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FIRE-INDUCED CRACKING OF MODERN WINDOW GLAZING
AN EXPERIMENTAL STUDY

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ABSTRACT

The knowledge of the behaviour of windows and, thus, of the actual ventilation in a fire room is paramount for predicting the fire development and the thermal response of structural elements. In this study, 75 tests were conducted on different glazing units made of annealed, toughened, and laminated glass, to investigate how modern insulating glazing units (IGUs) break and contribute to the ventilation factor in fires. The glass was tested as single, double, and triple pane glazing. The tests considered variations in glass pane thickness (3-8 mm) and sizes (side lengths 200-500 mm). A constant radiant heat flux of ca. 20 kW/m^2 was applied to simulate post-flashover conditions. No cracking and no fallout were observed in toughened and laminated glass panes, respectively. In annealed glass pane units, the onset of cracking of subsequent panes was delayed depending on the amount of fallout of the first pane, indicating that such unit could provide no ventilation at flashover.

KEYWORDS: insulating glass units, fire-induced breakage, radiant heat, cracking time, fallout

1 INTRODUCTION

Modern buildings are characterized by high insulation levels and low-energy windows to limit the emission of greenhouse gases for heating and cooling. Furthermore, to satisfy the new stricter requirements effectuated in the Danish building regulations (Danish Authority of Social Services and Housing, 2023) regarding the U-value of windows in regular building rooms, primarily triple-layer glazing with low-emissivity coatings will be used in buildings in Denmark in the future. Additionally, more complex glazing designed to mitigate overheating problems in buildings is entering the market. Unlike traditional windows, new low-energy windows with multiple glass layers are expected to resist the exposure to high temperatures longer and, therefore, might not break during the early phases of a fire. Thereby, modern windows may not provide good ventilation after flashover, such as commonly assumed for old windows (Shields *et al.*, 2005; Wang *et al.*, 2017a; Huizinga *et al.*, 2017). A lower ventilation factor leads to a longer fire and a higher thermal solicitation of the structural elements (Petterson *et al.*, 1976).

Despite some research has been devoted to understanding the failure mechanisms of window glass panes in fire (Skelly *et al.*, 1991; Pagni *et al.*, 1994a, 1994b), it is presently unknown whether, when, and to what extent multi-layer glazing commonly used in modern buildings will break during a fire. Consequently, the fire safety of modern buildings is affected by a high uncertainty.

The study presented in this paper aimed at closing this knowledge gap, by means of an experimental campaign, where different types of glazing units were exposed to radiant heat and compared in terms of cracking time and glass fallout.

2 EXPERIMENTAL SETUP

The adopted test plan is shown in Fig. 1 and was designed to isolate the effects of the parameters that were expected to influence the resistance of the glazing units most, such as:

- glass type: float/annealed (F), toughened (T), and toughened with integrated solar shading film (S)
- number of the pane layers: single (1), double (2b), or triple (3b) glass panes separated by a gas interlayer, as well as single laminated layer (2a) and laminated layer followed by another glass pane with a gas interlayer (3a)
- thickness of the pane: varying from 3 mm to 8 mm

- size of the pane: four square panes with dimensions of 200 mm, 300 mm and 500 mm, and one rectangular pane of dimension 200 x 400 mm

Other relevant parameters such as the shading width provided by the window frame (i.e., mechanical edge cover) and the incident heat flux has been subject of past research (Jørgensen *et al.*, 2022; Seindal and Jensen, 2023) and were kept constant in this study.

Each different test configuration was repeated three times to account for the experimental variability; thus, 75 experiments were conducted in total. The results of the tests with different sizes are not discussed in this paper.

A window frame replica was built out of a fire-resistant calcium silicate board (illustrated in Fig. 2), which covered 20 mm of glass around each edge. The mounting of the glazing was done in accordance with EN 12488 (European Committee for Standardization, 2016).

The specimens were irradiated by an H-TRIS; a vertical gas radiant panel of dimension 500 mm x 500 mm (shown in Fig. 2). The H-TRIS was placed 430 mm from the glazing samples, so that the heat flux received by the centre of the glazing was around 20 kW/m^2. This value was chosen as representative for flashover conditions based on the minimum conditions at onset of flashover observed by several research studies (Peacock *et al.*, 1999). The glazing was subjected to the heat flux until cracking or for a total exposure time of 30 minutes.

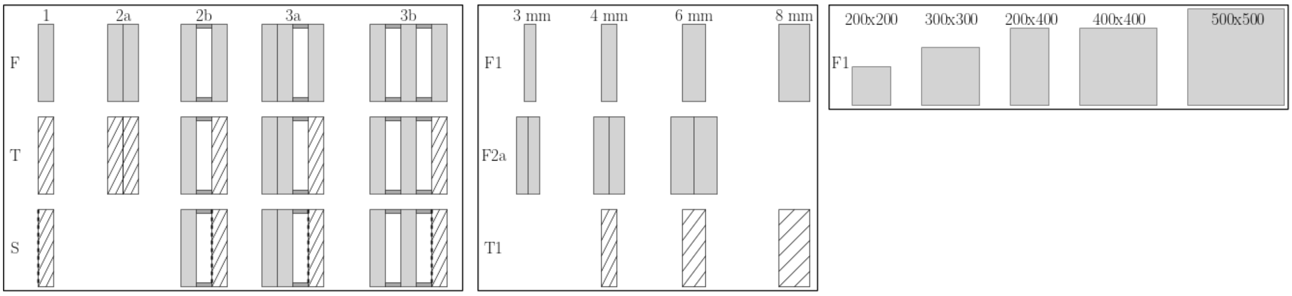

Fig. 1 Experimental plan.

Fig. 2 Front side (left) and back side (middle) of the window frame and radiant panel (right).

3 RESULTS

The time to crack onset of the different squared panes of size 400 mm and thickness 4 mm is shown in Fig. 3. Generally, it is seen that the first pane cracked at about the same time; to be precise, after 80 seconds with a standard deviation of 21 seconds. This is true for both float and laminated samples. It is also seen that the second pane broke sooner in glazing with a laminated layer, denoted by “a”, than in glazing with a gas cavity, denoted by “b”. On the other hand, none of the toughened panes cracked during the tests (that lasted 30 minutes), no matter whether the toughened pane was covered with solar shading film or not. The results, denoted with “S” in Fig. 3, suggest that the presence of solar shading film on the ambient layer did not influence the cracking time of preceding layers significantly either (Hvidberg, 2023). In three tests, due to technical problems, the cracking time of a pane could not be registered, namely tests F2b.1, F3a.1, and S2b.2, and therefore these tests are excluded from the results presented in Fig. 3.

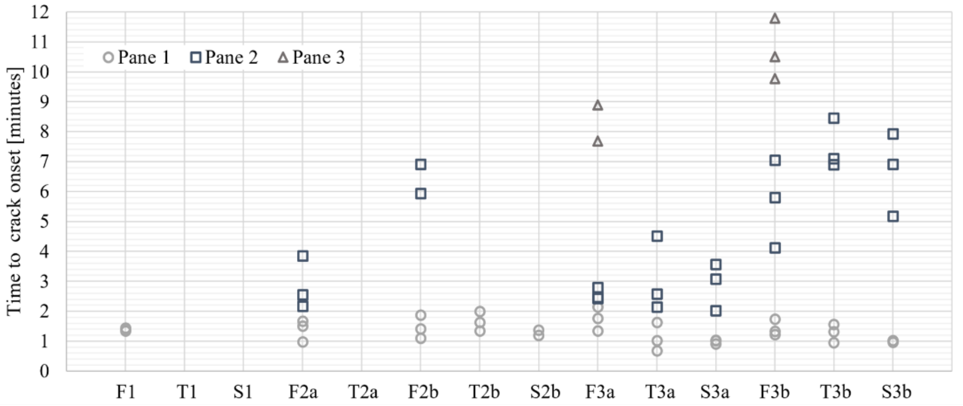

Fig. 3 Time to first crack for the specimen types of size 400 x 400 mm with pane thickness 4 mm.

3.1 Laminated glazing panes

Pane 1 in laminated glass layers cracked at an average of 78 seconds, which is only 2 seconds faster than the average time to the first crack of all first panes and 5 seconds faster than that of monolithic samples. This happened despite the change in boundary conditions (no convection and radiation on the backside, but rather conduction to the lamination foil). Thus, the altered boundary conditions on the back did not show any significant effect on the cracking time. This is consistent with the results of Wang *et al.* (2023), who found that, for glass thicknesses less than 15 mm, gradients in the planar direction are governing for breakage.

The average time to breakage of pane 2 in laminated glass is 171 seconds. The majority of first cracks in pane 2 happened after 2.0 to 3.5 minutes of exposure and 0.5 to 2.5 minutes after breakage of pane 1. Roughly, the crack onset of pane 2 happened after twice the time to crack of pane 1. These observations are similar to those found by Wang *et al.* (2017a).

Laminated glazing F2a was also observed with different thicknesses and the results are shown in Table 1:

Table 1 Time [s] to the first crack on each pane of laminated glazing with different thicknesses.

Sample	**First cracking time (first pane) [s]**	**Average first cracking time (first pane) [s]**	**First cracking time (second pane) [s]**	**Average first cracking time (second pane) [s]**
F2a.3mm.1	122[a]		141[a]	
F2a.3mm.2	67	91±33.94	129	125±6.36
F2a.3mm.3	115		120	
F2a.4mm.1	90		153	
F2a.4mm.2	100	83±21.80	130	171±52.94
F2a.4mm.3	59		231	
F2a.6mm.1	71		273	
F2a.6mm.2	78	77±5.57	331	302±29.00
F2a.6mm.3	82		303	

[a]The results of test F2a-3mm-1 were dismissed when calculating the average first cracking time due to the wrong placement of the radiant panel, i.e., wrong heat exposure.

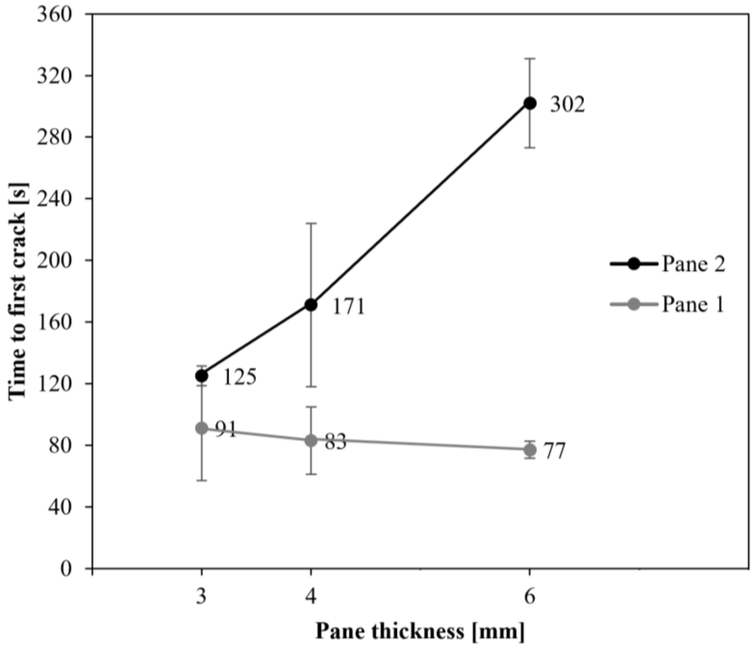

Fig. 5: Time to cracking onset of first and second pane of laminated glazing vs. pane thickness. The error bars indicate the standard deviation of the cracking time. Note: The observations for panes of thickness 3 mm exclude sample F2a-3mm-1 with a wrong level of exposure.

In Fig.5, the grey line illustrates that the average time to the initiation of the first crack on the first pane decreased slightly with increasing thickness. However, the standard deviation of these results was very high and do not allow to draw a conclusion on the trend. According to previous literature (Zhang *et al*., 2013; Yang *et al*., 2018) thicker glazing requires longer time to generate the critical temperature gradient. The discrepancy between the results and expectation can be explained by the large standard deviation observed in the results related to the panes with thickness of 3 and 4 mm. Therefore, more experiments should be conducted to decrease the uncertainty and verify this trend. In contrast, the black line in Fig. 5 shows that the average time to the first crack on the second pane increased significantly with the thickness, as also observed in the monolithic panes (Peng, 2023). Furthermore, the crack onset of pane 2 is delayed with respect to pane 1 with the same thickness, which could be caused by the higher specific heat capacity of the polyvinyl butyral foil (PVB) compared with the glazing layer (Wang *et al.*, 2017a). Therefore, the front surface of pane 2 received less heat, resulting in a much longer time to reach the critical temperature difference compared with pane 1.

None of the laminated samples experienced any fallout. Thus, no vent was created in these cases. In the tests, the PVB layer was sufficiently strong to keep the glazing unit together even though both layers cracked. For longer exposures after cracking, this might not be the case.

3.2 Insulated glazing units

Fallout was observed in 15 out of 18 tests of type “b” IGUs. Generally, the fallout of pane 1 was observed at the same time as cracking of pane 2 for all types of “3b” glazing, as reported in Table 2. For two-layered glazing, the fallout of pane 1 was observed in some cases right after it cracked (F2b.1 and F2b.2) and in other cases up to 22 minutes after crack onset (T2b.2, T2b.3, S2b.1, S2b.3). Generally, smaller fractions of glass fell out when the fallout happens at the time of crack (10-25 %), than when fallout was delayed (60-90 %). It is noted that 90 % fallout corresponds to 1 cm of glass remaining around the edge of the glass pane. In just one test, the fallout of pane 2 is observed (S3b.2), which had about 10 % fallout.

No fallout was observed in the layer facing the ambient temperature. This might be explained by the fact that the experiments were terminated shortly after cracking was observed of the last pane. Since it is found that the panes preceding the last pane are prone to fallout sometime after the first crack, it could be expected that the outer layer might also show fallout after a longer exposure. Thus, it should not be concluded that fallout will not happen based on these experiments. Rather, the observations regarding fallout can be used as a perspective on the varying times to crack in layers following pane 1 (Hvidberg, 2023).

Table 2 Time and rough fraction estimate of the fallout of pane 1 in type 'b' samples.

Sample code	**Time to fallout [min:sec]**	**Fraction [%]**	**Sample code**	**Time to fallout [min:sec]**	**Fraction [%]**
F2b.1	01:25[a]	25	F3b.1	05:48[b]	50
F2b.2	01:52[a]	10	F3b.2	07:03[b]	60
F2b.3	None	0	F3b.3	03:59	80
T2b.1	None	0	T3b.1	06:54[b]	80
T2b.2	02:00[a] 05:58	10 90	T3b.2	None	0
T2b.3	22:22	90	T3b.3	07:06[b]	90
S2b.1	20:35	60	S3b.1	04:21 05:11[b]	10 80
S2b.2	13:50	80	S3b.2	07:56[b]	80
S2b.3	13:52	70	S3b.3	06:55[b]	40

[a]Time to 1st crack of pane 1. [b]Time to 1st crack of pane 2.

All first cracks of pane 1 in IGUs occurred after 1-2 minutes of exposure at an average and median time of 81 seconds. Thereby, the breakage time of pane 1 was not noticeably affected by the different backside boundary condition compared to monolithic or laminated glazing. This observation corresponds to findings by Wang *et al.* (2017b).

The time to the first crack of the second pane has a larger variability than that of the first pane, ranging from 4 minutes to 8.5 minutes. The average time was 6 minutes and 34 seconds (394 s). The distribution is skewed toward the maximum with a median value of 6 minutes and 55 seconds. There is no distinct separation of the observations made for pane 2, when it is the middle glass versus when it is the final glass. It is noted that the two observations with the shortest time to crack of pane 2 (F3b.3 and S3b.1) were the only samples with fallout of pane 1 before the crack of pane 2. The fallout allows for a much larger proportion of the radiation to be absorbed by pane 2, which might be enough to influence the cracking time.

The time to first crack of pane 3 in the case where panes 1 and 2 were laminated (sample codes "3a") ranged from 7.5 to 9 minutes. This range is comparable to the range for pane 2 discussed above with the addition of the time to breakage of the laminated glass pane: The heating of pane 3 seems simply to be delayed by the time to heat pane 2 in the laminated pane.

The time to first crack of pane 3 in the case where panes 1 and 2 were monolithic (sample codes "3b") ranged from 9.5 to 12 minutes. It is observed that the cracking of any subsequent monolithic glass layer after the first one in a IGU occurs, on average, at a regular interval after the first crack of the preceding layer, i.e., 5:20 minutes average time regardless of whether it is pane 2 or pane 3. The glazing with the largest fallout of pane 1 (F3b.3) of about 80 % had the shortest time to crack pane 3, which is consistent with the previous explanation.

4 CONCLUSIONS

A series of experiments were conducted to investigate the effect of insulated glazing units, lamination, and thermal tempering on the breakage behaviour of glazing in fire conditions. The influence of the thickness was also investigated. The primary conclusions are:

- Toughened glass with or without solar shading film did not break during the whole duration of the test (30 min).
- In laminated layers, the time to crack of the pane furthest from the fire is on average twice the time to crack of the pane closest to the fire. Furthermore, it was observed that laminated glass panes retain enough stiffness after cracking to remain in the frame and not fall out.

- In insulated glazing units, the time to crack of a pane succeeding a gas-filled cavity is on average 5:20 minutes after the crack of the preceding layer. The time is shorter when the preceding layer falls out.

It can be concluded that toughened and laminated glass could resist flashover without fallout. Furthermore, the breakage of the last glass pane of IGUs is delayed depending on the number of the preceding glass layers and could therefore delay fallout after flashover. This would suggest that it could be not conservative to include such windows in the calculation of the ventilation factor of design fires for structural fire safety.

These results are limited to glazing of size 400x400 exposed to constant heat flux and no horizontal forces that could be generated by overpressure in a fire room. However, glazing that is larger than size 400 mm x 400 mm, which is more common in buildings, are expected to crack earlier, due to larger tensile stress and larger number of imperfections. To better understand this, tests on different sizes of glasses have been conducted as part of this campaign and their analysis is ongoing.

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