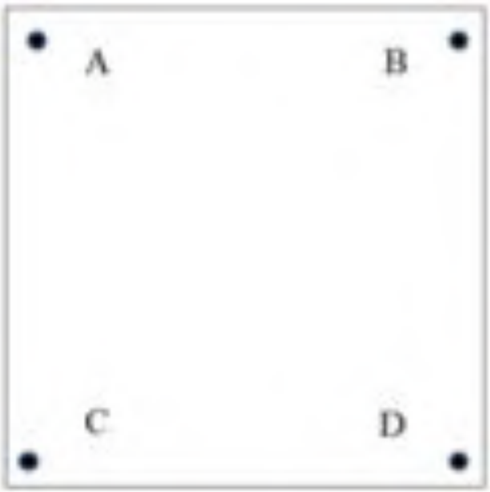


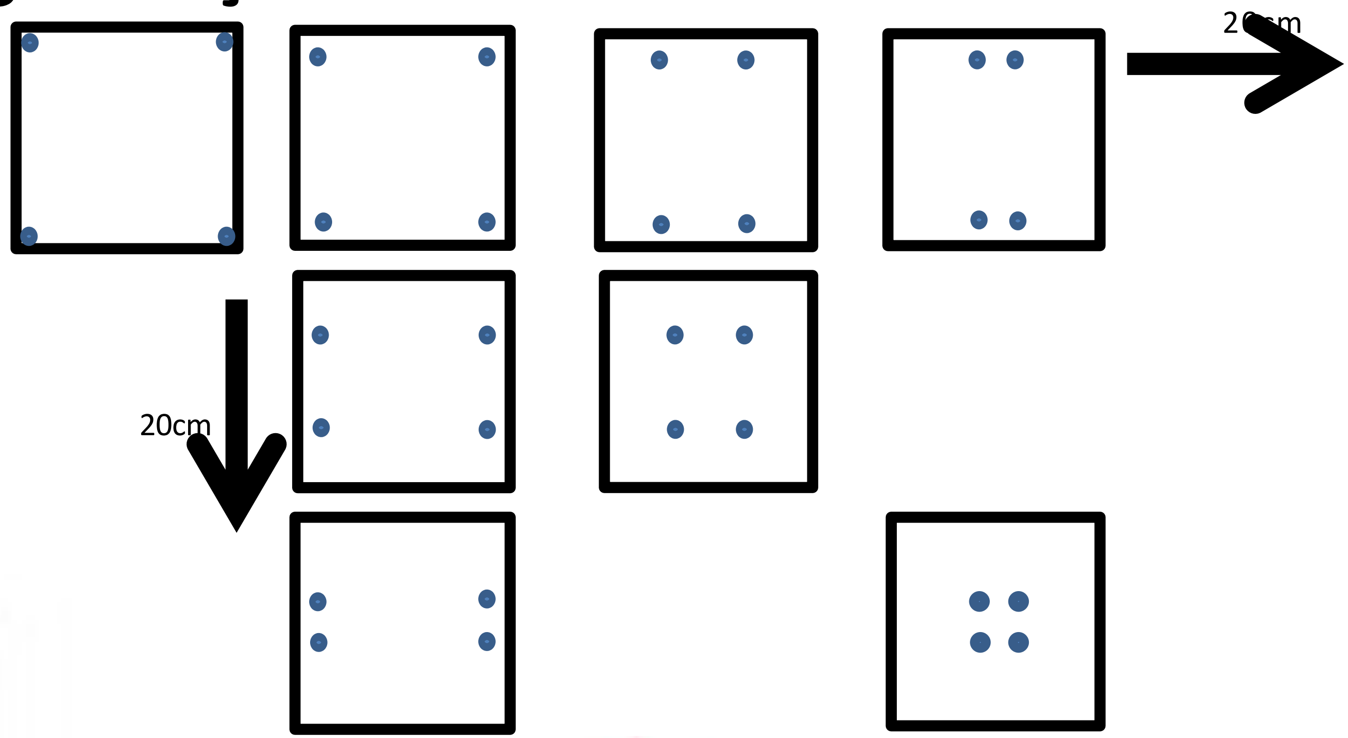


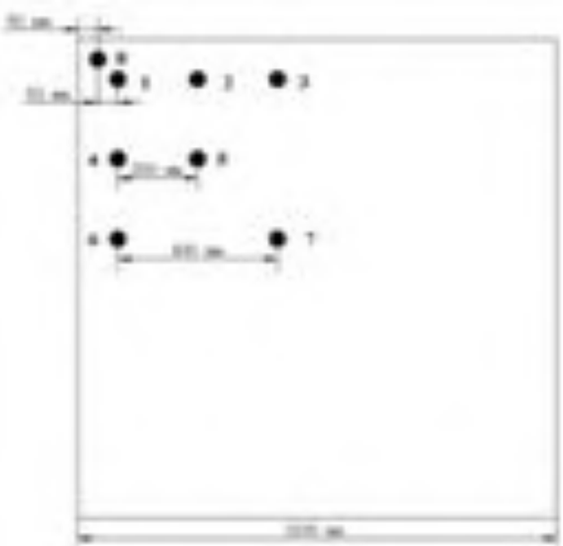
Glass frame

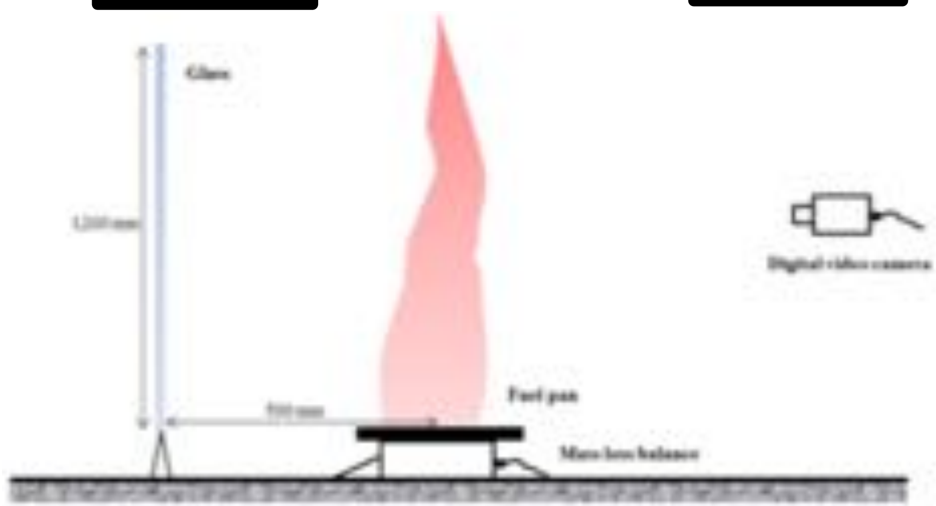
[7] Y. Wang, Q. Wang, G. Shao, H. Chen, Y. Su, J. Sun, L. He, K.M. Liew, Fracture behavior of a four-point fixed glass curtain wall under fire conditions, Fire Saf. J., 67 (2014) 24-34.

Point supported glass façades









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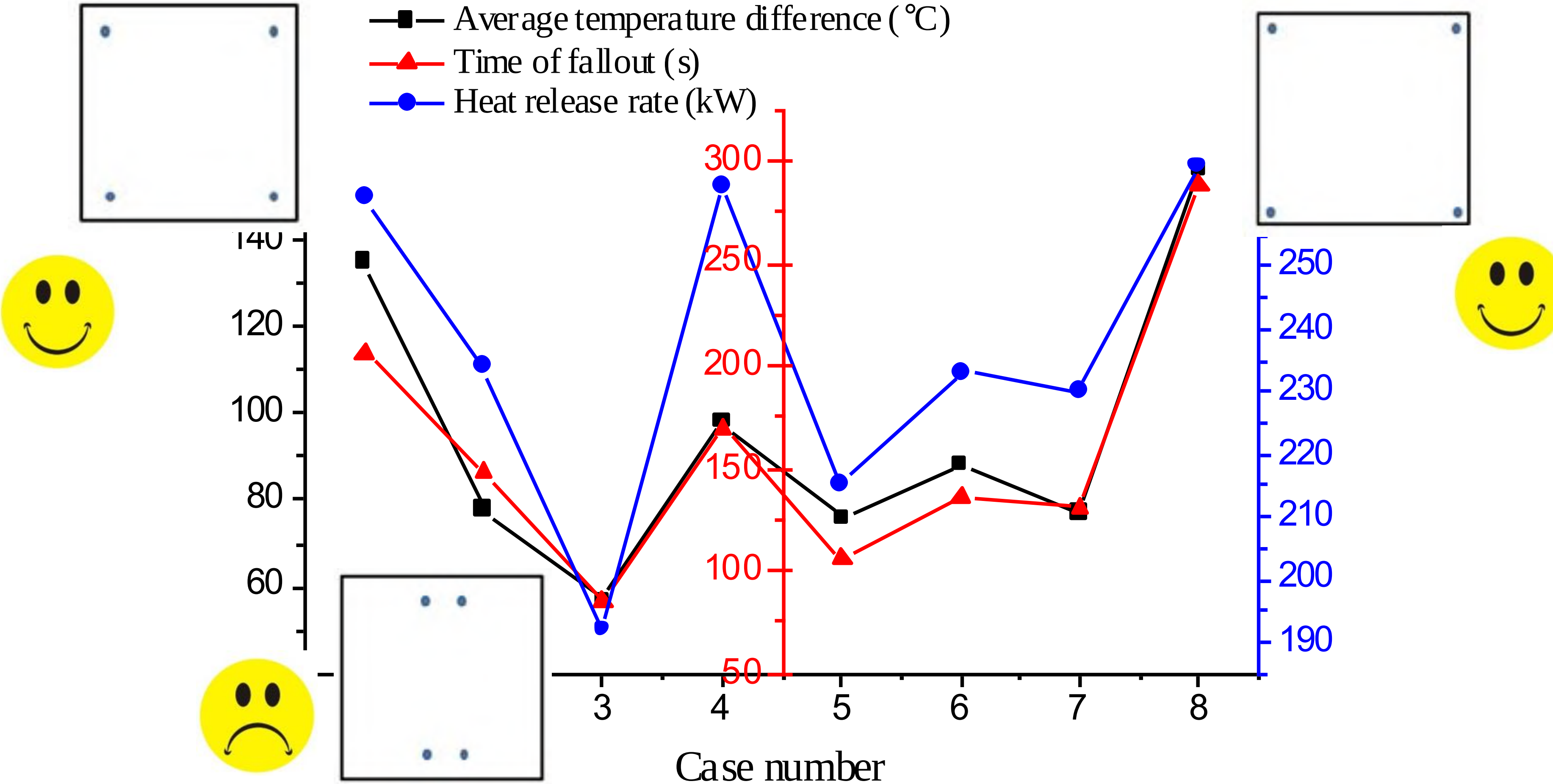
Point supported glass façades



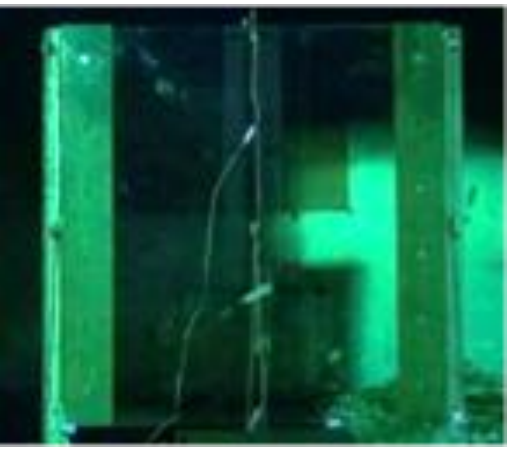
- Cracks initiated from fixing point
- Combined effect of thermal stress and mechanical stress causes breakage
- Relatively good fire resistance (5-10 cm to the edge)

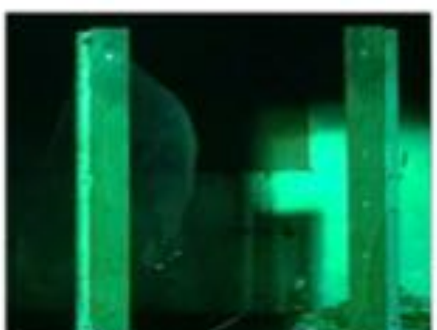
[7] Y. Wang, Q. Wang, G. Shao, H. Chen, Y. Su, J. Sun, L. He, K.M. Liew, Fracture behavior of a four-point fixed glass curtain wall under fire conditions, Fire Saf. J., 67 (2014) 24-34.

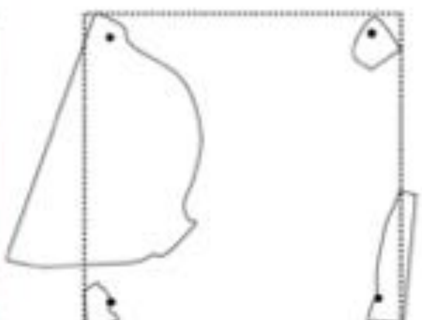
Point supported glass façades

Three kinds of breaking:

- Directly falling out (19 tests)
- Cracking firstly without pieces falling out (3 tests)
- No pieces falling out (2 tests)

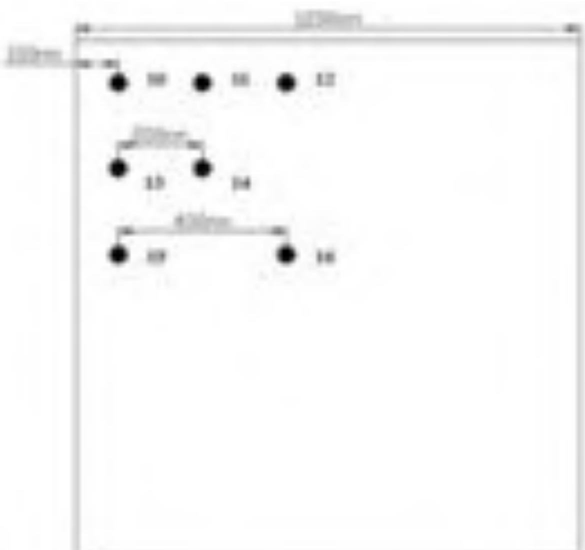


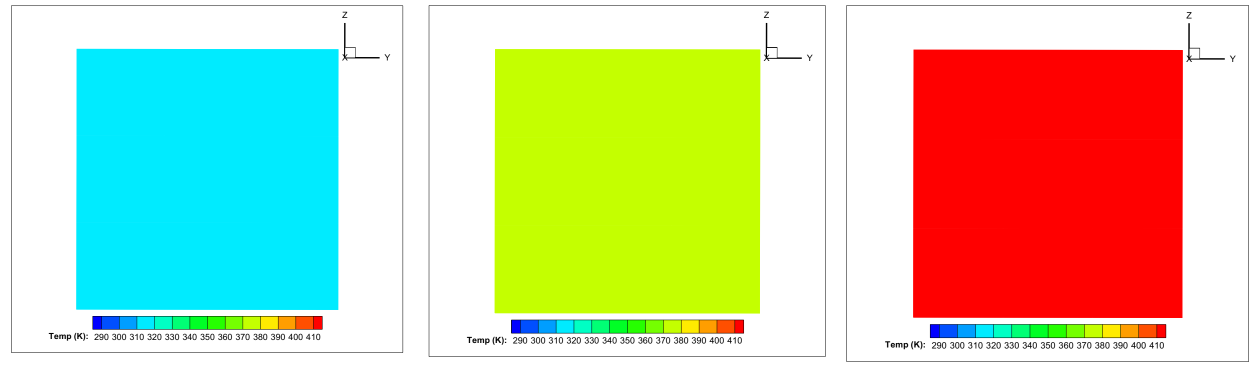




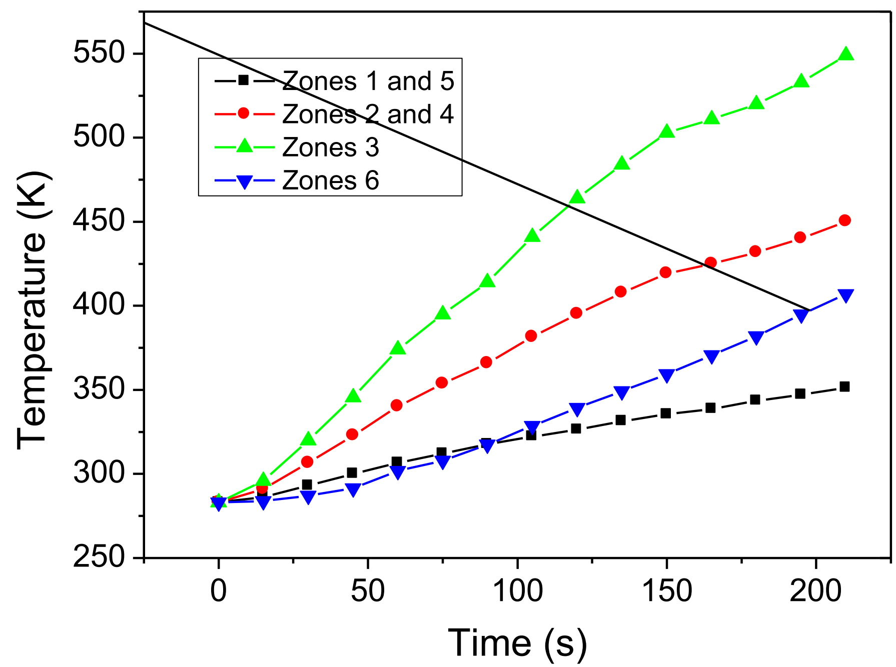
[7] Y. Wang, Q. Wang, G. Shao, H. Chen, Y. Su, J. Sun, L. He, K.M. Liew, Fracture behavior of a four-point fixed glass curtain wall under fire conditions, Fire Saf. J., 67 (2014) 24-34.

Point supported glass façades





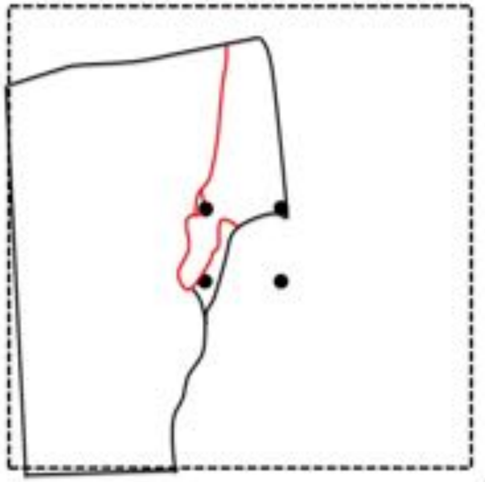
Uniform thermal loading

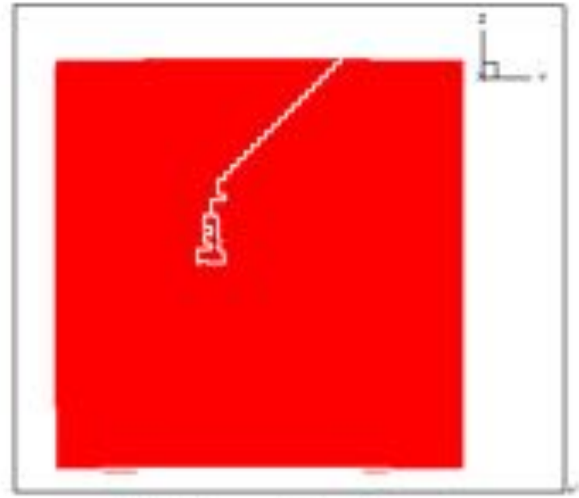


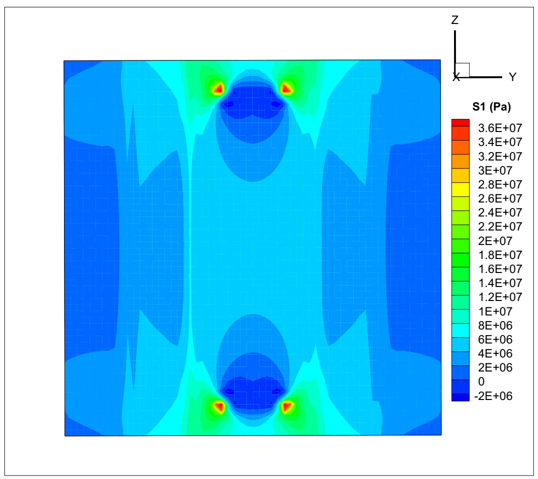
Non-uniform thermal loading

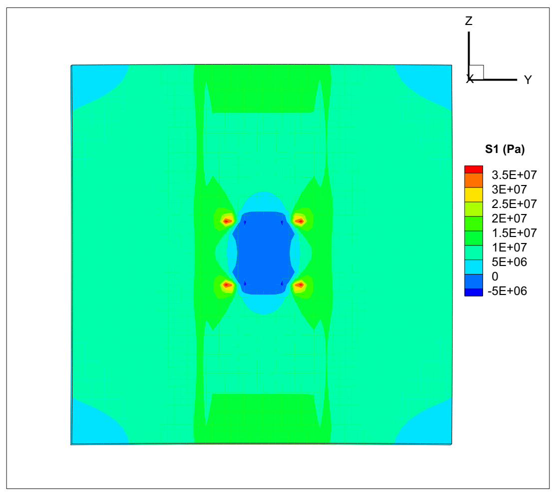
[8] Y. Wang, Q. Wang, J. Sun, L. He, K.M. Liew, Effects of fixing point positions on thermal response of four point-supported glass façades, Construction and Building Materials, 73 (2014) 235-246.

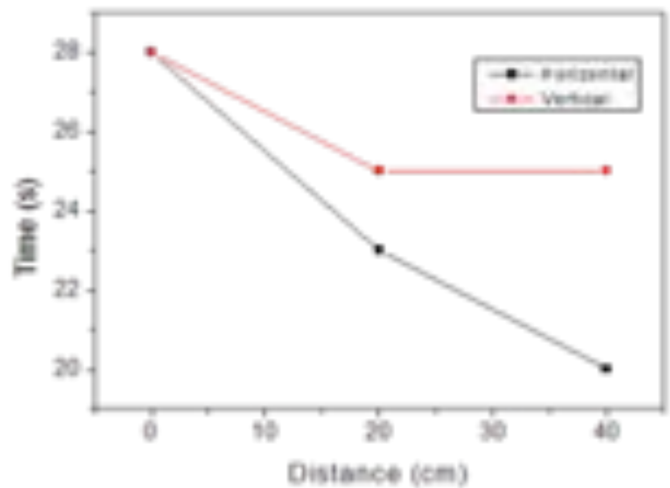
Point supported glass façades











- Breakage mechanism revealed
- Good agreement with experimental results

[8] Y. Wang, Q. Wang, J. Sun, L. He, K.M. Liew, Effects of fixing point positions on thermal response of four point-supported glass façades, Construction and Building Materials, 73 (2014) 235-246.

Installation form investigated,

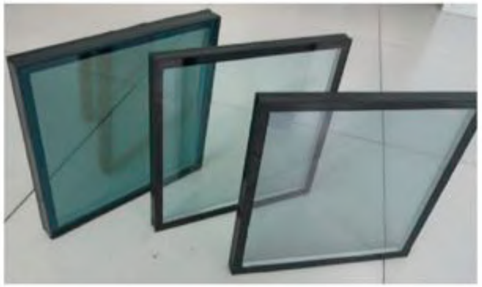
Then?

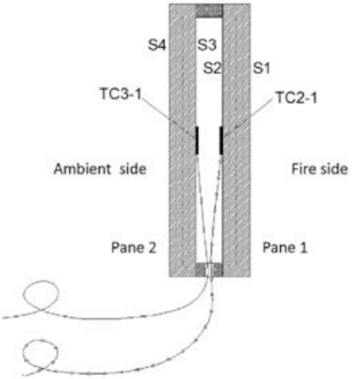
Glass type!

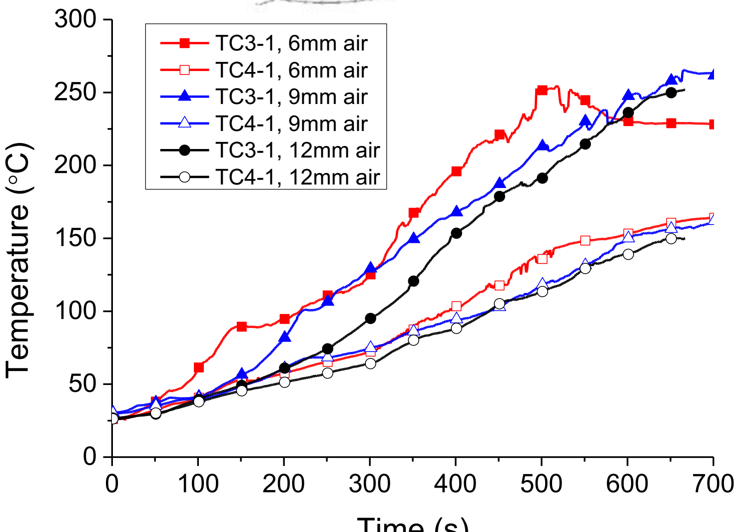
Different glass type: insulated glazing

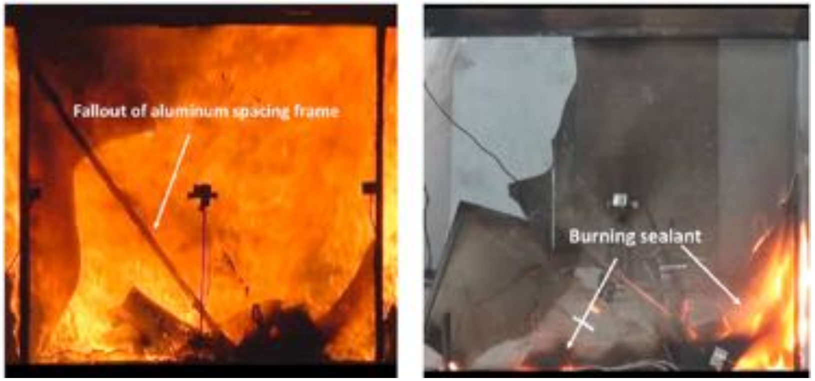
Summary of experimental tests.

Installation types	Fully exposed	Horizontal-hidden	Vertical-hidden
6 mm air	Case 1: Tests 1–3	Case 2: Tests 4–6	Case 3: Tests 7–9
9 mm air	Case 4: Tests 10–12	Case 5: Tests 13–15	Case 6: Tests 16–18
12 mm air	Case 7: Tests 19–21	Case 8: Tests 22–24	Case 9: Tests 25–27



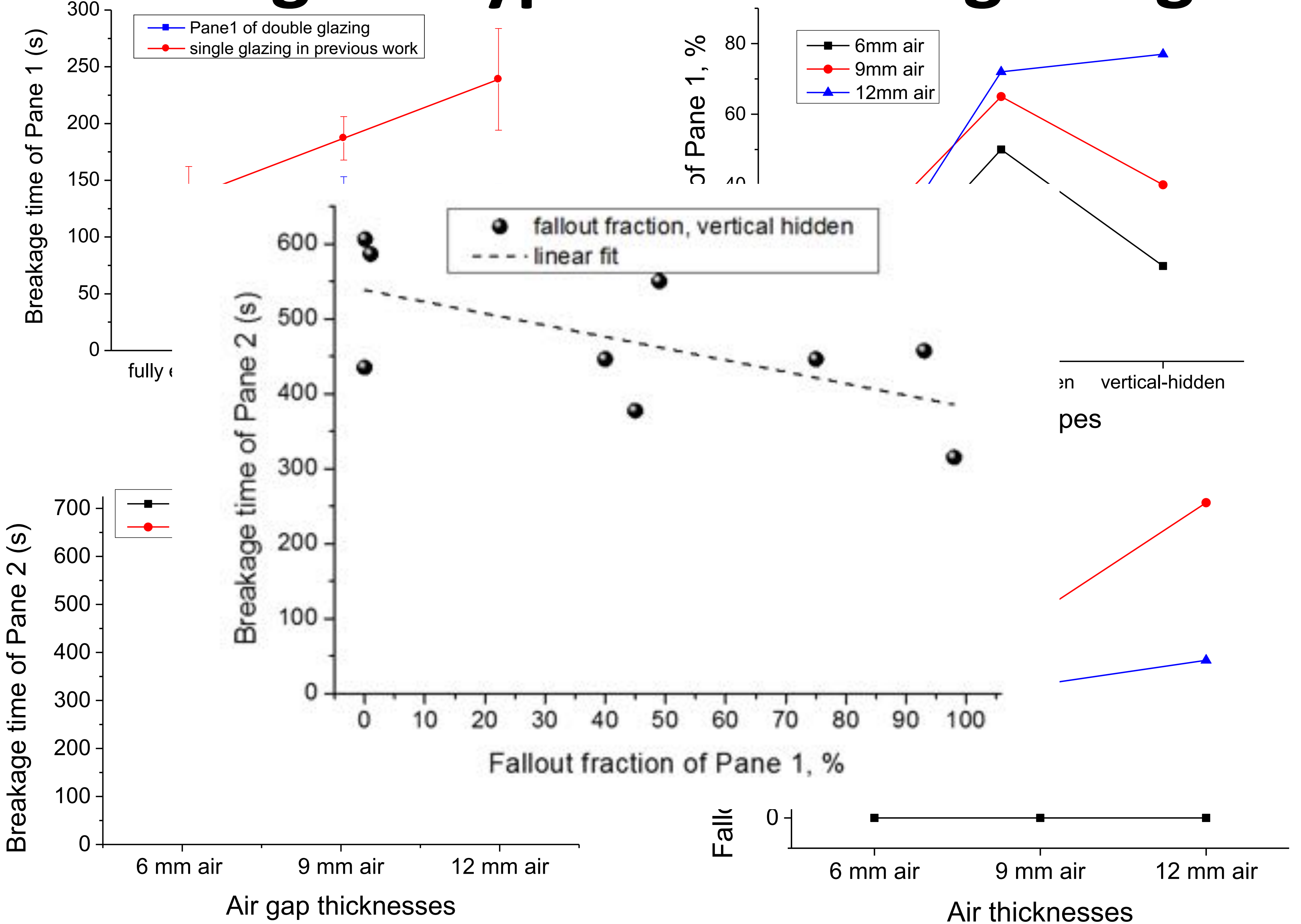






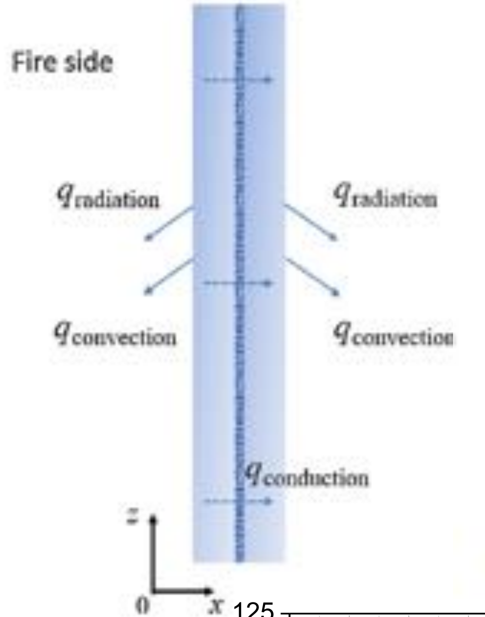
[9] Y. Wang, K. Li, Y. Su, et al, Determination of critical breakage conditions for double glazing in fire, Appl. Therm. Eng., 111 (2017) 20-29.
[10] Y. Wang, Q. Wang, Y. Su, J. Sun, L. He, K.M. Liew, Experimental study on fire response of double glazed panels in curtain walls, Fire Saf. J., 92 (2017) 53-63.

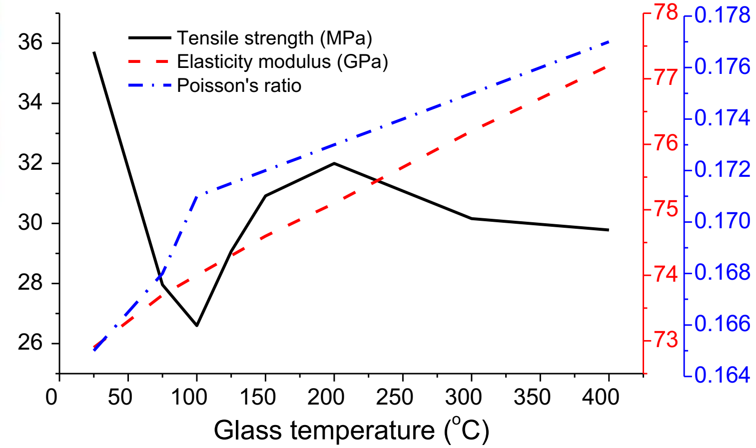
Different glass type: insulated glazing

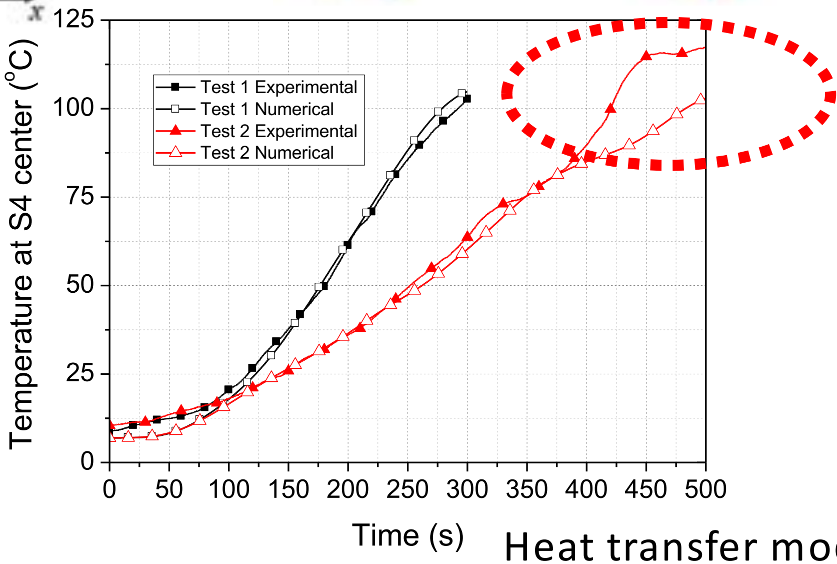


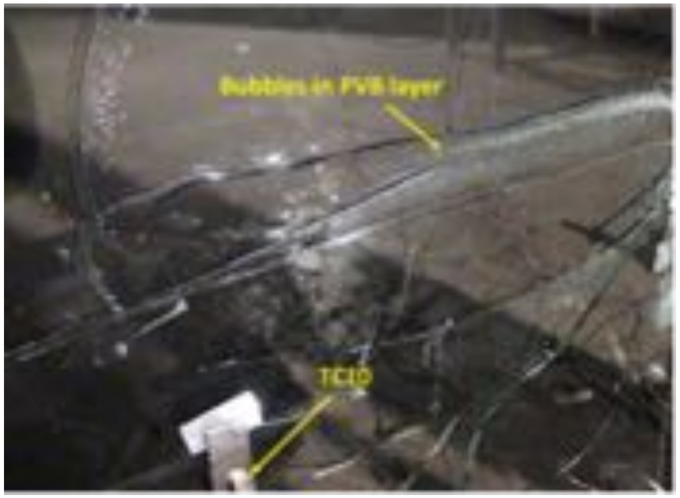
[9] Y. Wang, K. Li, Y. Su, et al, Determination of critical breakage conditions for double glazing in fire, Appl. Therm. Eng., 111 (2017) 20-29.
[10] Y. Wang, Q. Wang, Y. Su, J. Sun, L. He, K.M. Liew, Experimental study on fire response of double glazed panels in curtain walls, Fire Saf. J., 92 (2017) 53-63.

Different glass type: laminated glazing



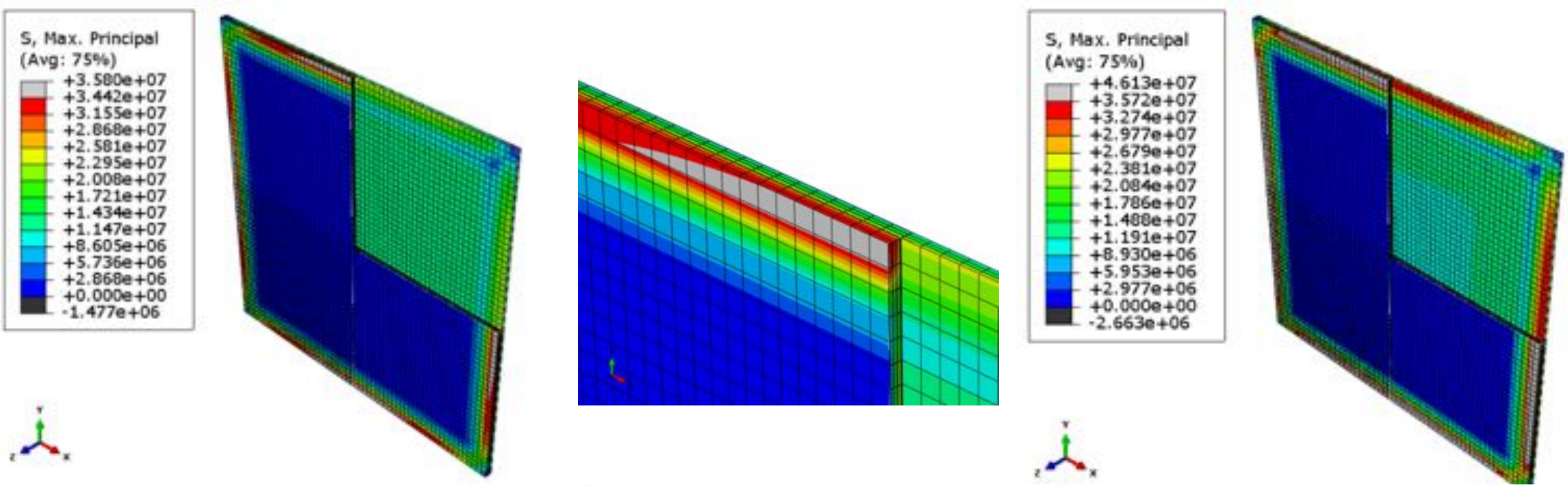






Heat transfer model verification

Different glass type: laminated glazing



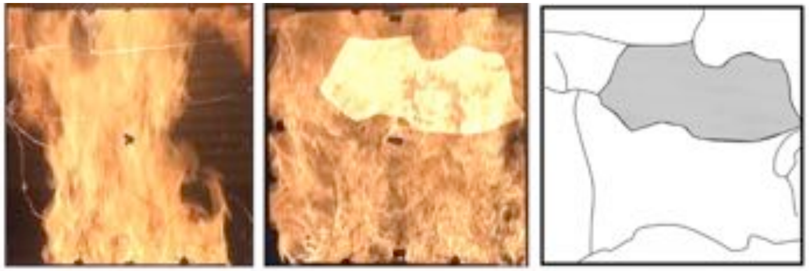
The summary of breakage times.

Glass panes		Experimental	Numerical
Test 1	Pane 1	118	124
	Pane 2	199	175
Test 2	Pane 1	258	237
	Pane 2	332	276

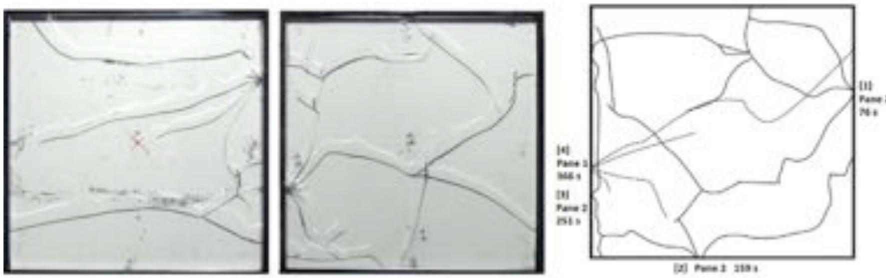
Mechanical model verification

Different glass type: laminated glazing

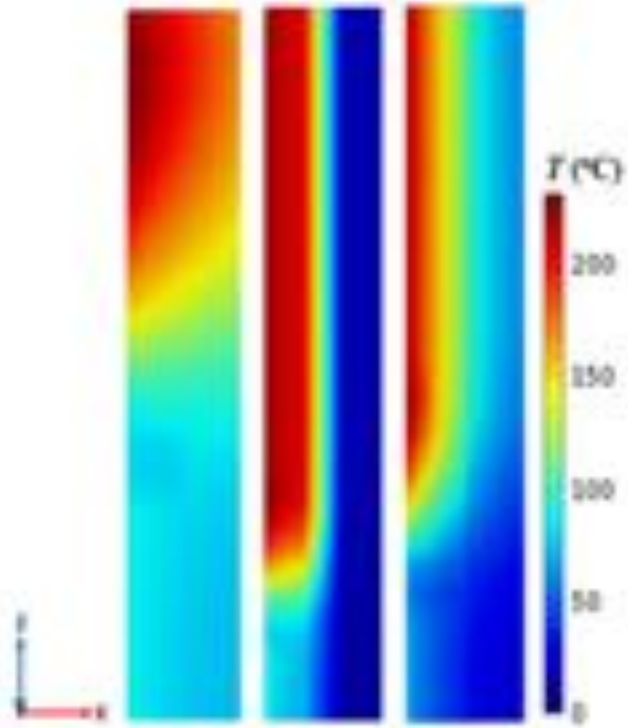
Single



Insulated



Laminated



The summary of strength and weakness of different glasses.

Glass type	Strength	Weakness
Single glazing	Lighter, lower expense	Falling out the most easily
Insulated glazing	Insulation	Falling out easily
Laminated glass	Good integrity	Most expensive

[11] Y. Wang, Q. Wang, J.X. Wen, J. Sun, K.M. Liew, Investigation of thermal breakage and heat transfer in single, insulated and laminated glazing under fire conditions, Appl. Therm. Eng., 125 (2017) 662-672.

“Mission Accomplished”,

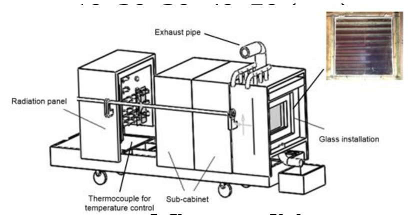
Then?

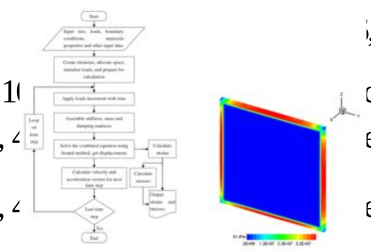
Summarize!

Sensitivity analysis of all factors

The summary of factors and corresponding time of occurrence of the first crack

Factor number	Primary factor	Cases	Repeated times in each case	Average breakage time (s)
		Uniform electric radiation condition		
1	Shading width(x_1)		2	644, 573, 580, 600, 671
2	Temperature increase rate in enclosure air(x_2)		2	1237, 646, 573, 495, 459
3	Glass thickness(x_3)		2	446, 573, 566, 557, 872
4	Wind load, FSG (x_4)		3	626, 602, 575, 552, 488
5	Wind load, PSG(x_5)		3	829, 812, 720, 579
		Pool fire condition		
6	Burner-glazing distance, FSG(x_6)	450, 500, 550, 600, 650, 700, 750 (mm)	2	96, 127, 139, 204, 292, 197, --
7	Burner-glazing distance, PSG(x_7)		1	89, 144, 208, --
8	Glazing type(x_8)		4	91, 164, 214, 332, 366
9	Installation form for FSG(x_9)		3	135, 187, 239
10	Horizontal fixing point position change, PSG(x_{10})		3	207, 148, 85
11	Vertical fixing point position change, PSG(x_{11})	10, 30, 50 (mm) (from point to pane upper edge)	3	207, 170, 136
12	Diagonal fixing point position change, PSG(x_{12})	71, 141, 424, 707 (mm) (from point to pane corner)	3	288, 207, 106, 131
		Numerical simulation		
13	Glass dimension(x_{13})		1	100, 59, 54, 52, 50, 50, 49, 49, 49, 48
14	Aspect ratio(x_{14})	400, 1(... cal area)	1	72, 64, 54, 48, 46, 44
15	Fire location, FSG(x_{15})	200, 4 ... een fire	1	44, 40, 38
16	Fire location, PSG(x_{16})	200, 4 ... een fire	1	19, 21, 28





[12] Yu Wang, Qimiao Xie, Yi Zhang, Qingsong Wang, Jinhua Sun, Sensitivity analysis of influencing factors on glass façade breakage in fire, Fire Safety Journal (Accepted).

Sensitivity analysis of all factors

$$CC_{x_i y} = \frac{\sum_{j=1}^{n}(x_{ij}-\overline{x}_i)(y_j-\overline{y})}{\left[\sum_{j=1}^{n}(x_{ij}-\overline{x}_i)^2\right]^{1/2}\left[\sum_{j=1}^{n}(y_j-\overline{y})^2\right]^{1/2}}$$

$$\overline{x}_i = \frac{1}{n}\sum_{j=1}^{n}(x_{ij}) \text{ and } \overline{y} = \frac{1}{n}\sum_{j=1}^{n}y_j$$

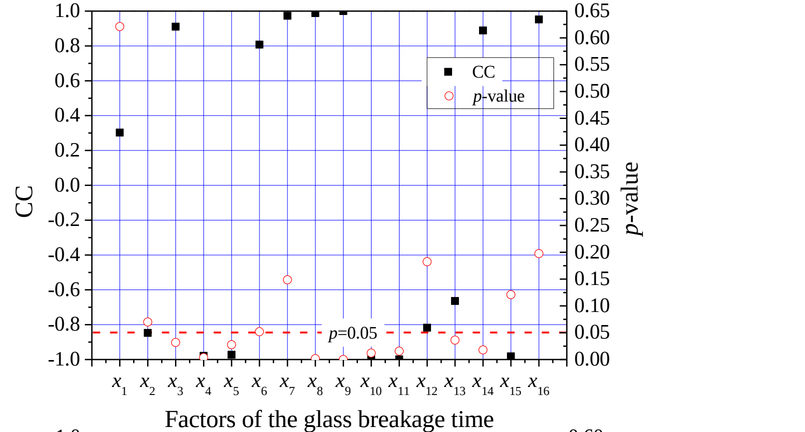
Correlation coefficient

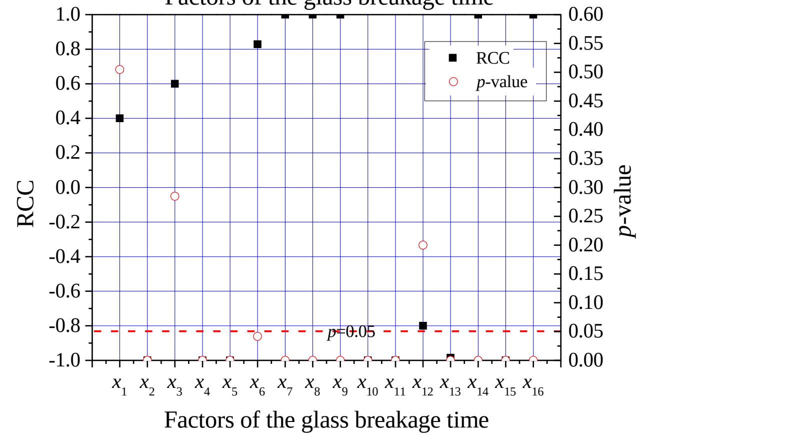
$$RCC_{x_i y} = \frac{\sum_{j=1}^{n}(R(x_{ij})-\frac{n+1}{2})(R(y_j)-\frac{n+1}{2})}{\left[\sum_{j=1}^{n}(R(x_{ij})-\frac{n+1}{2})^2\right]^{1/2}\left[\sum_{j=1}^{n}(R(y_i)-\frac{n+1}{2})^2\right]^{1/2}}$$

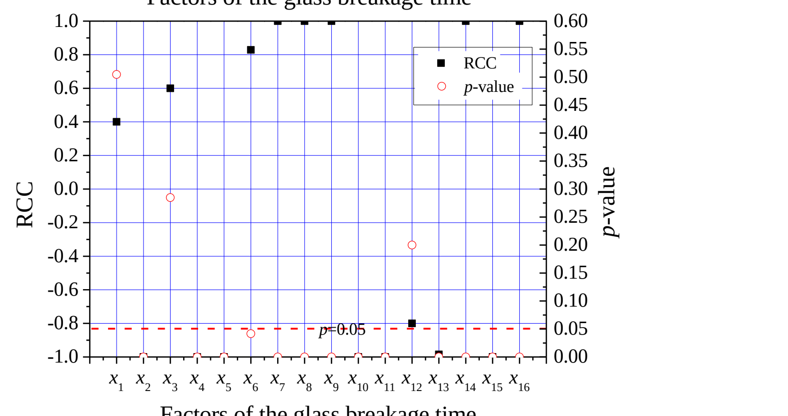
Rank correlation coefficient

$$NCV_{yx_i} = \frac{\left[\sum_{j=1}^{n}(y_j-\overline{y})^2\right]^{1/2} / \overline{y}}{\left[\sum_{j=1}^{n}(x_{ij}-\overline{x}_i)^2\right]^{1/2} / \overline{x}_i}$$

Normalized coefficient of variation

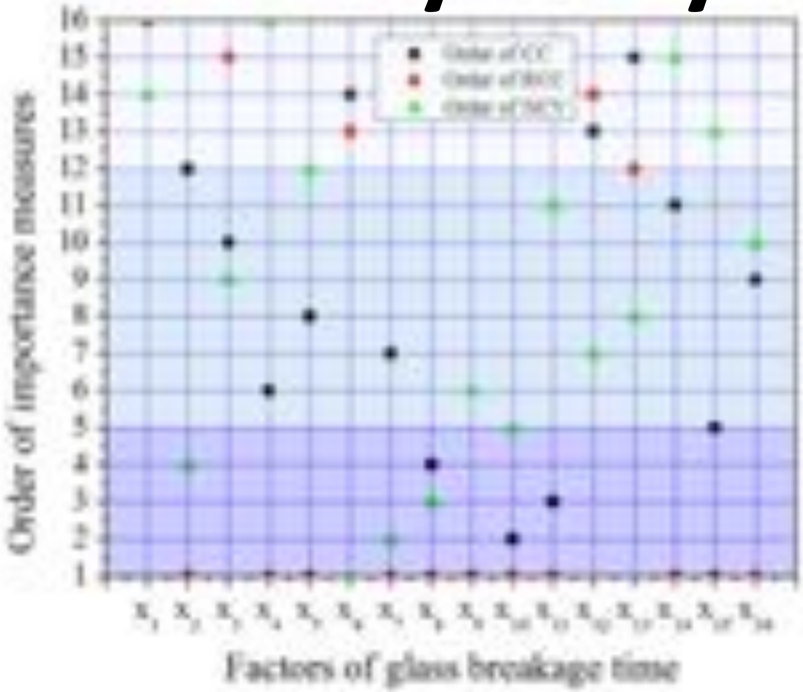


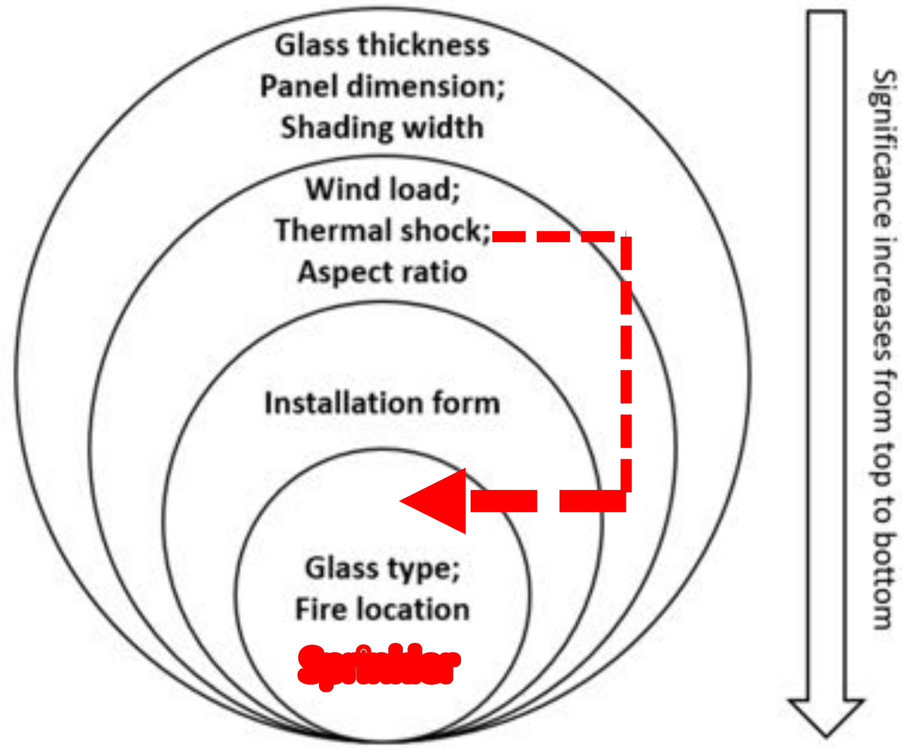




[19] Yu Wang, Qimiao Xie, Yi Zhang, Qingsong Wang, Jinhua Sun, Sensitivity analysis of influencing factors on glass façade breakage in fire, Fire Safety Journal (Accepted).

Sensitivity analysis of all factors





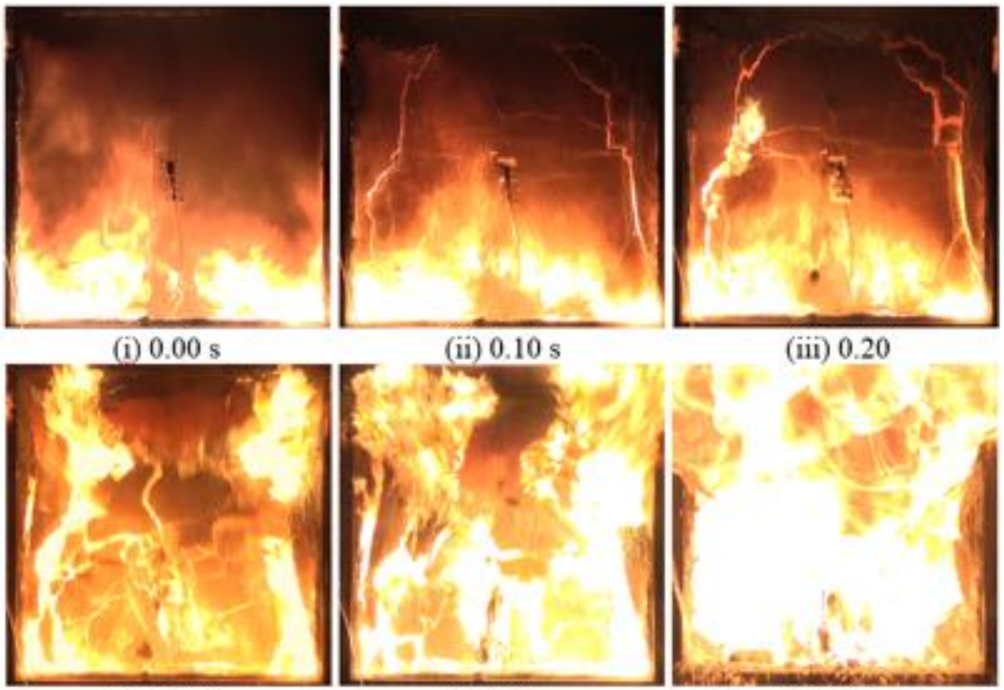
Summary of independent survey from six researchers.

Factor No.	Factors	Average	Standard deviation
1	Shading width	6.5	1.8
2	Temperature increase rate	7.8	1.2
3	Glass thickness	7.5	1.0
4	Wind load, FSG	6.0	1.3
5	Wind load, PSG	6.0	0.9
6	Burner-glazing distance, FSG	8.0	1.3
7	Burner-glazing distance, PSG	7.5	1.2
8	Glazing type	8.7	0.8
9	Installation form for FSG	7.8	1.5
10	Horizontal fixing point position change, PSG	7	1.4
11	Vertical fixing point position change, PSG	7.2	1.2
12	Diagonal fixing point position change, PSG	6.7	1.5
13	Glass dimension	6.8	0.8
14	Aspect ratio	6.3	1.0
15	Fire location, FSG	7.3	1.4
16	Fire location, PSG	7.3	1.4

x_1	Shading width	x_5	Wind load, PSG	x_9	Installation form for FSG	x_{13}	Glass dimension
x_2	Temperature increase rate	x_6	Burner-glazing distance, FSG	x_{10}	Horizontal fixing point position change, PSG	x_{14}	Aspect ratio
x_3	Glass thickness	x_7	Burner-glazing distance, PSG	x_{11}	Vertical fixing point position change, PSG	x_{15}	Fire location, FSG
x_4	Wind load, FSG	x_8	Glazing type	x_{12}	Diagonal fixing point position change, PSG	x_{16}	Fire location, PSG

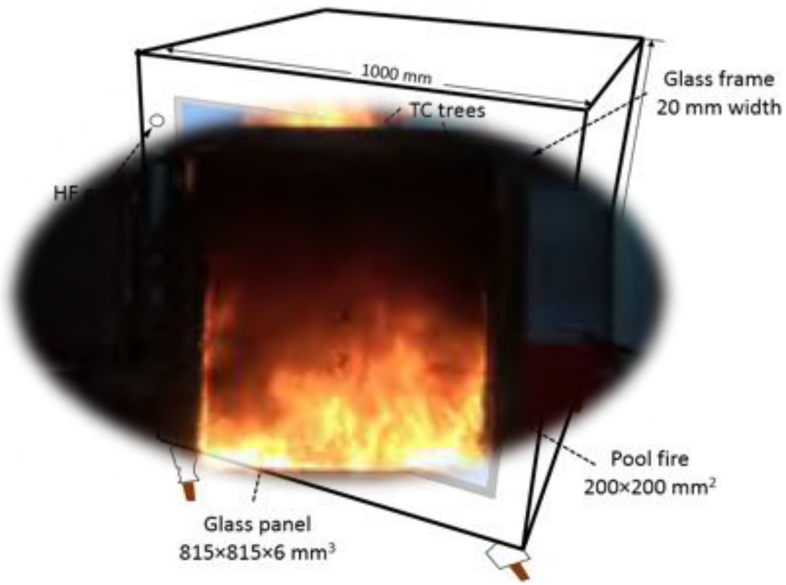
[19] Yu Wang, Qimiao Xie, Yi Zhang, Qingsong Wang, Jinhua Sun, Sensitivity analysis of influencing factors on glass façade breakage in fire, Fire Safety Journal (Accepted).

Interaction with fire (to be presented in combustion symposium)



(i) 0.00 s (ii) 0.10 s (iii) 0.20

(iv) 0.34 s (v) 0.40 s (vi) 0.70



(vii) 0.7 s (viii) 0.80 s (ix) 0.84 s (xi) 0.9 s (xii) 1.06 s

[13] Yu Wang, Jinhua Sun, Linghui He, Qingsong Wang, David Rush, Experimental study on fallout behaviour of tempered glass façades with different frame insulation conditions in an enclosure fire, 37th International Symposium on Combustion, Dublin, Ireland, 2018 (Oral)

Conclusions

- Glass ***breakage mechanism*** was revealed by small scale experiments and FEM analysis.

- Full scale experiments were conducted for understanding the performance of glass façades with different ***installation forms*** and ***glass types***.

- Sensitivity analysis was conducted to ***summarize*** the all above tests.

- Investigation on ***interaction*** between fire and glass is ongoing.

Thanks very much

Any question is welcome