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Bengtsson, Hjalte; Giuliani, Luisa; Sørensen, Lars Schiøtt

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Hjalte Bengtsson, Luisa Giuliani, Lars Schiøtt Sørensen
Technical University of Denmark, Department of Civil and Mechanical Engineering

Introduction

Ventilation conditions are a key parameter in predicting fire development and thereby the thermal loads on building structures in a fire. A broken window can radically change the ventilation conditions in a room, and the increased supply of oxygen can lead to a fiercer fire. This could prove critical for the building structure if not probably accounted for in the structural design.

This poster highlights recent results from an ongoing research project at DTU and suggests a roadmap for future studies in pursuit of a better understanding of fire-induced glass breakage in modern windows.

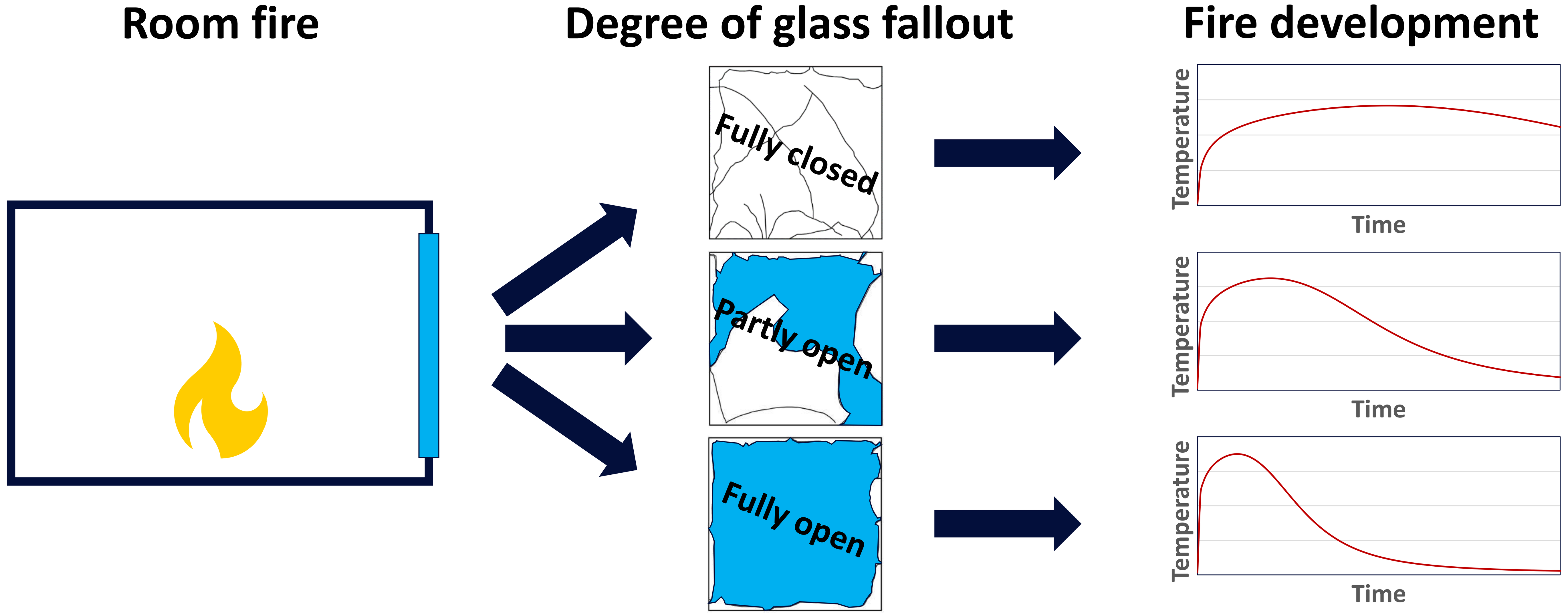

Fig. 1: Cracked glass panes after testing. Photo by Hvidberg [7].

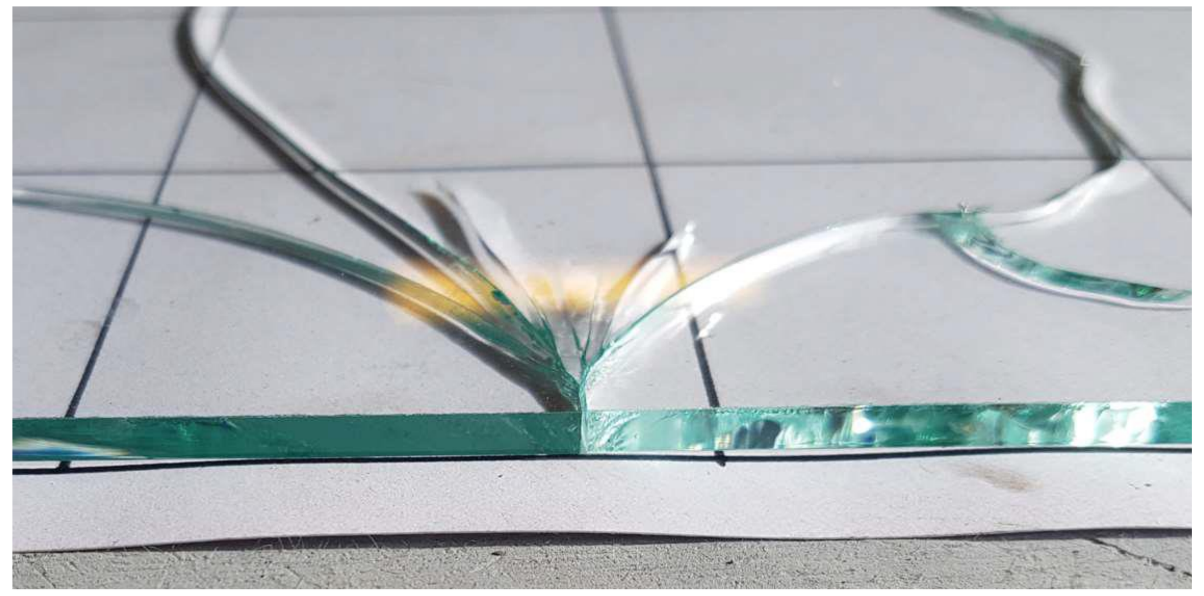

Fig. 2: Origin of first crack in a glass pane along an edge. The first crack is always perpendicular to the edge. Photo by Nielsen [5].

Fig. 3: Cracked glass and charring wood frame on exposed side. Photo by Nielsen [4].

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Knowledge about parameters for glass breakage

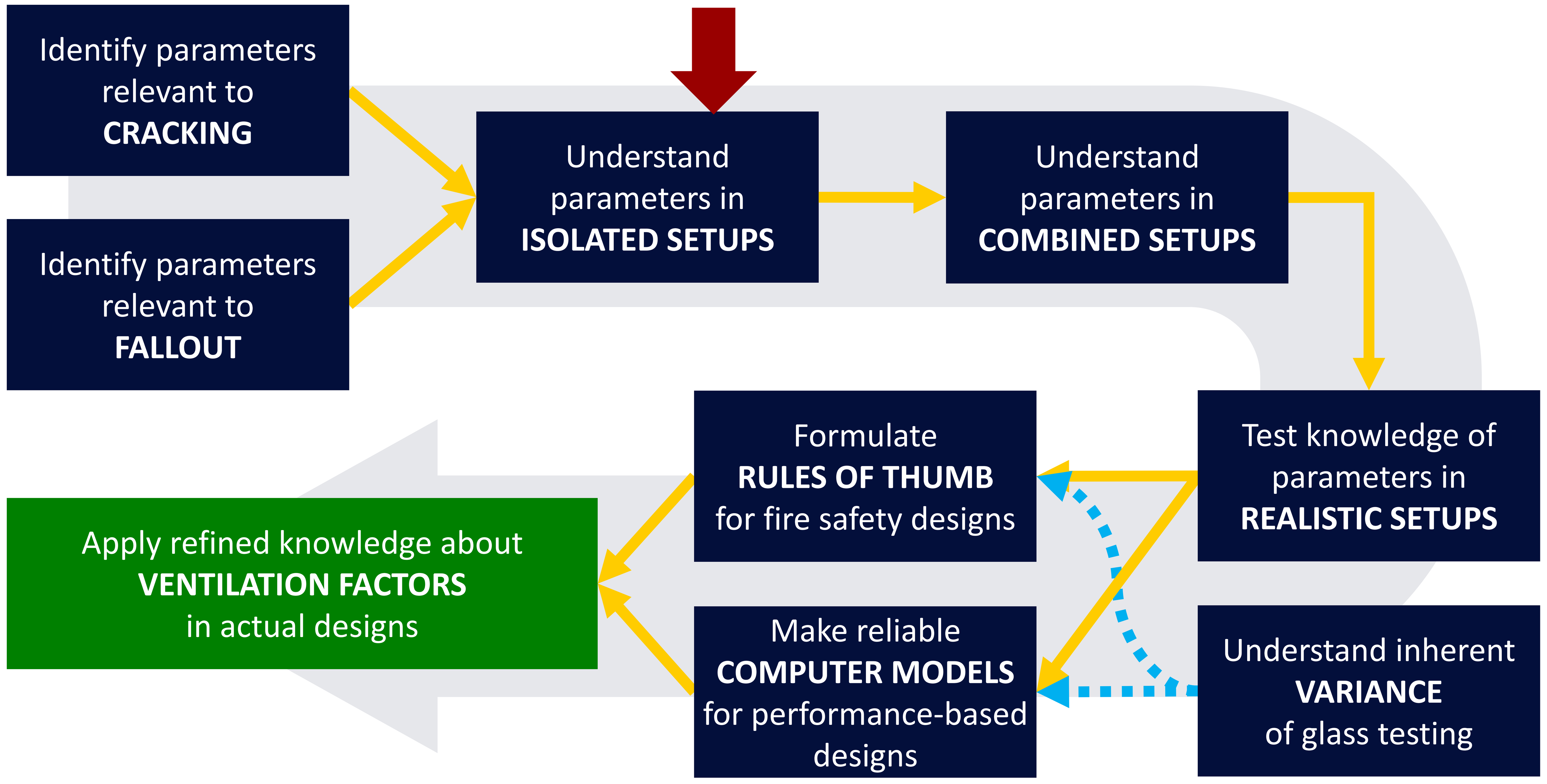
A literature review has been conducted to establish which parameters influence glass breakage in windows. The identified parameters can be sorted into four main groups as shown in the table below.

	Parameter	Explanation/examples	Current knowledge level[1]
Geometric properties	**Size**	Area	MEDIUM
	Form/shape	Square, rectangular, circular etc.	MEDIUM
	Thickness	4 mm, 6 mm etc.	MEDIUM
	No. of layers	Single pane, multi-pane	MEDIUM
	Gap between layers	Filling of air, argon, krypton	LOW
	Shading width	Width of glass edge covered by frame	HIGH
Material properties	**Type of glass**	Annealed, fully tempered (toughened)	HIGH
	Coatings	Low-energy coating, solar shading, reflective foils	LOW
	Lamination	Lamination of two, three or more panes	HIGH
	Frame type/support	Frame of wood, metal, combination	LOW
	Stress history	New or used windows	LOW
Fire effects	**Heating rate**	Incident heat flux	HIGH
	Heating curve	Constant heat flux, growing fire	MEDIUM
	Exposure type	Radiant, flame, smoke, uniform/non-uniform heating	HIGH
	Over-pressure in fire room	Mechanical force on the inside of window in combination with fire effects	LOW
Environ-mental effects	**Humidity**	Humidity of surrounding air	LOW
	Wind	Mechanical force on the outside of window in combination with fire effects	MEDIUM

[1] The current level of knowledge is coarsely assessed based on the literature review of 134 papers, cf. [1].

Roadmap for future studies

A roadmap is proposed for improving the current knowledge level and better utilise precise knowledge on the ventilation factor in structural designs. The roadmap seeks to describe the entire process of expanding the knowledge. It is assessed that presently; the scientific community as a whole is at the red arrow in the process.



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Recent experimental results from DTU

Studies by Peng [2] and Seindal and Jensen [3] found that modern multi-pane windows might not break enough to form a vent; at least not until long after flashover.

Nielsen [4] found that applying over-pressure in the fire enclosure of 100 Pa increased the fallout area compared to similar tests without over-pressure [3]. Additionally, Nielsen [5] found that the variance in single-pane glass could be described by a Weibull distribution with a goodness-of-fit of around 0,97 for both annealed and toughened glass, see figure 4.

Jørgensen et al. [6] investigated the importance of shading width and found that increased shading decreased the cracking time for low heat exposures.

References

[1] H. Bengtsson, L. Giuliani, and L. S. Sørensen, "Fire-induced Glass Breakage in Windows: Review of Knowledge and Planning Ahead", in "Proceedings from the 8th International Conference on the Applications of Structural Fire Engineering (ASFE'24)", pp. 21-27, 2024.

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

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

[4] A. Nielsen, "Fire Testing of Windows", Report, Technical University of Denmark (DTU), Kgs. Lyngby, Denmark, 2023.

[5] A. Nielsen, "Experimental study of variance in thermally induced breakage of single-pane glass", Master's thesis, Technical University of Denmark (DTU), Kgs. Lyngby, Denmark, 2024.

[6] J. D. Jørgensen, J. H. Nielsen, and L. Giuliani, "Thermal resistance of framed windows: Experimental study on the influence of frame shading width," Safety Science, vol. 149, 2022.

[7] J. L. Hvidberg, "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, 2023.

For three-pane windows, Hvidberg [7] showed that the origin of the first crack is random along all four edges for the first pane (closest to the fire), random along the edges in the upper half for the second pane (middle pane), and always located at the upper edge for the third pane (towards the outside). This could indicate differences in heat transfer modes in the subsequent layers.

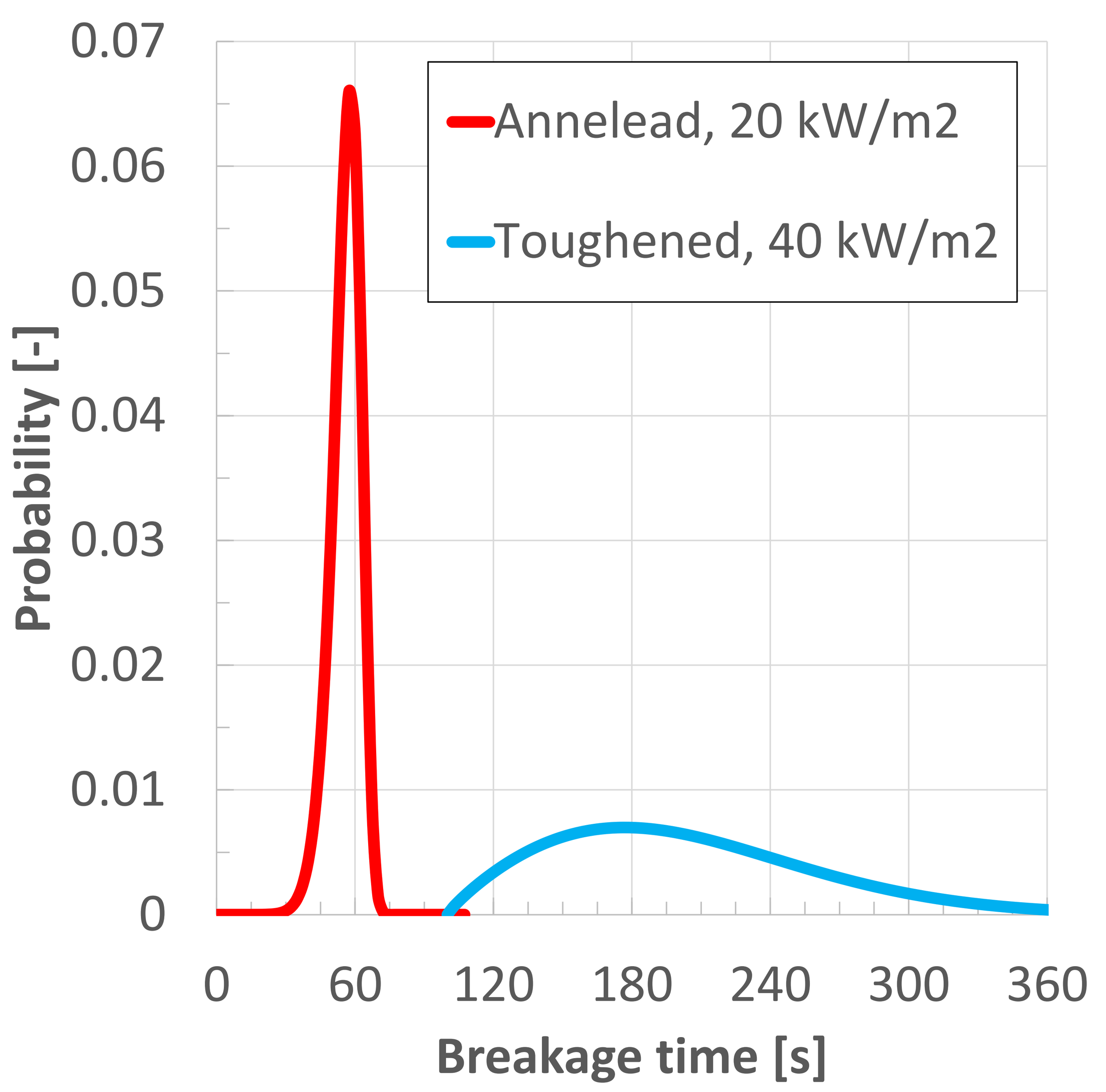

Fig. 4: Weibull distributions for single panes of annealed and toughened glass, respectively, as reported by Nielsen [5]. Note the difference in exposure levels for the different materials.

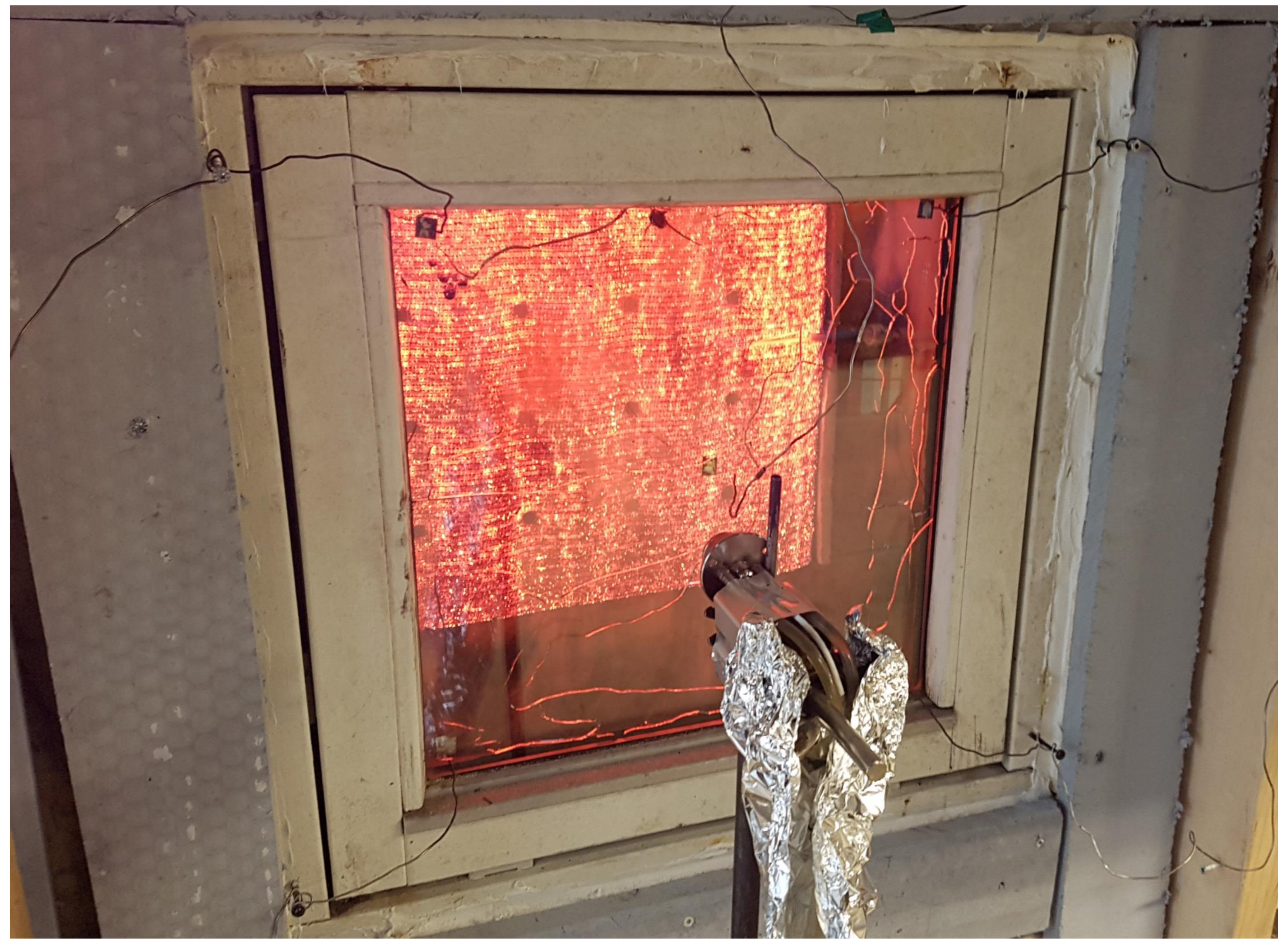

Fig. 5: Experimental setup seen from the unexposed side. The hot, radiant H-TRIS panel is seen through the test specimen. Photo by Nielsen [4].