Presentation of Recent Results from DTU

Fire-Induced Glass Breakage in Windows

Who am I?

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Hjalte Bengtsson (35)

- PhD student at DTU (2023-2026)
- B.Sc. (2011), M.Sc. (2014) in civil engineering from DTU
- Experience:
  - Fire safety consultant at Sweco DK+NO (2014-2023)
  - Technical manager (fire safety) at Sweco DK (2019-2023)
  - Fire fighter at DEMA (2012)
  - Safety steward at concert and sports venues (2009-2012)

Pictures: Energy island (North Sea); Rigshospitalet (Denmark); Nasjonaltheatret stasjon (Norway), Mjøstårnet (Norway)

Agenda

- **Background and motivation**
  - What is happening when glass breaks?
  - Why is it important?
- **Literature review**
  - What do we know?
  - What do we know, we do not know?
  - What do we not know, we do not know?
- **Recent and current work at DTU**
  - What new results do we have?
  - What are we planning?
- **Conclusions**

Picture AI generated by Dall-E 3

Background and motivation

Motivation

- High-rise timber structures must avoid collapse during a full fire duration
- Parametric fires can be used for this, but the opening factor must be known
- See e.g. Brandon et al. (2021), and Isaksen & Hagen (2023)

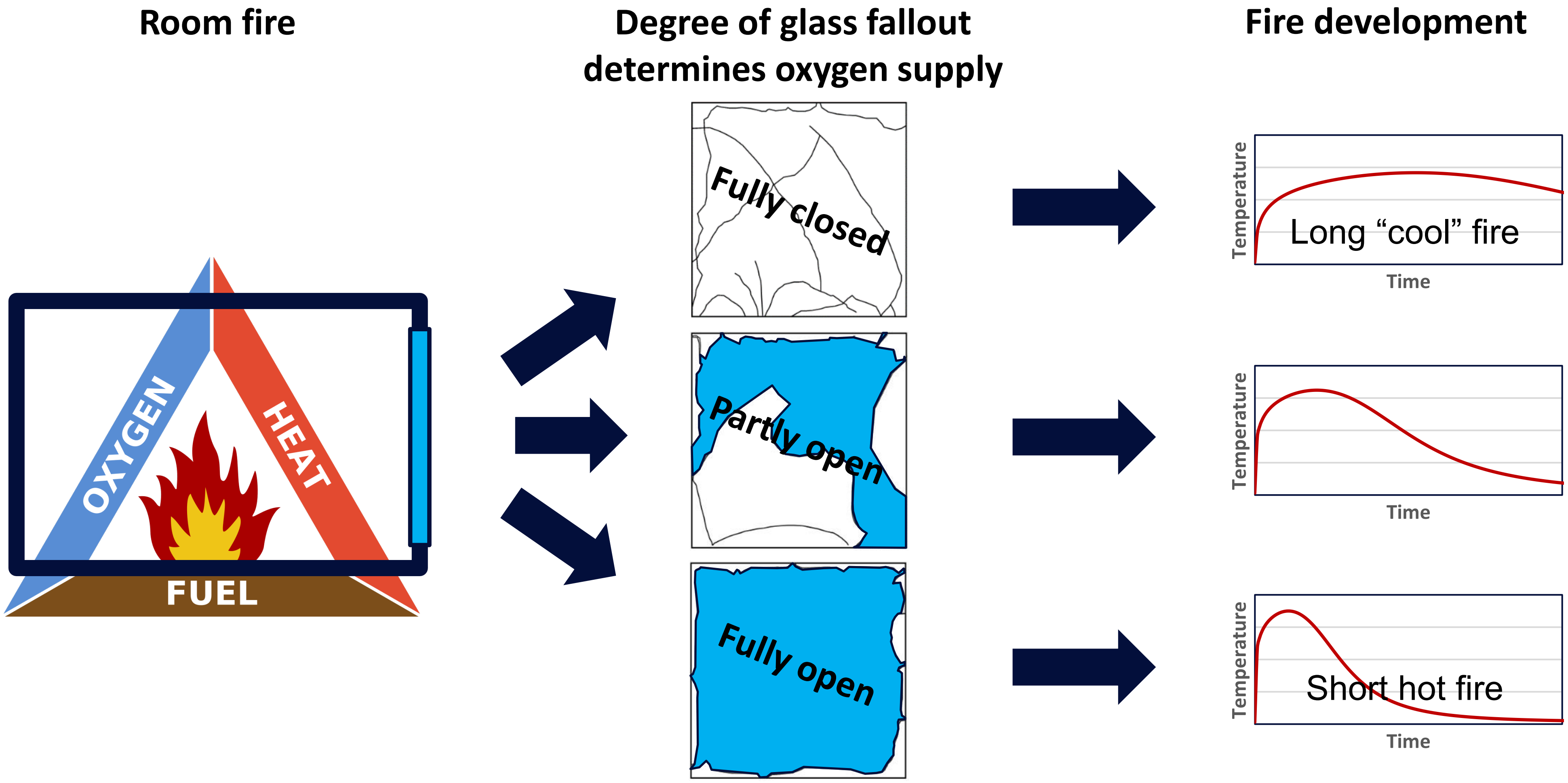
Picture: Mjøstårnet (Norway)

Motivation

- Current practices for fire testing of materials are based on 100-year-old assumptions on ventilation conditions
- Modern windows are increasingly complex, and research is not up-to-date:
  - Larger windows need tougher glass
  - Increasing number of layers
  - Energy coatings
  - More airtight buildings → higher over-pressure → more mechanical load on windows

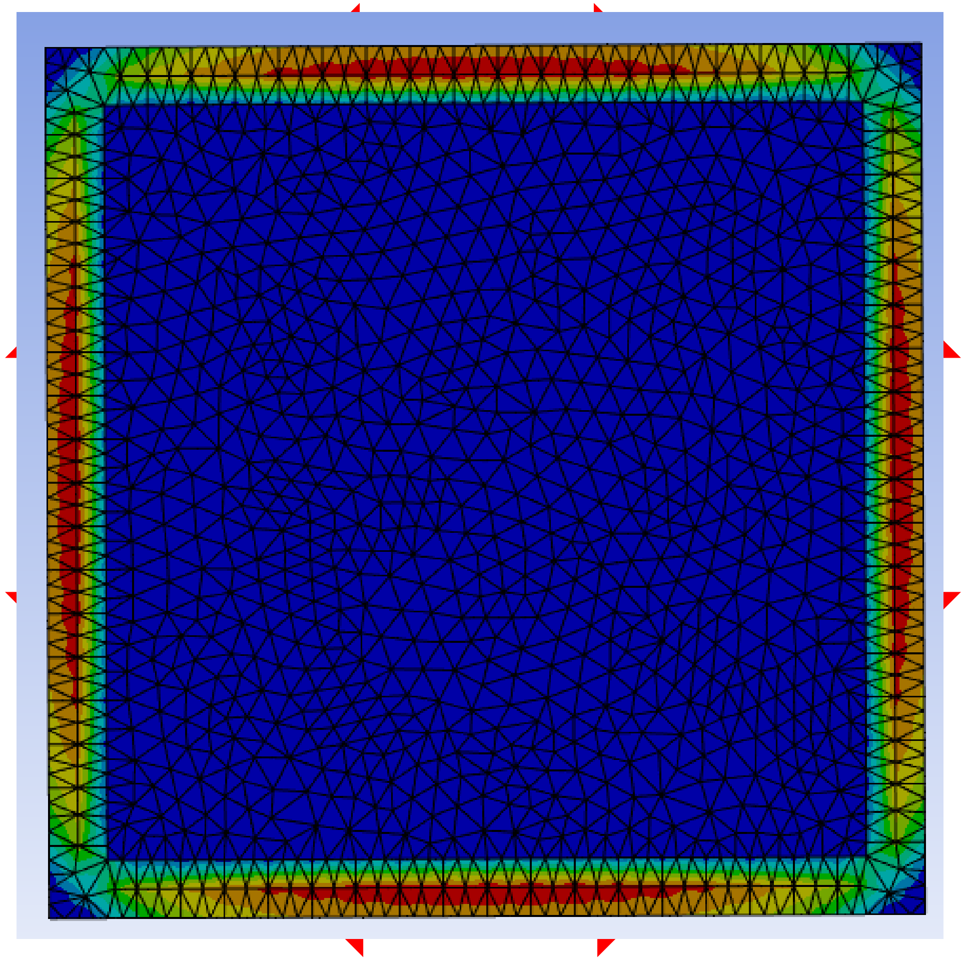
Furnace fire test anno 1902

Fundamentals of fire development



Fundamentals of fire-induced glass breakage

- Emmons (1986) first described fire-induced windows breakage
- Window glass typically break due to:
  - Hot exposed area in centre leads to thermal expansion
  - Cold shaded area around edges limits expansion, creating tension
  - Glass has low tensile strength; thus, breakage happens at the edges



FE-model by Peng (2023)

My research

“Predicting fire development from breakage of modern windows” *(working title)*

Supervisors: Lars S. Sørensen & Luisa Giuliani, DTU Construct

Reality: New windows must be energy-efficient to reduce heating costs and carbon emissions

→ **Hypothesis**: Low-energy windows are less prone to break open in a fire

→ **Fact**: Less opening area means longer fire durations (lack of oxygen)

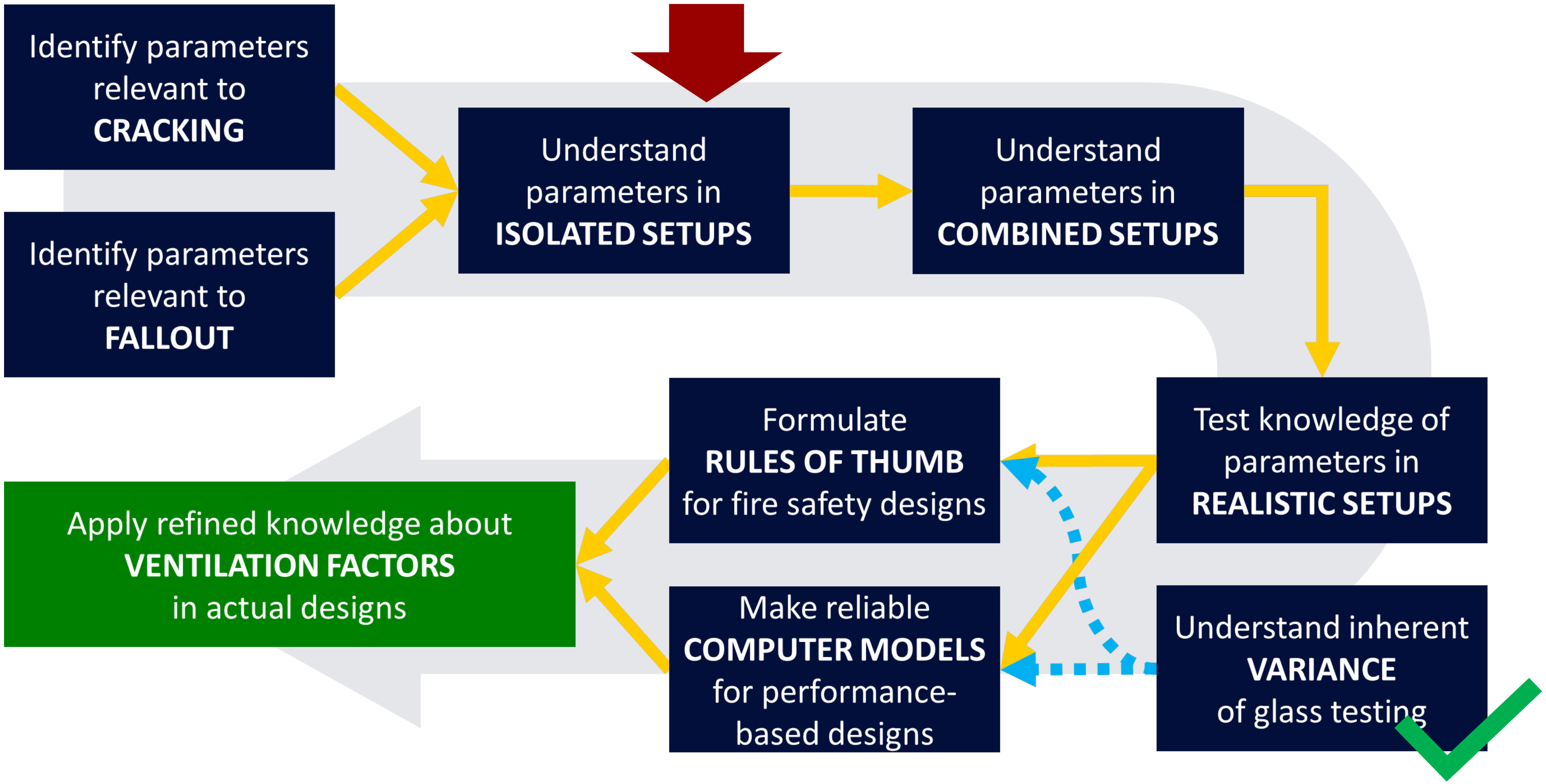
→ **Fact**: Longer fire durations are (typically) bad for structures, especially timber and steel

→ **Problem**: Ensuring fire safety in new timber buildings and old energy renovated buildings, means knowing how windows react to fire

Research questions:

- How do we assess realistic opening areas in buildings in order to design buildings in a fire safe way?
- What does fire development mean for window breakage (feedback loop)?

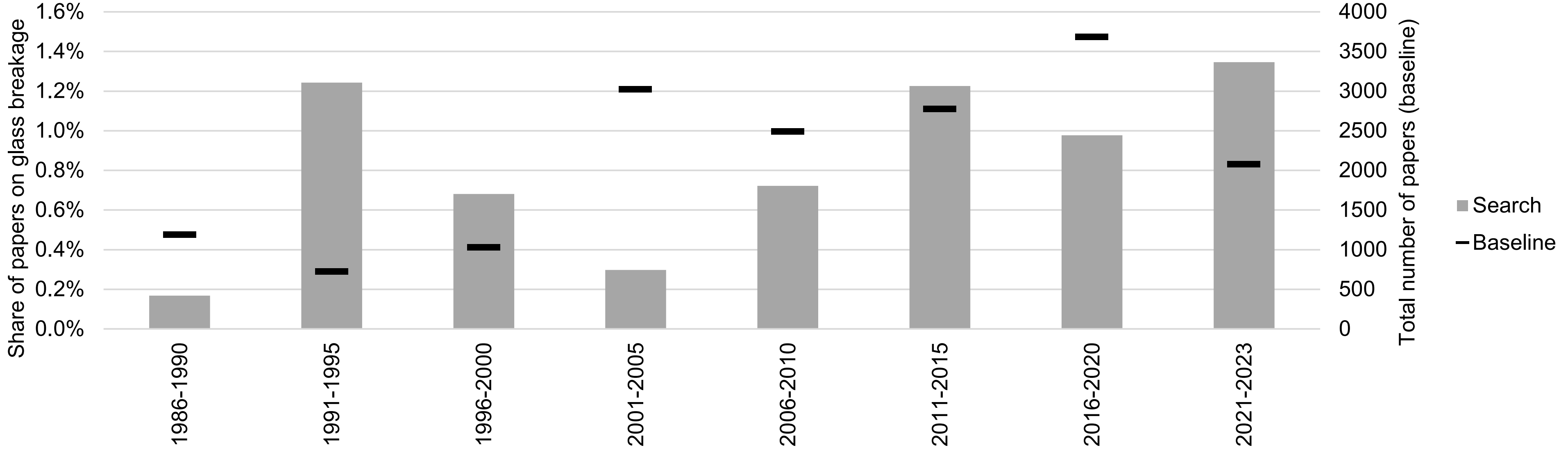
My research roadmap



Literature review

Literature review

- Literature study of 134 scientific papers and research reports (1986-2023)
  - 10 review papers
  - 31 papers on numerical modelling
  - 66 papers on experiments (some also include numerical modelling)
  - 27 papers of secondary relevance (e.g. applications of knowledge, glass façades, non-fire related thermal breakage



* Baseline from Scopus papers indexed under “fire safety” and/or “fire protection”

Overview of parameters

- 17 parameters identified
- Four main groups of parameters established

Geometric properties	Material properties	Fire effects	Environmental effects
Size	Type of glass	Heating rate	Humidity
Form/shape	Coatings	Heating curve	Wind
Thickness	Lamination	Exposure type	
No. of glass layers	Frame type/support	Over-pressure in fire room	
Gap between layers	Stress history		
Shading width (rabbet)			

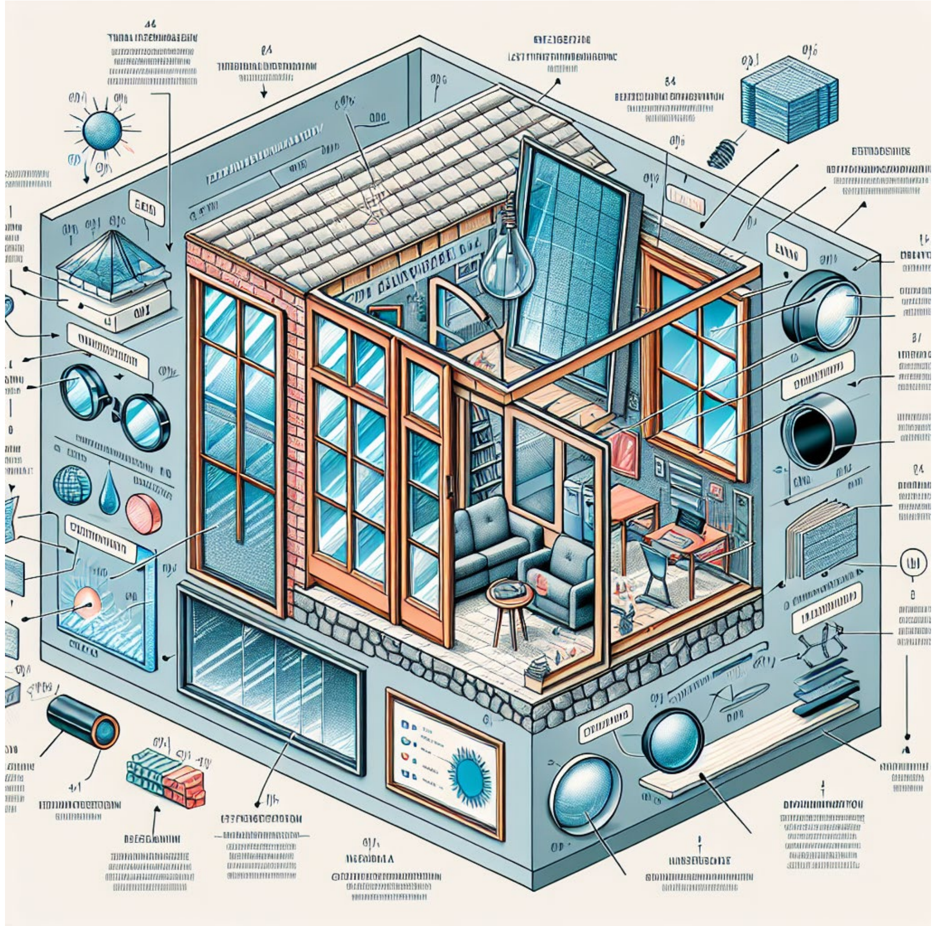
Geometric parameters

- **Size:** Area of glass
- **Form/shape:** Square, rectangular, circular etc.
- **Thickness:** Typically, 4 or 6 mm
- **No. of layers:** Single, double, triple, (quadruple) pane
- **Gap between layers:** Distance, gas filling (air, argon, krypton)
- **Shading width:** Width of covered area around edges (in Denmark 15 mm, typically)

Picture AI generated by Dall-E 3

Material properties

- **Type of glass:** Annealed, toughened
- **Coatings:** Low-energy coating, solar shading, reflective foils
- **Lamination:** Lamination of two, three or more panes. Type of lamination foil
- **Frame type/support:** Frame of wood, metal, combination
- **Stress history:** New or old windows



Picture AI generated by Dall-E 3

Fire effects

- **Heating rate:** Incident heat flux
- **Heating curve:** Constant heat flux, growing fire
- **Exposure type:** Radiant, flame, smoke, uniform/non-uniform heating
- **Over-pressure in fire room:** Mechanical force on the inside of window in combination with fire effects

Picture AI generated by Dall-E 3

Environmental effects

- **Humidity:** Humidity of surrounding air
- **Wind:** Mechanical force on the outside of window in combination with fire effects

Picture AI generated by Dall-E 3

Level of knowledge

	Parameter	Current know-ledge level
Geometric properties	Size	MEDIUM
	Form/shape	MEDIUM
	Thickness	MEDIUM
	No. of layers	MEDIUM
	Gap between layers	LOW
	Shading width	HIGH
Material properties	Type of glass	HIGH
	Coatings	LOW
	Lamination	HIGH
	Frame type/support	LOW
	Stress history	LOW
Fire effects	Heating rate	HIGH
	Heating curve	MEDIUM
	Exposure type	HIGH
	Over-pressure in fire room	LOW
Environ-mental effects	Humidity	LOW
	Wind	MEDIUM

- Current level of knowledge assessed based on literature review
- See our paper for references: Bengtsson et al. (2024)

Findings

- Many parameters are well-described
- Some parameters need further study
- **Combination of parameters are under-studied**

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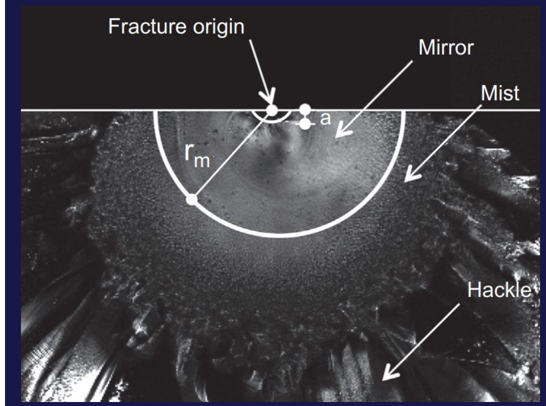
Unknown unknowns

Picture AI generated by Dall-E 3

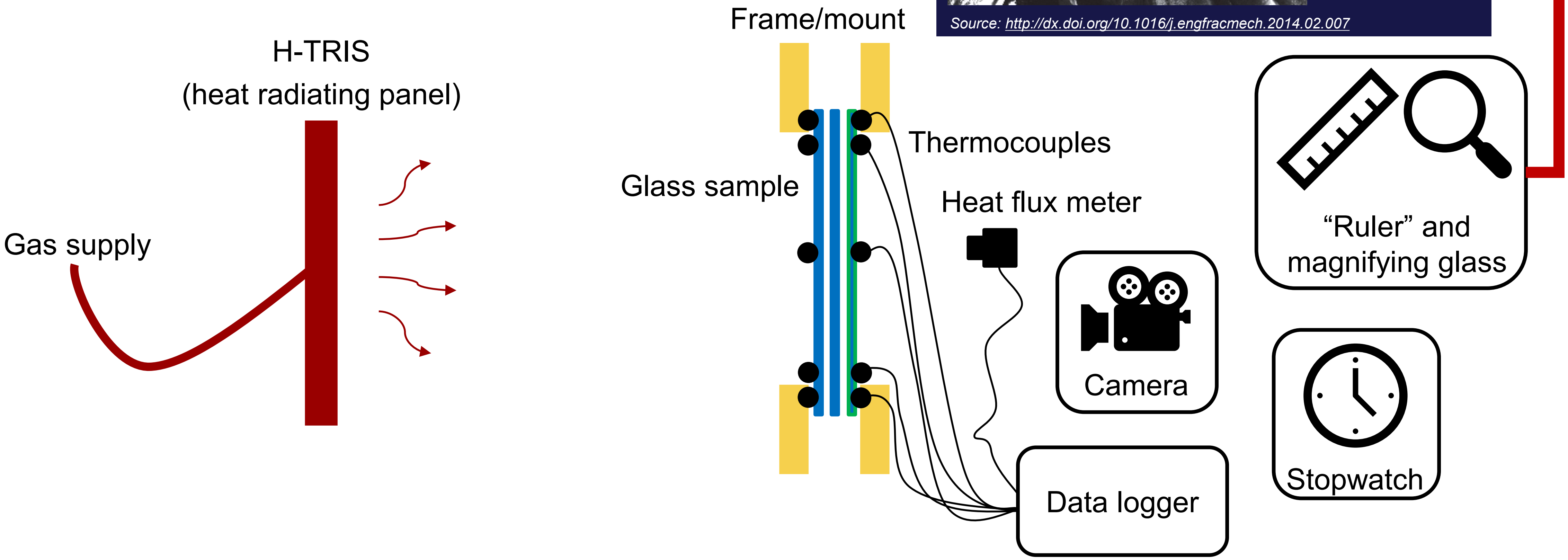
Recent and current work at DTU

General experimental setup

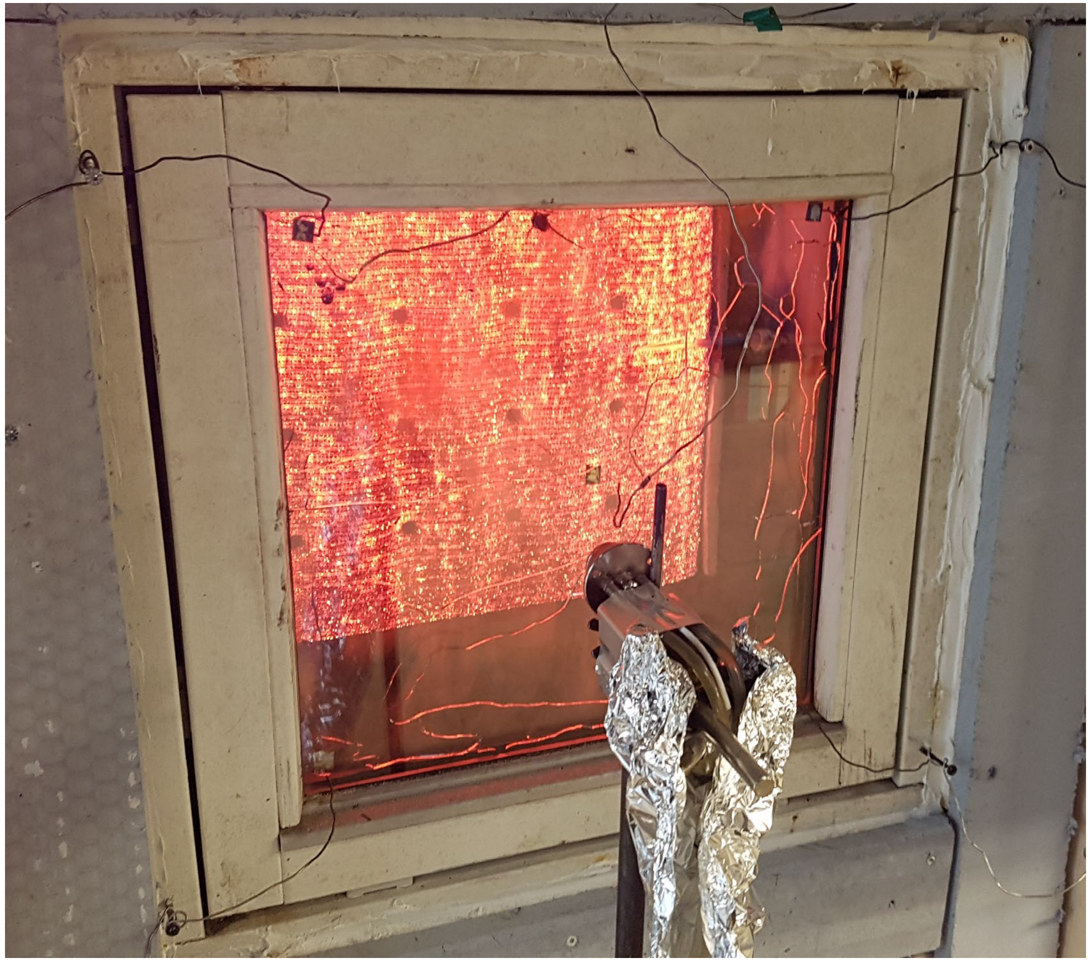


$$\sigma_f = \frac{B}{\sqrt{r_m}}$$

Source: http://dx.doi.org/10.1016/j.engfracmech.2014.02.007



General experimental setup



Picture by Nielsen (2023)

Shading width at different exposure levels

- Study by **Jørgensen et al. (2022)**
- **Single pane** samples
- Four different shading widths:
  10, 15, 20, and 25 mm
- Three different exposure levels:
  5, 10, 15 kW/m^2
- Findings: Shading width **matters most at low exposure** levels

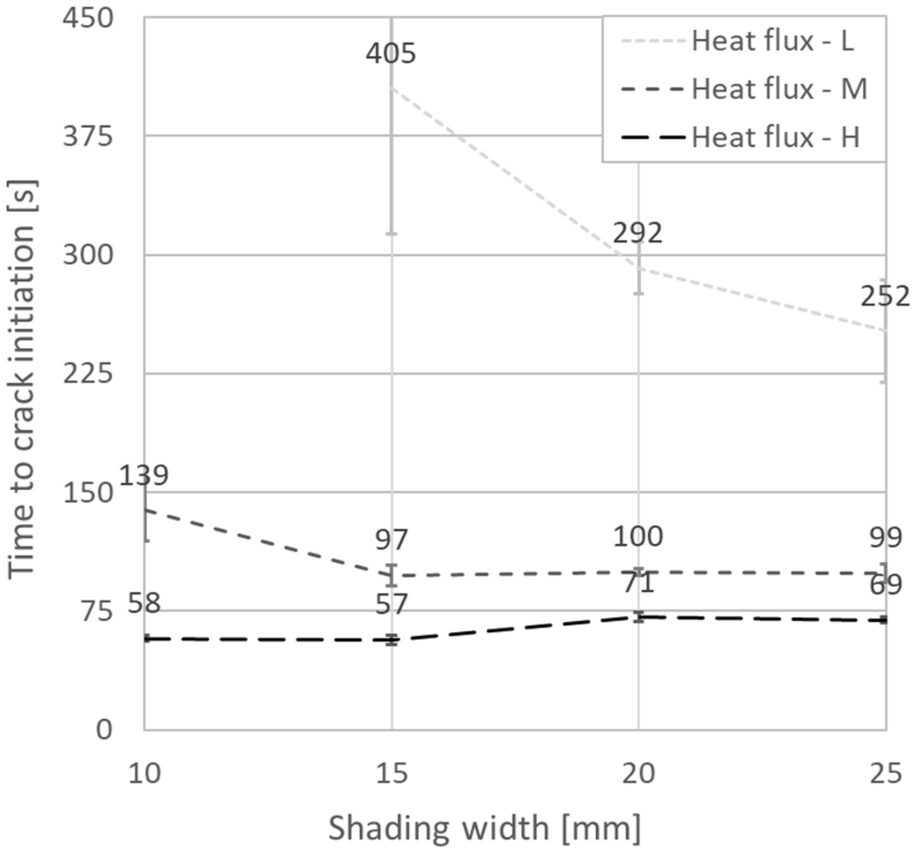


Figure from Jørgensen et al. (2022)

Low-energy windows in growing fires

- Study by **Seindal & Jensen (2023)**
- Studied:
  - Exposure from **growing fires** on
  - two- and three-layer **thermo windows** and **low-energy windows** with
  - different **framing materials**
- Findings:
  - Frame material had insignificant impact on results
  - Low-energy windows had higher fire resistance

- Supplementary study by **Nielsen (2023)**
- Findings: **Increasing fallout area** when applying simulated over-pressure on fire side

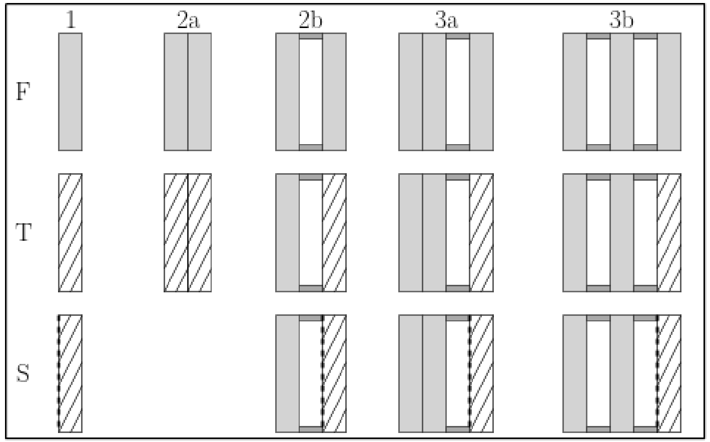
Multi-pane windows and different glass types

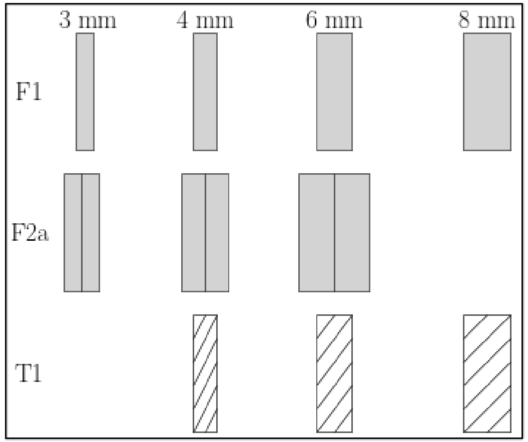
- Twin studies by **Hvidberg (2023)** and **Peng (2023)**; see also Peng et al. (2024)

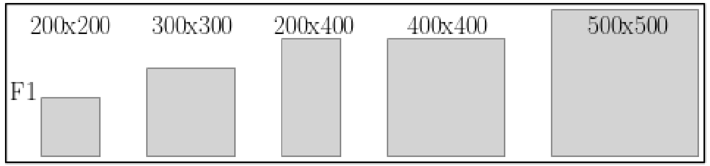
F: **Annealed** float glass
T: **Toughened** float glass
S: **Toughened** float glass with **integrated solar shading**

a: Laminated layer
b: Void between all layers

- Test series 1: **Multi-pane assemblies**, 400 x 400 mm, 4 mm thick
- Test series 2: Single pane, 400 x 400 mm, **3-8 mm thick**
- Test series 3: Single pane, **200-500 x 200-500 mm**, 4 mm thick

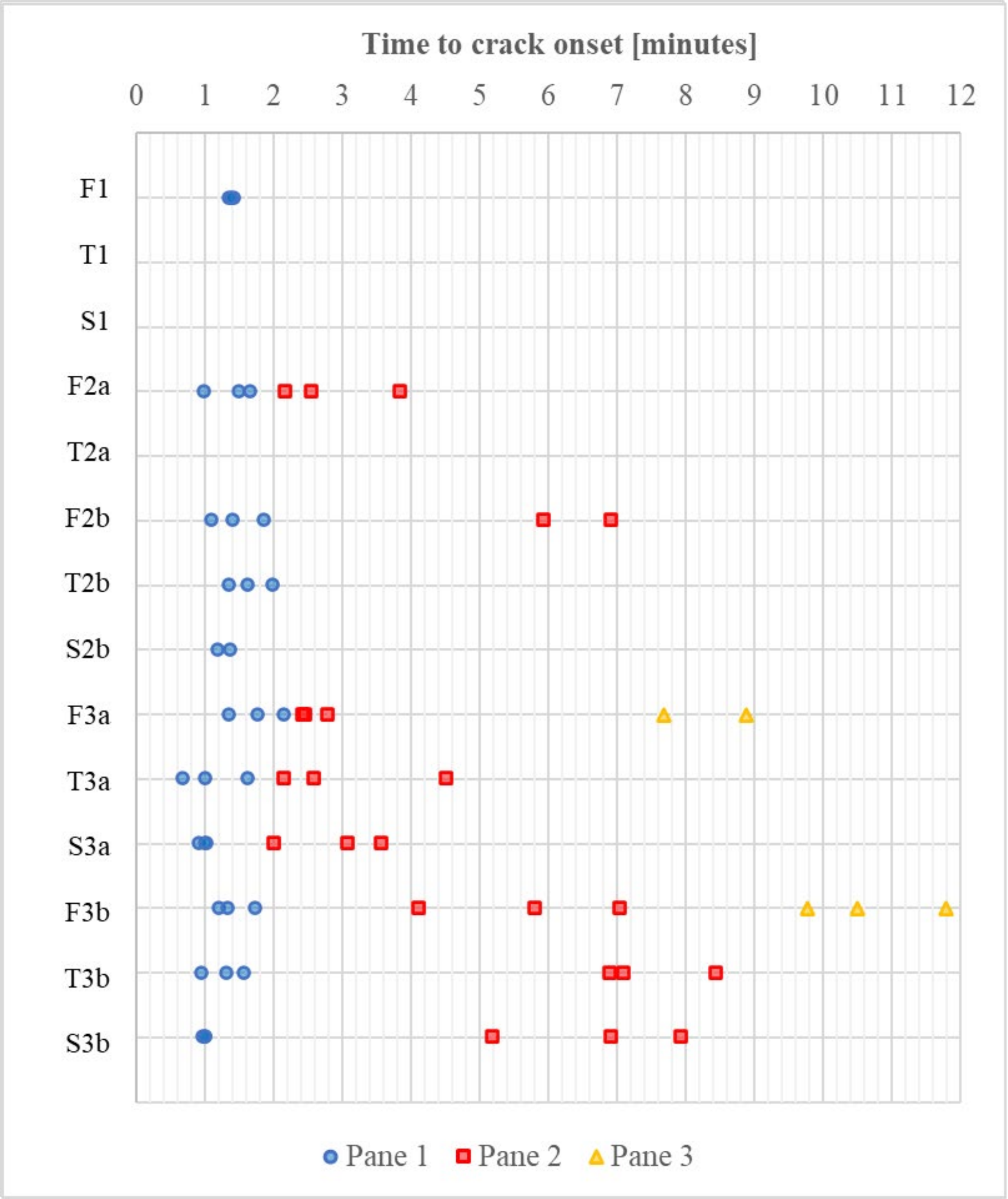






Multi-pane windows

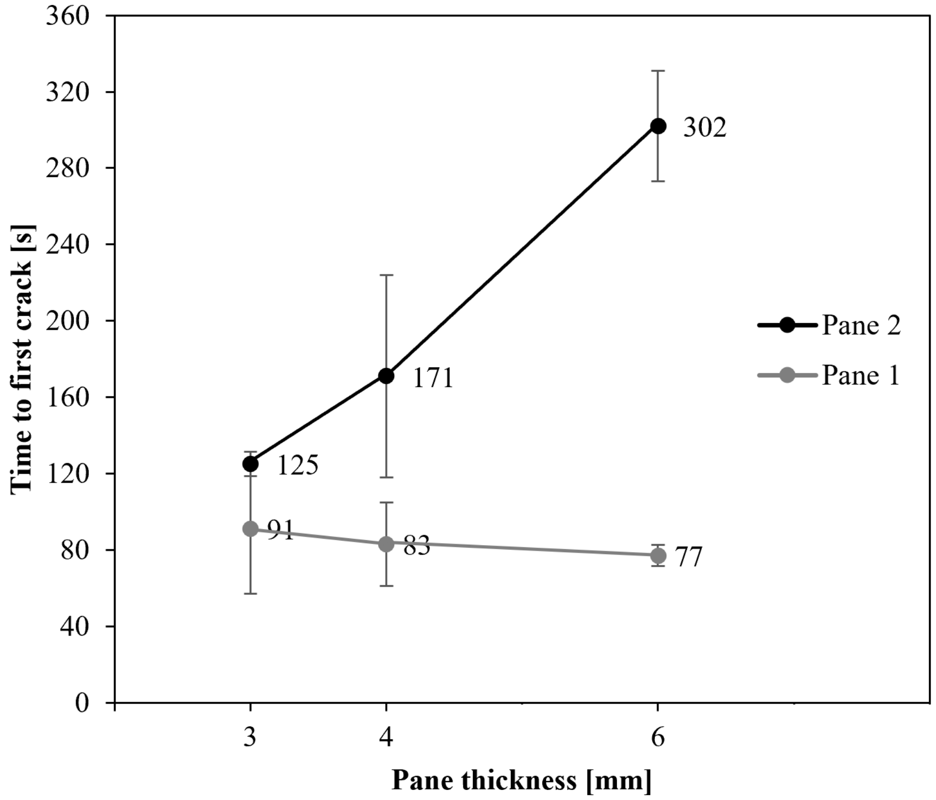
- **No toughened panes broke** under the exposure of 20 kW/m^2
- Time to breakage of 1st pane: **80 ± 21 s**
- Time to breakage of **first pane independent of lamination**
- Time to breakage of **second pane significantly different in laminated panes** (faster)
- Succeeding annealed panes (non-laminated) **broke roughly 5 minutes and 20 seconds after breakage of previous pane**
- Neither toughened glass nor solar shading influenced results of preceding panes



Peng et al. (2024)

Laminated Panes

- In general, thickness **does not** matter for pane 1 in laminated assemblies
- Thickness increases breakage time for pane 2 in laminated assemblies
- **No fallout** was observed in laminated samples



Peng et al. (2024)

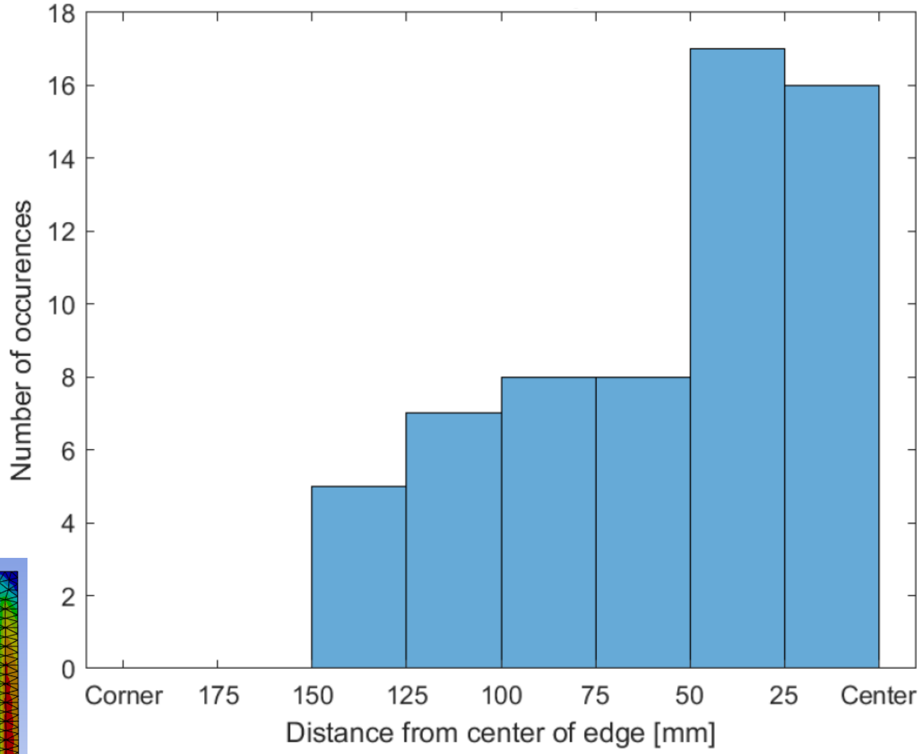
Fallout in Insulated Glazing Units

Sample code	Time to fallout [min:sec]	Fallout fraction (1st pane) [%]	Sample code	Time to fallout [min:sec]	Fallout fraction (1st pane) [%]
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

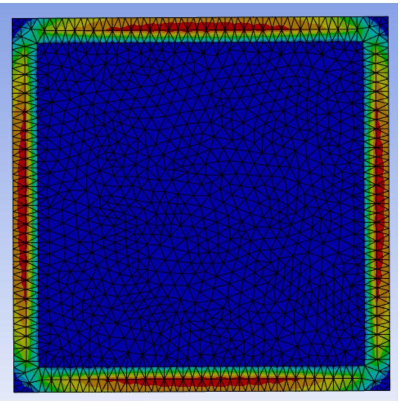
[a] Time to 1st crack of pane 1. [b] Time to 1st crack of pane 2.

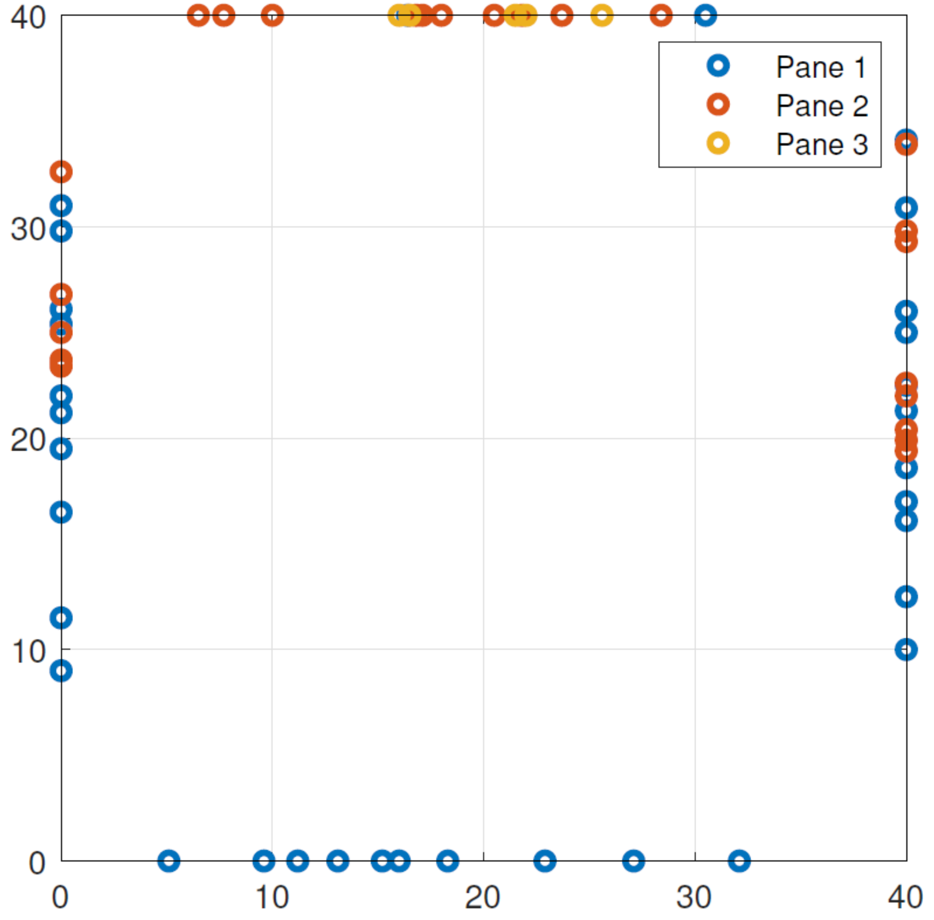
Peng et al. (2024)

Crack initiation point for multi-pane windows



Hvidberg (2023)



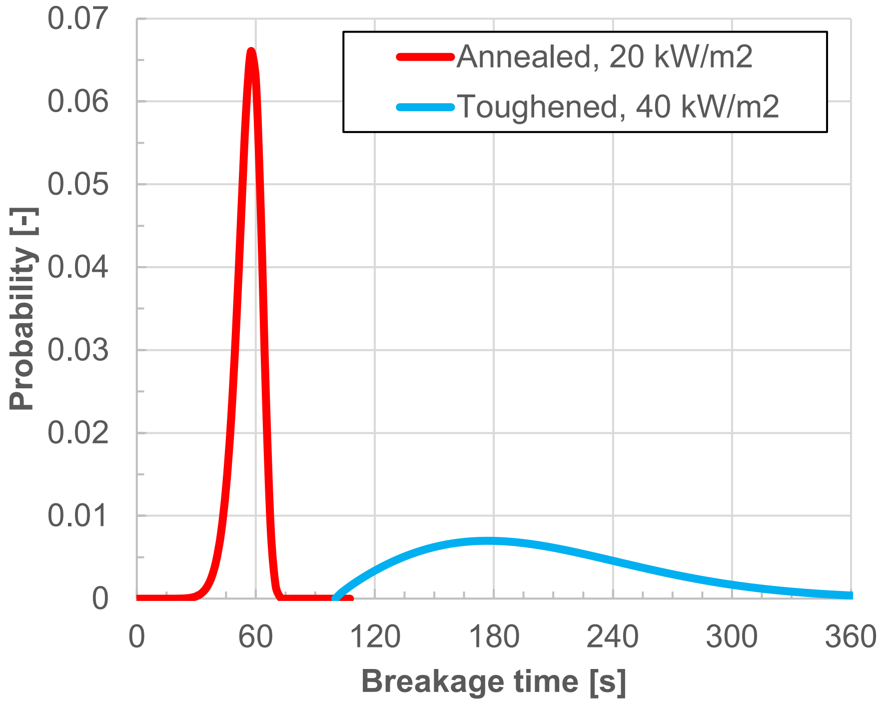


Hvidberg (2023)

Variance of fire-induced glass breakage

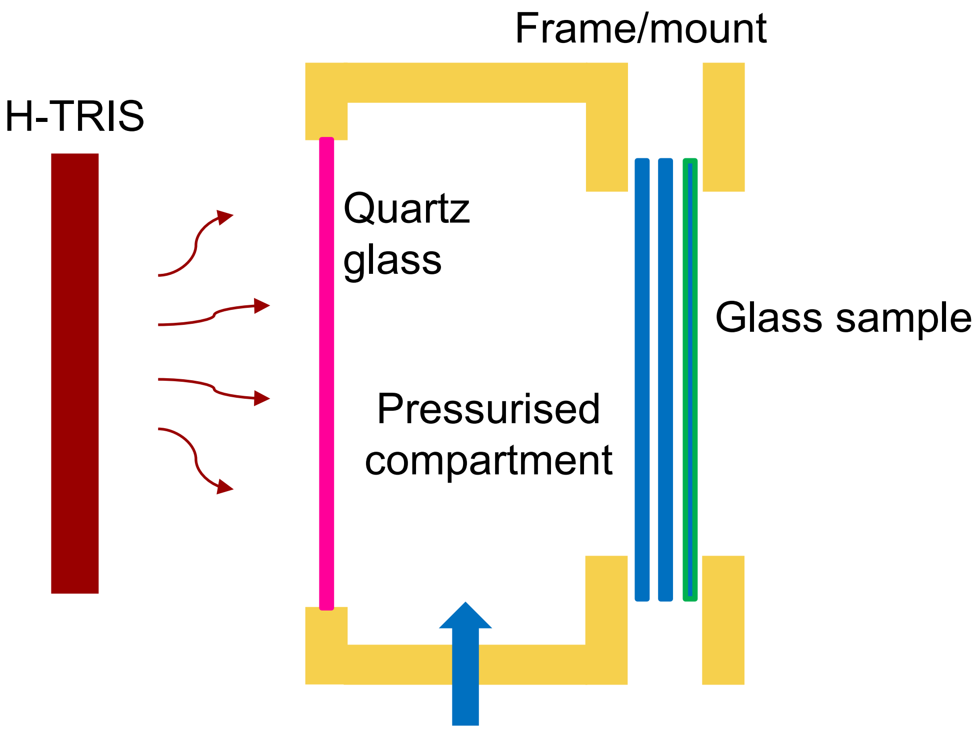
- Study by **Nielsen (2024)**
- Test of **single pane glass** samples:
  - 20 annealed panes
  - 20 toughened panes
- Exposure was **20 kW/m²** and **40 kW/m²**, respectively
- Breakage times:
  - Annealed: 55.8 ± 6.9 s
  - Toughened: 203.4 ± 60.0 s
- Found Weibull distributions for modelling glass breakage with parameters:

Glass type	Scale, η	Shape, β	Location, γ
Annealed	58.649	10.535	-
Toughened	117.089	1.849	100



What’s next?

- Mid-scale experimental campaign investigating:
  - Energy coatings
  - Void filling (air and argon)
  - Over-pressure
- Large-scale experiments with realistic window sizes
- Full-scale experiments in actual enclosures fitted with real windows



Conclusion

Conclusions

- Glass breakage in windows is a complex topic with many parameters to consider
- We still lack knowledge to accurately predict ventilation factor
- DOs and DON'Ts for applications in designs (as of right now):
  - DON'T model glass breakage at a set temperature
  - DON'T assume that multi-pane windows break at once
  - DO consider temperature gradients in glass
  - DO be careful in assessing fallout area
  - DO test the actual windows in a specific design, if you want to know the actual ventilation factor in your building
- Regarding applications related to structural timber, someone may have to answer: *Which is better; using structural timber with lower carbon footprint, or using less energy-efficient windows with higher operational carbon footprint?*

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