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FIRE-INDUCED GLASS BREAKAGE IN WINDOWS: REVIEW OF KNOWLEDGE AND PLANNING AHEAD

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Abstract
Along fuel load, ventilation conditions govern fire development in compartment fires. Therefore, a breaking window can change the fire and thereby the thermal loads on structures. In this paper, the current literature on the topic is studied to identify key parameters for glass breakage and map the current level of knowledge for each of them. It is found that the level of knowledge for the different parameters varies a lot. Based on the results, it is recommended that especially the effects of multi-pane windows, gas filling between layers, low-energy coatings, and over-pressure in the fire room are investigated further. The knowledge gained from these results should later be transformed into practical design rules to assess a realistic ventilation factor and have a better prediction of the structure temperature and load capacity during a compartment fire.

Keywords: Fire-induced glass breakage, breaking time, ventilation factor, fire dynamics

1 INTRODUCTION

Window breakage is important for fire dynamics in enclosures, as a change in ventilation conditions can change the fire development and, thus, change the temperature in the enclosure. Thereby, window breakage can directly govern the thermal load on structures in a fire compartment.

The time-temperature curve for the full duration of a fire in a given enclosure can be calculated using a parametric fire, taking into account ventilation conditions (opening factor) and the thermal inertia of the surrounding structures. An application of a variation of this method was recently published, where parametric fires were used in an actual building project to analyse the burnout resistance of a tall mass timber building (Isaksen and Hagen, 2023).

Current models for parametric fires assume that the ventilation openings are constant and that they are present and functional at the initiation of the fire (or at least at the onset of flashover). Experiments suggest that this may not be a reasonable assumption for all types of modern, low-energy windows. Therefore, there is a need to better understand glass breakage and the resulting impact on the opening factor and fire development.

In this paper, the current knowledge of window glass breakage is reviewed and a roadmap for future research into the subject is presented. The focus of the paper is window glass, thus, thermal breakage of e.g., full glass façades, glass partition walls, or glass balustrades, is not included.

2 DEVELOPMENT OF THE RESEARCH TOPIC

As a foundation for the work, a literature study was conducted comprising of a combination of random searches, cited reference searches, and block searches. The searches were done primarily in the Scopus database, but various other search engines and databases were also utilised. In total, 134 papers and reports were identified as relevant to the subject of fire-induced window breakage.

Fire-induced glass breakage was identified as a needed field of study for fire safety engineering in a paper by Emmons (1986), and the field has since branched to cover different aspects of fire-induced glass breakage and the effects on compartment fire dynamics.

In order to investigate the trends in the published research, the results of the literature study have been compared to the total number of published papers indexed under the terms “fire safety” or “fire protection” in the Scopus database as of August 2023; a total of 16991 entries in the years 1986 to 2023. It was found that there was relatively large interest in the subject in the 1990’s. However, in the 2000's the relative interest in the field halted, before a new relative interest in the field is seen from the beginning of the 2010's.

A critical difference from the studies from the 1990's and the studies after 2010 is that the first group of studies were only concerned with window glass, whereas the more recent studies also include studies on different types of glass façades etc. Therefore, the amount of new research on window glass is more limited than it appears at first glance. This also means that much of the research on window glass, which the design of modern buildings is based upon, is more than 20 years old. Given the development of windows in the same time frame, there is a mismatch between knowledge and practice. Thus, there is a risk that outdated knowledge is being used to design modern buildings, and therefore, the performance of modern windows in a fire scenario should be studied.

3 CURRENT KNOWLEDGE

Based on the literature review, 17 parameters have been identified as influencing the breakage of window glass in fires. The parameters can be sorted into four main groups as shown in table 1, where the order of parameters is random. The parameters and the corresponding selected parametric studies are described further in the following sections.

Table 1 Overview of identified parameters influencing breakage of window glass in fires.

Group	Parameter	Explanation	Selected studies[1]
Geometric properties	Size	Area	(Klassen et al., 2006; Peng, 2023; Wang et al., 2018b)
	Form/shape	Square, rectangular, circular etc.	(Keski‐Rahkonen, 1988, 1991; Peng, 2023; Wang et al., 2018b)
	Thickness	4 mm, 6 mm etc.	(Li et al., 2012; Wang et al., 2023; Zhang et al., 2011)
	No. of layers	Single pane, multi-pane	(Hvidberg, 2023; Seindal and Jensen, 2023; Shields et al., 1998; Wang et al., 2017a)
	Gap between layers	Filling of air, argon, krypton	(Seindal and Jensen, 2023)
	Shading width	Mechanical edge cover, i.e., width of glass edge covered by frame	(Chen et al., 2017a; Jørgensen et al., 2022; Wang et al., 2013)
Material properties	Type of glass	Annealed, fully tempered (toughened)	(Hvidberg, 2023; Mowrer, 1998; Wang et al., 2023)
	Coatings	Low-energy coating, solar shading, reflective foils	(Hvidberg, 2023; Wang et al., 2014, 2015)
	Lamination	Lamination of two, three or more panes	(Wang et al., 2017b; Wang and Hu, 2019)
	Frame type/support	Frame of wood, metal, combination	(Harada et al., 2000; Seindal and Jensen, 2023; Wang et al., 2019)
	Stress history	New or used windows	[2, 3]
Fire effects	Heating rate	Incident heat flux	(Chen et al., 2017b; Harada et al., 2000; Jørgensen et al., 2022; Klassen et al., 2006; Wang et al., 2017a)
	Heating curve	Constant heat flux, growing fire	[2]
	Exposure type	Radiant, flame, smoke, uniform/non-uniform heating	(Hassani et al., 1994; Klassen et al., 2006)
	Over-pressure in fire room	Mechanical force on the inside of window in combination with fire effects	(Nielsen, 2023)
Environmental effects	Humidity	Humidity of surrounding air	[3]
	Wind	Mechanical force on the outside of window in combination with fire effects	(Chen et al., 2017c; Lu et al., 2018)

[1]: Studies are selected based on their focus on variation of a parameter, i.e., comparison between different values etc.
[2]: No studies have been found, where different values of this parameter are compared.
[3]: No fire-related study of the parameter has been found. The inclusion of the parameter is based on general knowledge of the behaviour of glass, based on "Structural use of glass" (Haldimann et al., 2008).

3.1 Geometric properties

Size is the first parameter listed in relation to the geometric configuration of a window. Window size has been investigated by several studies under different circumstances. Klassen et al. (2006) found that smaller sizes broke quicker due to lower heat capacity. However, both Peng (2023) and Wang et al. (2018b) found that larger panes broke quicker, because increasing the size increases both the tensile stresses and the number of randomly distributed surface flaws weakening the glass.

Keski-Rahkonen (1988, 1991) have formulated basic principles for analytical calculations of stresses in window panes, exposed to fire for different shapes. Wang et al. (2018b) have made numerical models for investigating different aspect ratios of rectangular panes. They found that increasing the aspect ratio increased the breakage time. Additionally, they found that a high aspect ratio decreases the likelihood of larger fallout of the glass leading to a potential smaller ventilation opening.

Another important parameter that has been largely studied is the glass thickness. Studies have found that, overall, increasing the glass pane thickness leads to increased breakage time (Li et al., 2012; Zhang et al., 2011). However, Wang et al. (2023) highlighted that, for thicknesses up to 15 mm, temperature gradients in the planar direction are governing. This explanation supports the results obtained by Li et al. (2012), who did not see any effect of thickness on the critical temperature difference for cracking between shaded and unshaded parts. Wang et al. (2023) found that gradients across the thickness has an effect for thicknesses over 19 mm. However, this value is significantly bigger than the thickness of most window panes.

Several studies have shown that the number of panes in a window assembly have a large impact on the resulting ventilation opening. Studies show that the panes closest to the fire behaves like a single pane assembly; however, the subsequent panes break later and can have smaller or even no fallout areas (Hvidberg, 2023; Seindal and Jensen, 2023; Shields et al., 1998; Wang et al., 2017a).

The effect of the size of the gaps between panes in multi-pane windows has not been studied thoroughly. However, Seindal and Jensen (2023) found that, seemingly, differences in gas fillings had little effect on glass breakage times.

The effect of the shading width (also referred to as mechanical edge cover) has been investigated in several studies. Chen et al. (2017a) found that increasing the shading width increases the breakage time. However, they also proposed that there is a critical shading width, that yields the lowest breakage times, which was found to be around 30 mm in their study. Jørgensen et al. (2022) found that shading width had the most significant effect at low heat exposures. In such cases they found that increasing the shading width decreases the breakage time, which contrasts with the findings by Chen et al. (2017a). Jørgensen et al. (2022) also found that fallout increased with increasing shading width, but the variability of the fallout percentage was very large. Wang et al. (2013) simulated different shading conditions that might be relevant when describing multi-pane windows, where subsequent panes might be shaded by the first pane if complete fallout is not achieved.

3.2 Material properties

The type of glass determines the strength of the pane. Several studies have investigated the differences between annealed float glass and toughened float glass (Hvidberg, 2023; Mowrer, 1998; Wang et al., 2023). All studies found that toughened glass has a significant higher fire resistance than annealed glass. Both the minimum required heat flux, the breakage time, and the critical temperature difference between shaded and exposed areas are higher for toughened glass. However, complete fallout is much more likely when the toughened glass breaks, as the fracture pattern is much different compared to annealed glass.

Wang et al. (2014) found that a low-energy coating improved the fire resistance of single glass panes. Neither Wang et al. (2015) nor Hvidberg (2023) found any measurable effect of solar shading on the fire resistance of glass panes.

The effect of lamination has been investigated in several studies. Both Wang et al. (2017b) and Wang and Hu (2019) found that using laminated panes alters the fire resistance of windows. The first pane in a laminated glass assembly was found to have similar cracking behaviour as a non-laminated sample, but a much lower fallout or no fallout at all. This is explained by considering that the presence of the lamination layer holds the glass panes together. Also, the thickness of the lamination layer was found to influence the fire resistance of the assembly.

For all types of glass panes, the frame material and the support conditions determine the thermal and mechanical boundary conditions, respectively. In theory, better insulating frames should yield faster breakage times, as the shaded areas are heated less leading to a larger temperature difference between exposed and unexposed areas. This was confirmed in experiments by Wang et al. (2019). However, Seindal and Jensen (2023) found no significant effect of this in experiments with more realistic framing materials. Support conditions has mainly been studied in relation to glass façades, which is fundamentally different from support conditions in window assemblies. However, Harada et al. (2000) found that different support conditions relevant for window glass had little effect on breakage behaviour.

In general, the stress history of a glass pane determines the number and state of sub-critical cracks in the pane (Haldimann et al., 2008). A glass pane that has undergone different stresses over time will have more micro-cracks that will (slightly) decrease its strength. No studies were found that investigates how this affects the behaviour of glass panes in fires. However, in actual buildings, where window glass typically has a stress history when exposed to fire, shorter breakage times could be expected compared to experiments done with glass with no stress history.

3.3 Fire effects

The influence of different heating rates, or incident heat fluxes, on glass panes have been studied by several different research teams (Chen et al., 2017b; Harada et al., 2000; Jørgensen et al., 2022; Klassen et al., 2006; Wang et al., 2017a). Generally, a higher heat exposure has been found to decrease the breakage time. Additionally, a higher heat exposure is more likely to cause a larger fallout after breakage (Harada et al., 2000; Jørgensen et al., 2022).

No studies have been found, where different heating curves have been compared. All the studies in the literature either uses a constant heating rate (see above) or have some sort of heating curve that is the same for all experiments, e.g., Seindal and Jensen (2023). Therefore, the differences between exposure to a constant fire and a growing fire is poorly documented.

Different types of exposure, e.g., heat radiation, heat convection, and direct flame exposure, is used in the different studies found in the literature review. However, the most common form of exposure has been found to be radiation from either a pool fire or radiant panel. These two types of exposure were found to yield similar results (Klassen et al., 2006). In general, it can be concluded that the heat source has little significance, and that the importance of the exposure type is related to the resulting heat flux to the glass. For non-uniform heating, Hassani et al. (1994) found that the cracking of the glass pane will start in the most heated part of the window.

In compartment fires, over-pressure in the fire room is a well-described phenomenon. However, few studies have investigated the effects of over-pressure in relation to glass breakage. Using a ventilator, Nielsen (2023) was able to apply under-pressure on the unexposed side of windows exposed to heat radiation (corresponding to over-pressure on the exposed side). He found that applying the pressure effect increased the fallout area, i.e., created a larger ventilation opening, compared to similar experiments by Seindal and Jensen (2023) without pressure effects.

3.4 Environmental effects

Humidity of surrounding air influences the formation of micro-cracks in glass and the crack propagation velocity (Haldimann et al., 2008). However, no studies have been found investigating the phenomenon in relation to fire-induced cracking. Nonetheless, one could suspect that humidity has a low impact on cracking behaviour in fires due to the short time spans and high temperatures typically involved in this situation.

Wind-induced stresses on windows coupled with thermal exposures have been investigated for single-pane glass façade elements (Chen et al., 2017c; Lu et al., 2018). Both studies found that including wind pressure on the specimen decreased the breakage time.

4 ROADMAP FOR BETTER ESTIMATION OF OPENING FACTORS

Based on the literature review, it is seen that most of the identified parameters have been investigated to some extent. Wang et al. (2018a) used sensitivity analysis to find that of the 16 parameters they studied, the most important for breakage were glass type, fire location (i.e., heating rate), and installation form (i.e., shading conditions). Based on the literature review in the previous section, the knowledge level of these three parameters is reasonably high. However, few studies were found, where the combination of parameters were assessed. Also, some parameters with potential key importance for fallout, such as pressure effects in fire room, are understudied.

We suggest that the effect of the following parameters is investigated further to increase the accuracy of predictions of opening factors in compartment fires: number of layers, gap between layers, low-energy coatings, and over-pressure in fire room. These parameters are chosen both based on the current level of knowledge and because they are increasingly relevant in modern windows. The highlighted parameters should be investigated both independently and in combination with other parameters to map the effects and assess their importance. Also the variance of the parameters should be investigated further, as most of the tests presented in the experimental studies here reviewed were repeated too few times to get information on the actual variance of the results.

Furthermore, a move towards more realistic experimental conditions should be sought when all individual parameters are well-described. The final goal of these studies should be the formulation of design rules to be used in fire safety designs to predict the fire development, implement more reliable computer models, and assess realistic ventilation factors that can be used in existing design methods to estimate the temperature and load capacity of structural elements during compartment fires.

5 CONCLUSIONS AND RECOMMENDATIONS

Overall, the literature review presented in this paper shows that many parameters influence window glass breakage. Although many experimental and numerical tests have been conducted over the years, the individual effect of many of these parameters is still not well understood or formalized. As a result, designers are left with little scientific foundation or large uncertainties to predict the ventilation factor of a fire and thus provide a reliable structural design in return.

Based on the literature review, it is concluded that:

- Central parameters relevant in modern window assemblies are understudied. In particular, the following parameters needs further investigation: number of layers in glass assemblies, gap between layers, low-energy coatings, and over-pressure in fire room.
- Reliable tools and rules of thumb are needed to improve current design practice regarding assessment of opening factors for modern windows.

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REFERENCES

Chen, H., Wang, Q., Wang, Y., Zhao, H., Sun, J., He, L., 2017a. *Experimental and Numerical Study of Window Glass Breakage with Varying Shaded Widths under Thermal Loading*. Fire Technology 53, 43–64.

Chen, H., Wang, Y., Zhang, Y., Wang, Q., Zhao, H., Shao, G., Su, Y., Sun, J., He, L., 2017b. *Crack evolution process of window glass under radiant heating*. Fire and Materials 41, 1016–1026.

Chen, H., Zhao, H., Wang, Y., Wang, Q., Sun, J., 2017c. *The Breakage of Float Glass with Four-Edge Shading Under the Combined Effect of Wind Loading and Thermal Loading*. Fire Technology 53, 1233–1248.

Emmons, H.W., 1986. The Needed Fire Science, in: *Fire Safety Science 1*. IAFSS, pp. 33–53.

Haldimann, M., Luible, A., Overend, M., 2008. *Structural use of glass*. International Association for Bridge and Structural Engineering.

Harada, K., Enomoto, A., Uede, K., Wakamatsu, T., 2000. An Experimental Study on Glass Cracking and Fallout by Radiant Heat Exposure, in: *Fire Safety Science 6*. IAFSS, pp. 1063–1074.

Hassani, S.K.S., Shields, J., Silcock, G.W., 1994. *An Experimental Investigation into the Behaviour of Glazing in Enclosure Fire*. Journal of Applied Fire Science 4, 303–323.

Hvidberg, J.L., 2023. *Study on the fire-induced breaking of multi-layered glazing used in modern windows* (Master's thesis). Technical University of Denmark (DTU), Kgs. Lyngby, Denmark.

Isaksen, L.T., Hagen, M., 2023. Fire Safety Engineering of Buildings with Visible Timber Constructions, in: *World Conference on Timber Engineering*. WCTE, Oslo, Norway.

Jørgensen, J.D., Nielsen, J.H., Giuliani, L., 2022. *Thermal resistance of framed windows: Experimental study on the influence of frame shading width*. Safety Science 149.

Keski-Rahkonen, O., 1988. *Breaking of window glass close to fire*. Fire and Materials 12, 61–69.

Keski-Rahkonen, O., 1991. *Breaking of window glass close to fire, II: Circular panes*. Fire and Materials 15, 11–16.

Klassen, M.S., Sutula, J.A., Holton, M.M., Roby, R.J., Izbicki, T., 2006. *Transmission through and breakage of multi-pane glazing due to radiant exposure*. Fire Technology 42, 79–107.

Li, L., Xie, Q., Cheng, X., Zhang, H., 2012. *Cracking behavior of glazings with different thicknesses by radiant exposure*. Fire and Materials 36, 264–276.

Lu, W., Wang, Y., Chen, H., Jiang, L., Duan, Q., Li, M., Wang, Q., Sun, J., 2018. *Investigation of the thermal response and breakage mechanism of point-supported glass facade under wind load*. Construction and Building Materials 186, 635–643.

Mowrer, F.W., 1998. *Window Breakage Induced by Exterior Fires* (Report). National Institute of Standards and Technology, Gaithersburg, MD, USA.

Nielsen, A., 2023. *Fire testing of Windows* (Report). Technical University of Denmark (DTU), Kgs. Lyngby, Denmark.

Peng, M., 2023. *Experimental and numerical study of thermally exposed window glass panes* (Master's thesis). Technical University of Denmark (DTU), Kgs. Lyngby, Denmark.

Seindal, J.G., Jensen, T.L., 2023. *Energy windows versus traditional double-glazed windows - Fire and breakage properties* (Master's thesis). Technical University of Denmark (DTU), Kgs. Lyngby, Denmark.

Shields, T.J., Silcock, G.W.H., Hassani, S.K.S., 1998. *Behavior of glazing in a large simulated office block in a multi-story building*. Journal of Applied Fire Science 7, 333–352.

Wang, Q., Wang, Y., Zhang, Y., Chen, H., Sun, J., He, L., 2014. *A stochastic analysis of glass crack initiation under thermal loading*. Applied Thermal Engineering 67, 447–457.

Wang, Y., Wang, Q., Fan, X., Sun, J., 2013. *Simulating the Thermal Response of Glass Under Various Shading Conditions in a Fire*. Procedia Engineering 62, 702–709.

Wang, Y., Wang, Q., Su, Y., Sun, J., He, L., Liew, K.M., 2015. *Fracture behavior of framing coated glass curtain walls under fire conditions*. Fire Safety Journal 75, 45–58.

Wang, Y., Li, K., Su, Y., Lu, W., Wang, Q., Sun, J., He, L., Liew, K.M., 2017a. *Determination of critical breakage conditions for double glazing in fire*. Applied Thermal Eng 111, 20–29.

Wang, Y., Li, X., Bisby, L., 2023. *Comparative study of thermal breakage of annealed and tempered glazing with different thicknesses under uniform radiation conditions*. Fire Safety Journal 140, 103867.

Wang, Y., Wang, Q., Wen, J.X., Sun, J., Liew, K.M., 2017b. *Investigation of thermal breakage and heat transfer in single, insulated and laminated glazing under fire conditions*. Applied Thermal Engineering 125, 662–672.

Wang, Y., Xie, Q., Zhang, Y., Wang, Q., Sun, J., 2018a. *Sensitivity analysis of influencing factors on glass façade breakage in fire*. Fire Safety Journal 98, 38–47.

Wang, Y., Zhang, Y., Wang, Q., Yang, Y., Sun, J., 2018b. *The effect of glass panel dimension on the fire response of glass façades*. Construction and Building Materials 181, 588–597.

Wang, Y., Hu, J., 2019. *Performance of laminated glazing under fire conditions*. Composite Structures 223, 110903.

Wang, Y., Sun, J., He, L., Wang, Q., Rush, D., 2019. *Experimental study on fallout behaviour of tempered glass façades with different frame insulation conditions in an enclosure fire*. Proceedings of the Combustion Institute 37, 3889–3898.

Zhang, Y., Wang, Q., Zhu, X., Huang, X., Sun, J., 2011. *Experimental study on crack of float glass with different thicknesses exposed to radiant heating*. Procedia Engineering 11, 710–718.