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Computational analysis of failure criteria of a multi-storey steel frame exposed to fires: thermal vs. structural

Egle Rackauskaite, Panagiotis Kotsovinos, and Guillermo Rein

IMPERIAL HAZELAB

ARUP EPSRC Engineering and Physical Sciences Research Council SFPE CERIB

WHY? – Real Fires


NIST


Foad Ashtari


2A + P/A


Alfonso Correas

WHY? – Traditional Design

Traditional Design Fires
- Standard Fire ~1880
- Swedish Curves ~1972
- Eurocode Parametric Curve ~1995

- Based on small scale tests (<100 m^2)
- *Assume uniform temperatures within the compartment*
- *Have strict limitations on the applicability to compartments*

- *most of new buildings fall outside of these limitations*

e.g., only 8% of volume within limitations
in survey at Edinburgh

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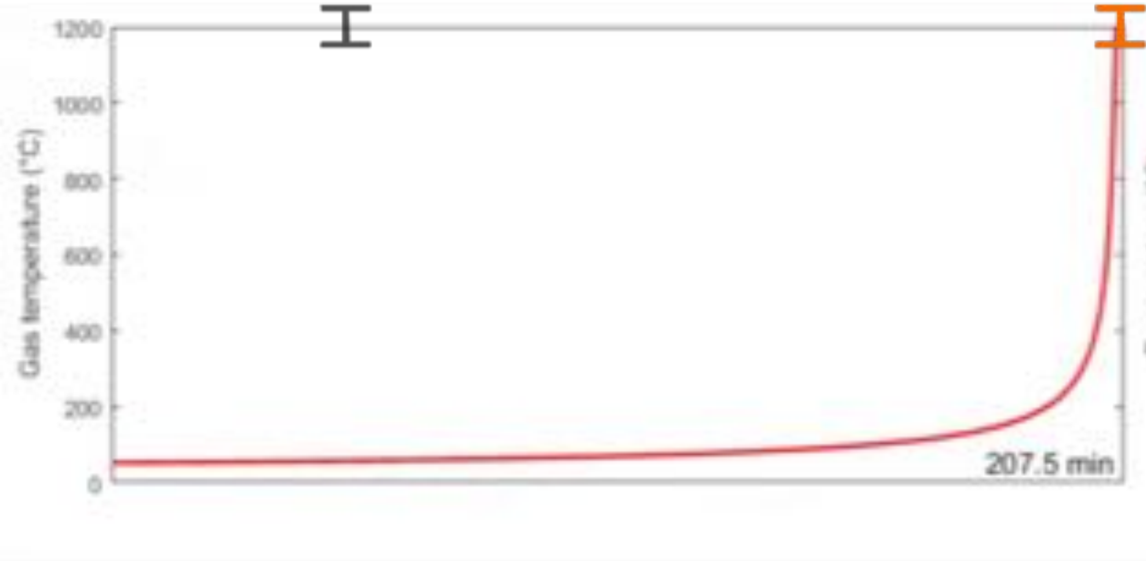
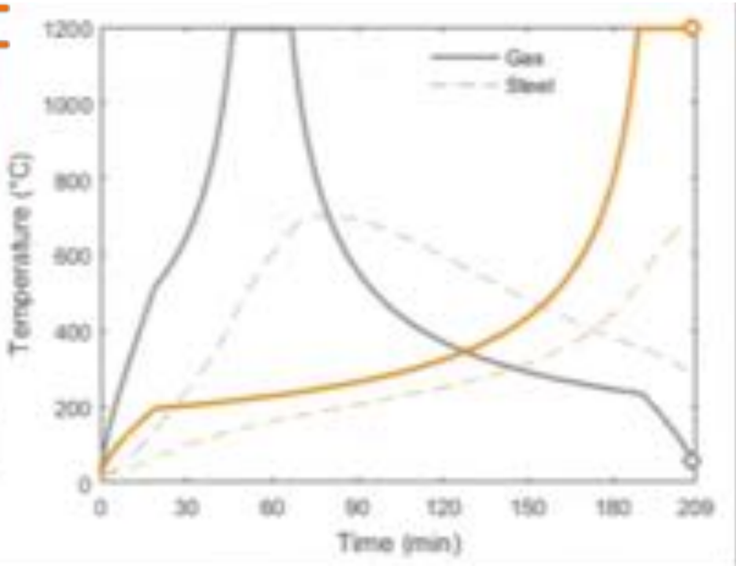
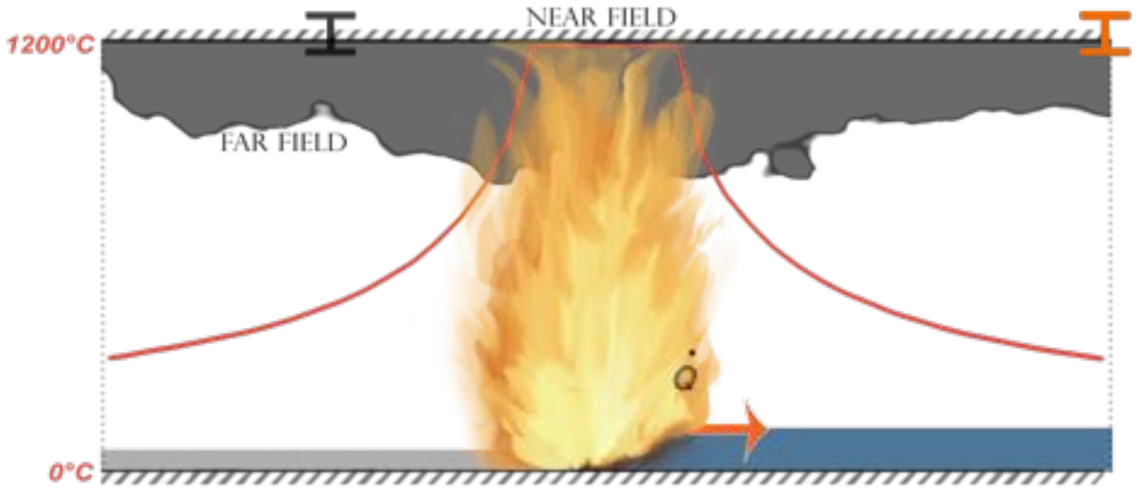
Travelling Fires Methodology (iTFM)

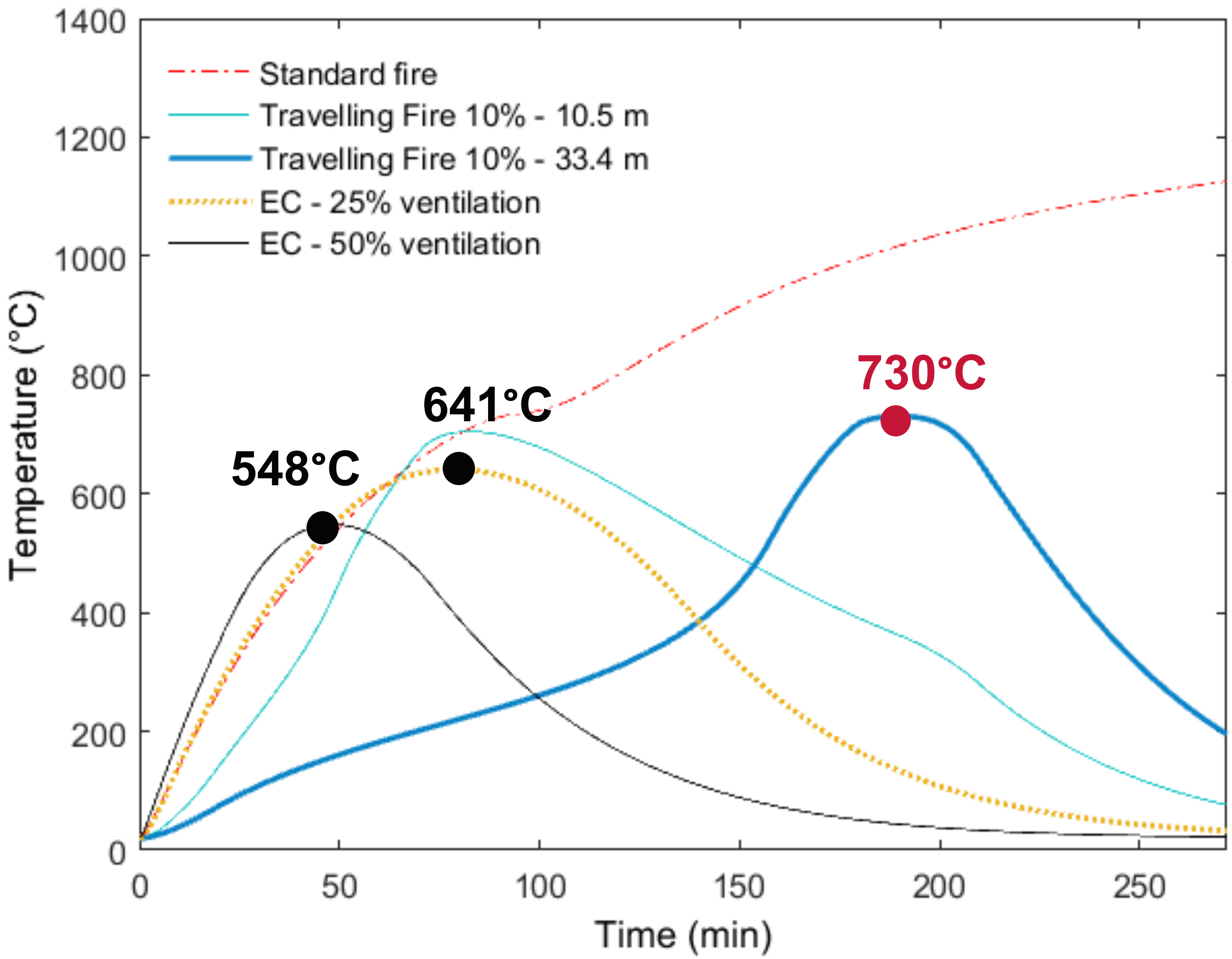






- TFM - Stern-Gottfried, Law and Rein (2007-2012)
- iTFM - Rackauskaite, Hamel, Law and Rein (2015)
- Considers a **family of fires** → different % of floor areas engulfed in flames
- Takes into account highly **non-uniform** temperature distributions

Travelling Fires Methodology (iTFM)



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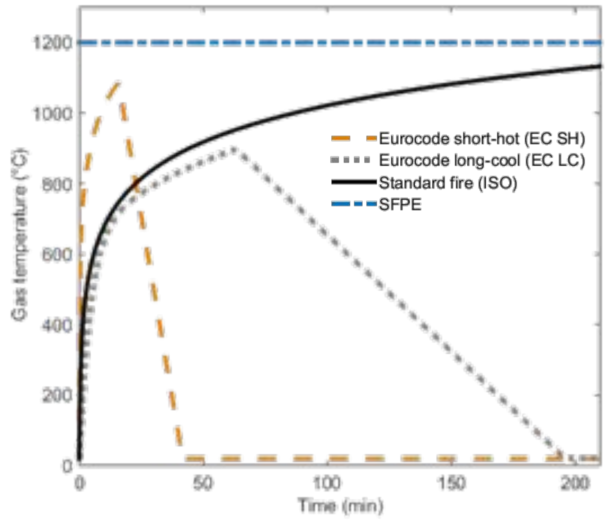
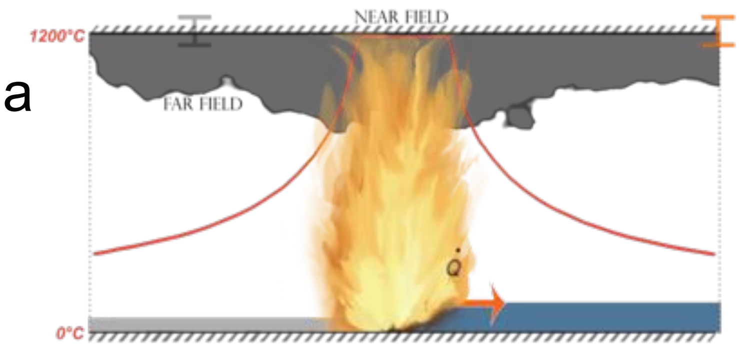
AIM OF THE STUDY

- Apply iTFM and **compare** the structural response of the steel frame subjected to **traditional fires** and **travelling fires**





- Investigate **validity** of **limiting temperature** as a failure criterion for non-uniform fires

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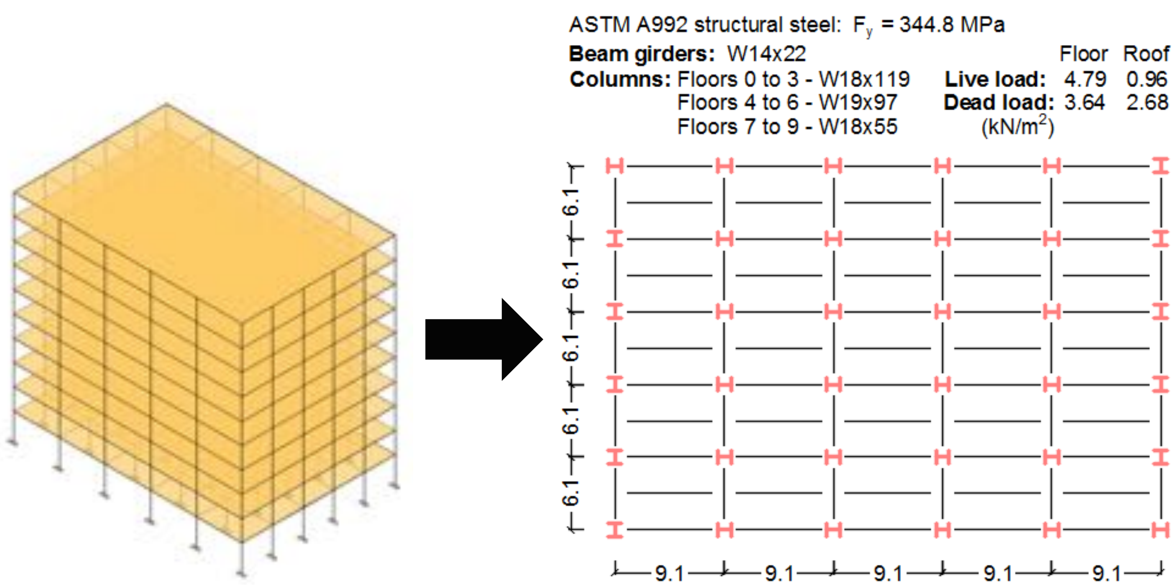
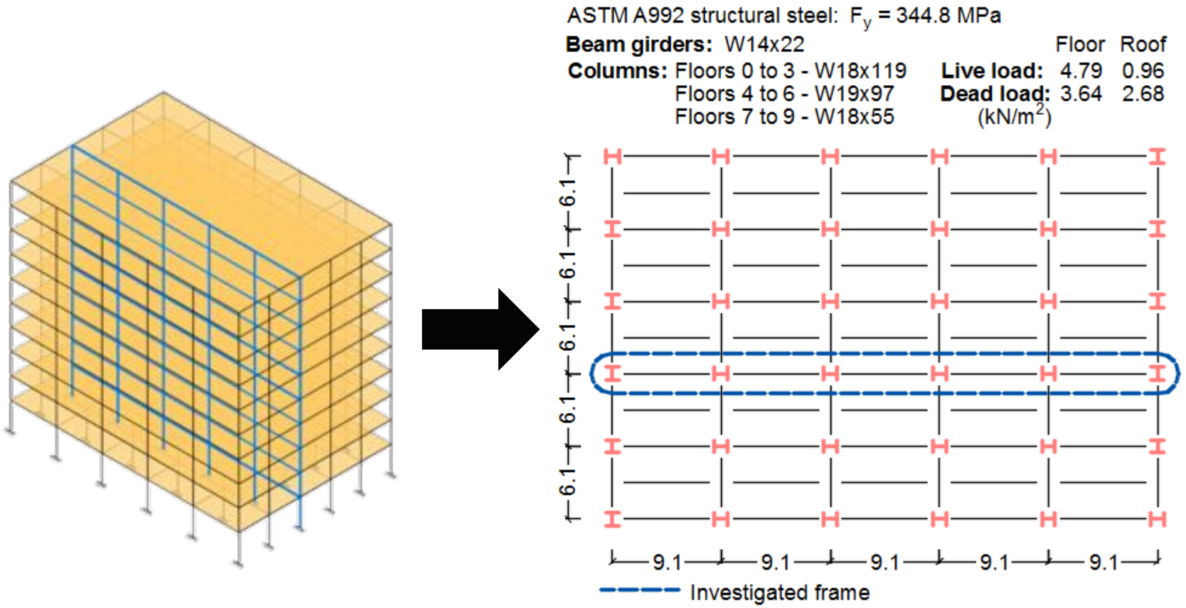
INVESTIGATED STEEL FRAME



- Design (in accordance to ASCE 7-02 standard) published by NIST

INVESTIGATED STEEL FRAME



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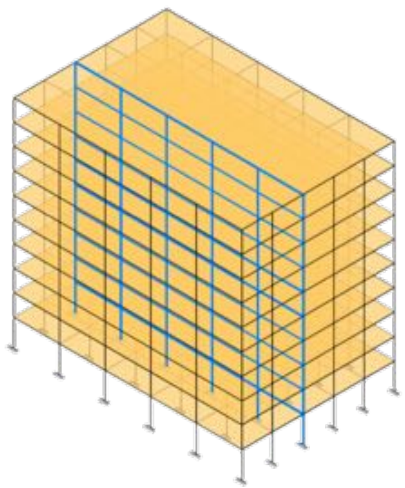

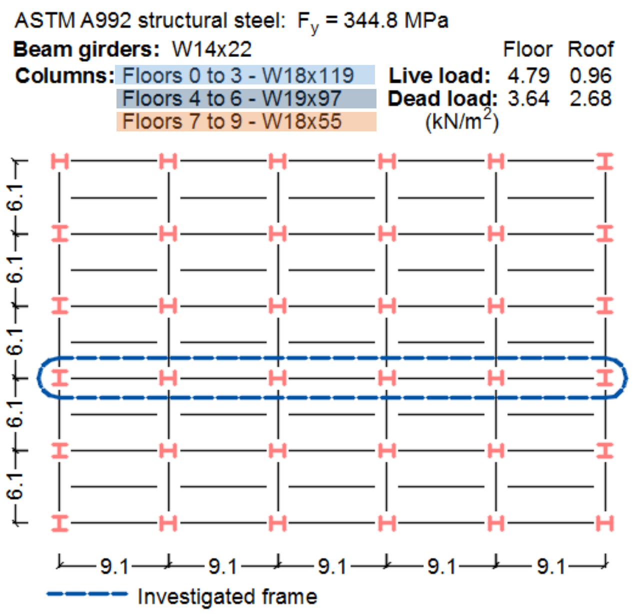

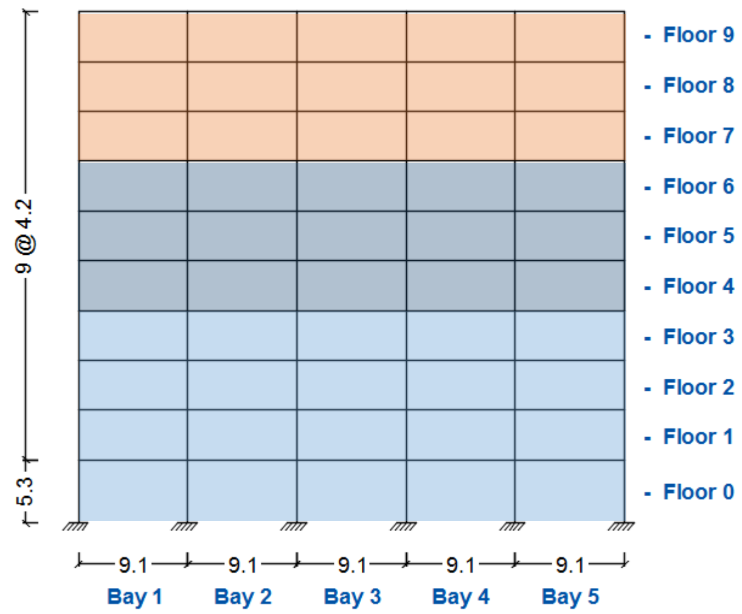

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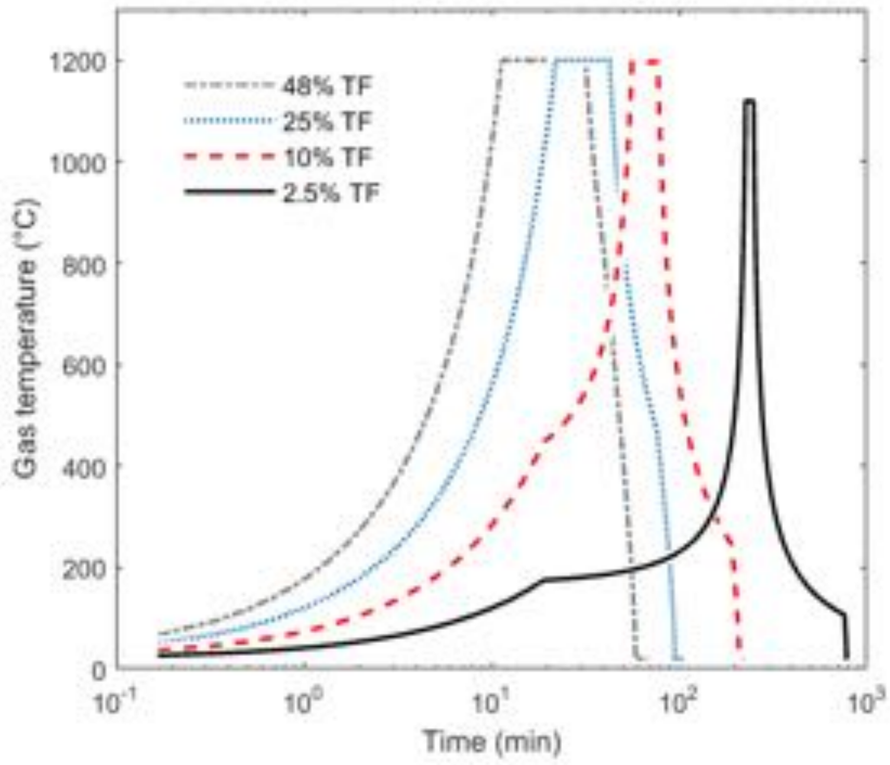
FIRE SCENARIOS

4 travelling fires (TF)

- 2.5%, 10%, 25%, and 48%

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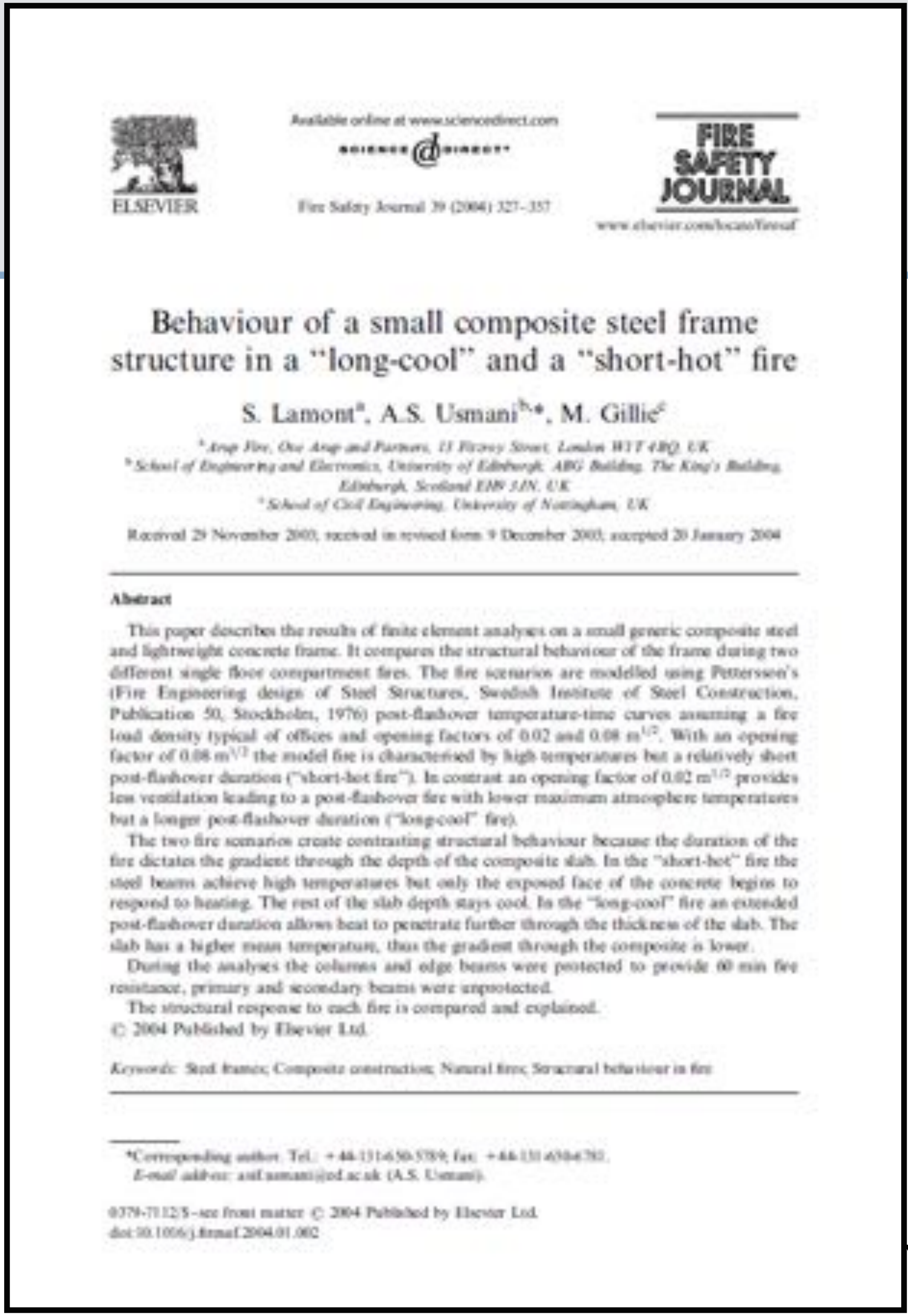
Improved Formulation of Travelling Fires and Application to Concrete and Steel Structures

Egle Rackauskaite [a], Catherine Hamel [a,b], Angus Law [c], Guillermo Rein [a,*]

ARTICLE INFO

ABSTRACT

1. Introduction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Behaviour of a small composite steel frame structure in a "long-cool" and a "short-hot" fire

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[b] School of Engineering and Electronics, University of Edinburgh, AGB Building, The King's Buildings, Edinburgh, Scotland EH9 3JN, UK
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Abstract

This paper describes the results of finite element analyses on a small generic composite steel and lightweight concrete frame. It compares the structural behaviour of the frame during two different single floor compartment fires. The fire scenarios are modelled using Pettersson's (Fire Engineering design of Steel Structures, Swedish Institute of Steel Construction, Publication 50, Stockholm, 1976) post-flashover temperature-time curves assuming a fire load density typical of offices and opening factors of 0.02 and 0.08 $m^{1/2}$. With an opening factor of 0.08 $m^{1/2}$ the model fire is characterised by high temperatures but a relatively short post-flashover duration ("short-hot fire"). In contrast an opening factor of 0.02 $m^{1/2}$ provides less ventilation leading to a post-flashover fire with lower maximum atmosphere temperatures but a longer post-flashover duration ("long-cool" fire).

The two fire scenarios create contrasting structural behaviour because the duration of the fire dictates the gradient through the depth of the composite slab. In the "short-hot" fire the steel beams achieve high temperatures but only the exposed face of the concrete begins to respond to heating. The rest of the slab depth stays cool. In the "long-cool" fire an extended post-flashover duration allows heat to penetrate further through the thickness of the slab. The slab has a higher mean temperature, thus the gradient through the composite is lower.

During the analyses the columns and edge beams were protected to provide 60 min fire resistance, primary and secondary beams were unprotected.

The structural response to each fire is compared and explained.

Keywords: Steel frames; Composite construction; Natural fires; Structural behaviour in fire

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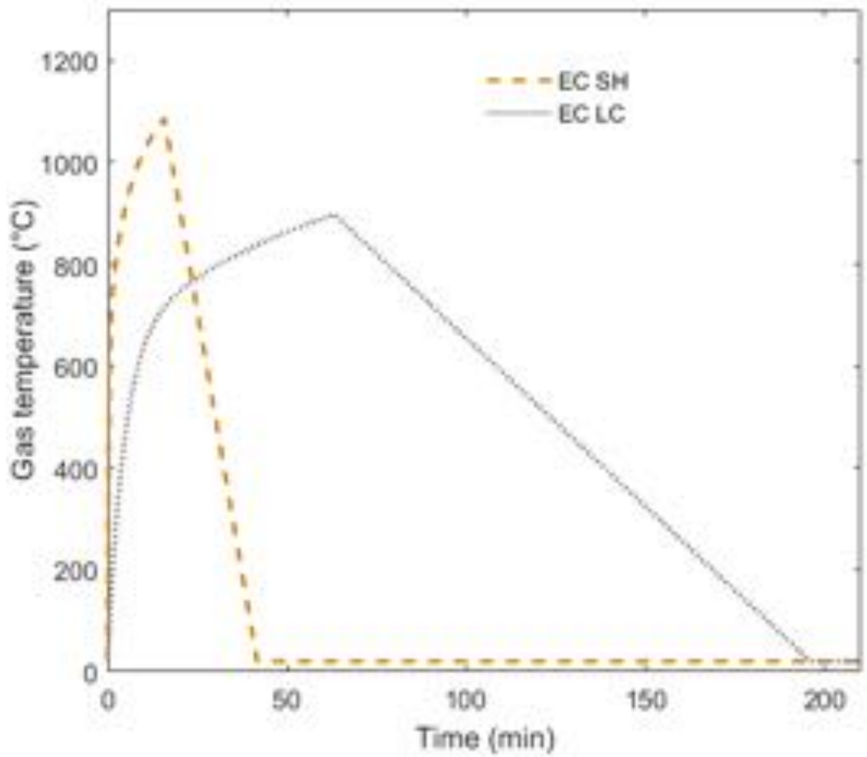
2 Eurocode (EC) parametric curves

- short-hot (SH) and long-cool (LC)



me → **117 fire scenarios in total**

THE MODEL

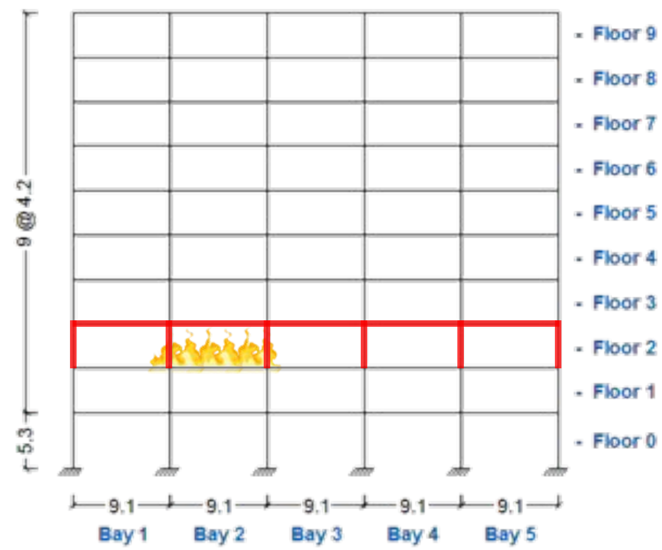
Heat transfer

- Protected beams (60 min) and columns (120 min)
- Buchanan (2009):

$$\Delta T_s = \frac{H_p}{A}\frac{k_i}{d_i \rho_s c_s}\frac{\rho_s c_s}{\left[\rho_s c_s + (H_p/A)\, d_i \rho_i c_i / A\right]}(T_g - T_s)\Delta t$$

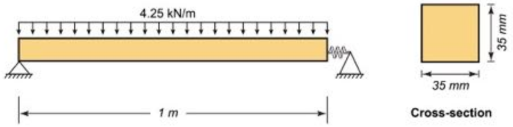
Structural analysis

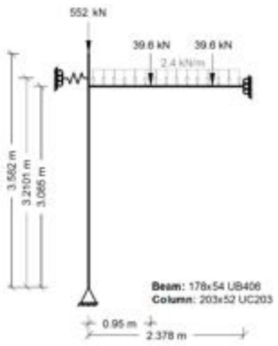
- Finite Element Software LS-DYNA (explicit dynamic solver)
- Temperature dependent steel properties according to the Eurocode



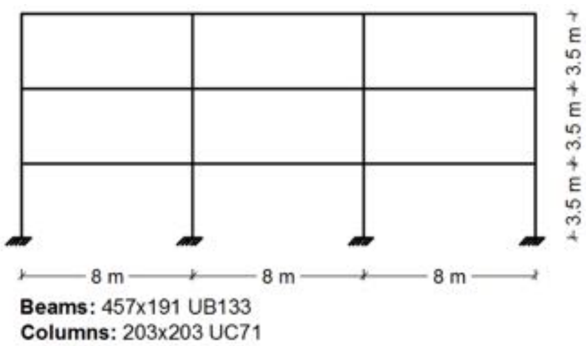
BENCHMARKING OF LS-DYNA

- BM1: Gillie (2009)





- BM2: Cooke
  & Latham (1987)



- BM3: Rackauskaite
  & El-Rimawi (2015)

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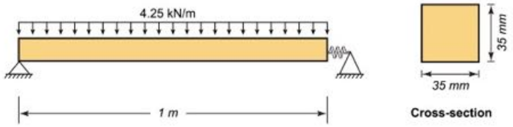

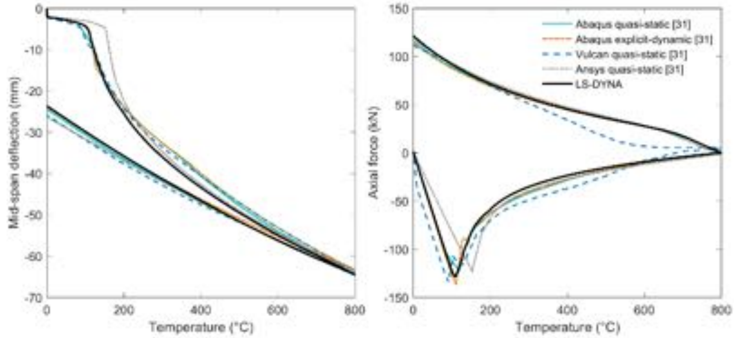

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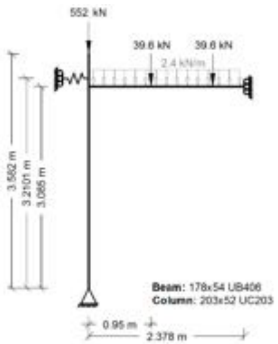

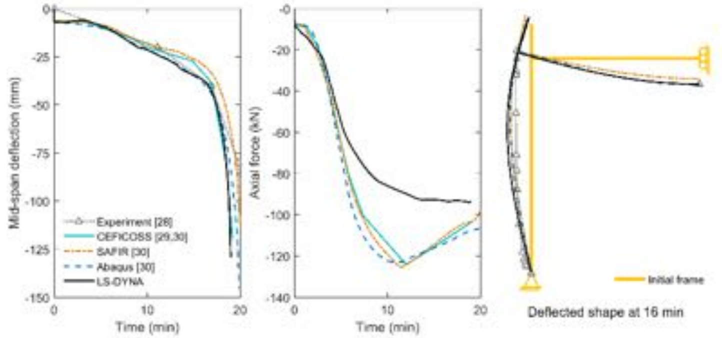

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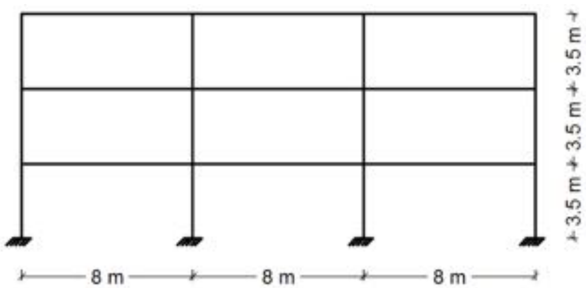
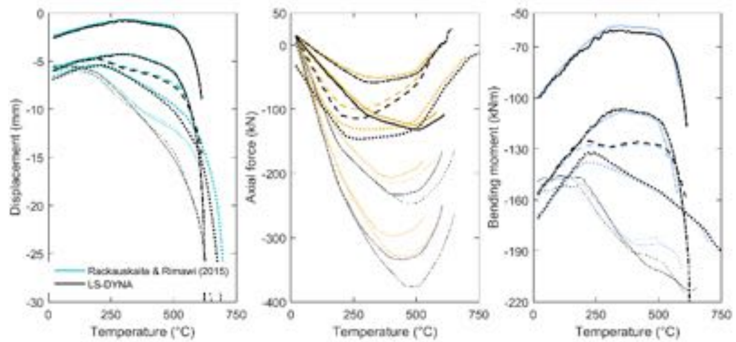


Beams: 457x191 UB133
Columns: 203x203 UC71



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FAILURE CRITERIA

Thermal:

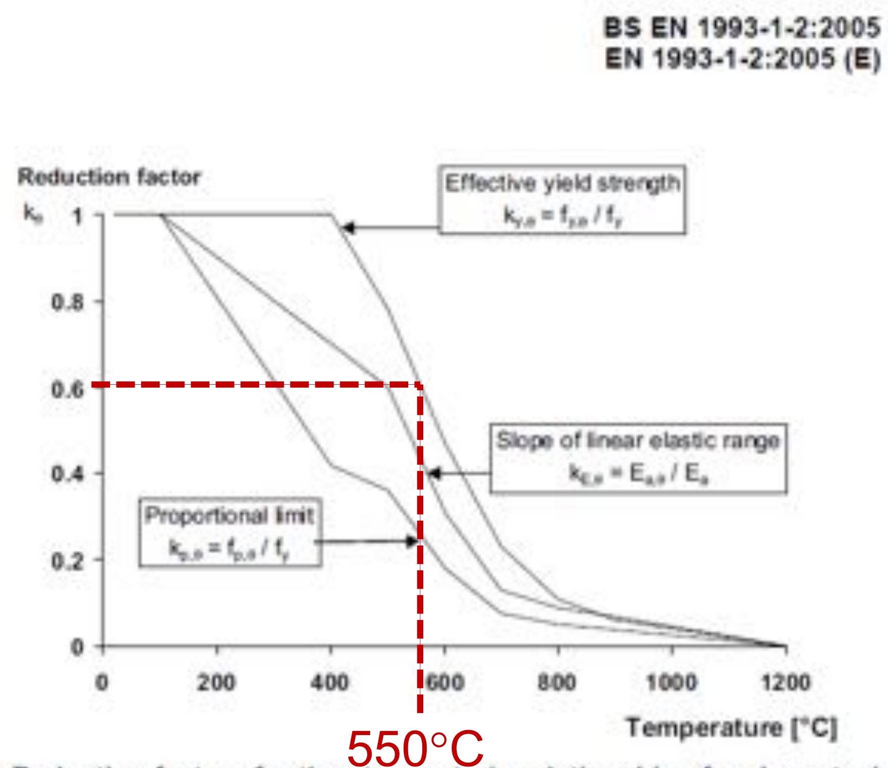
Structural:

FAILURE CRITERIA

Thermal:

- Critical temperature of 550°C

Structural:



Reduction factors for the stress-strain relationship of carbon steel at elevated temperatures

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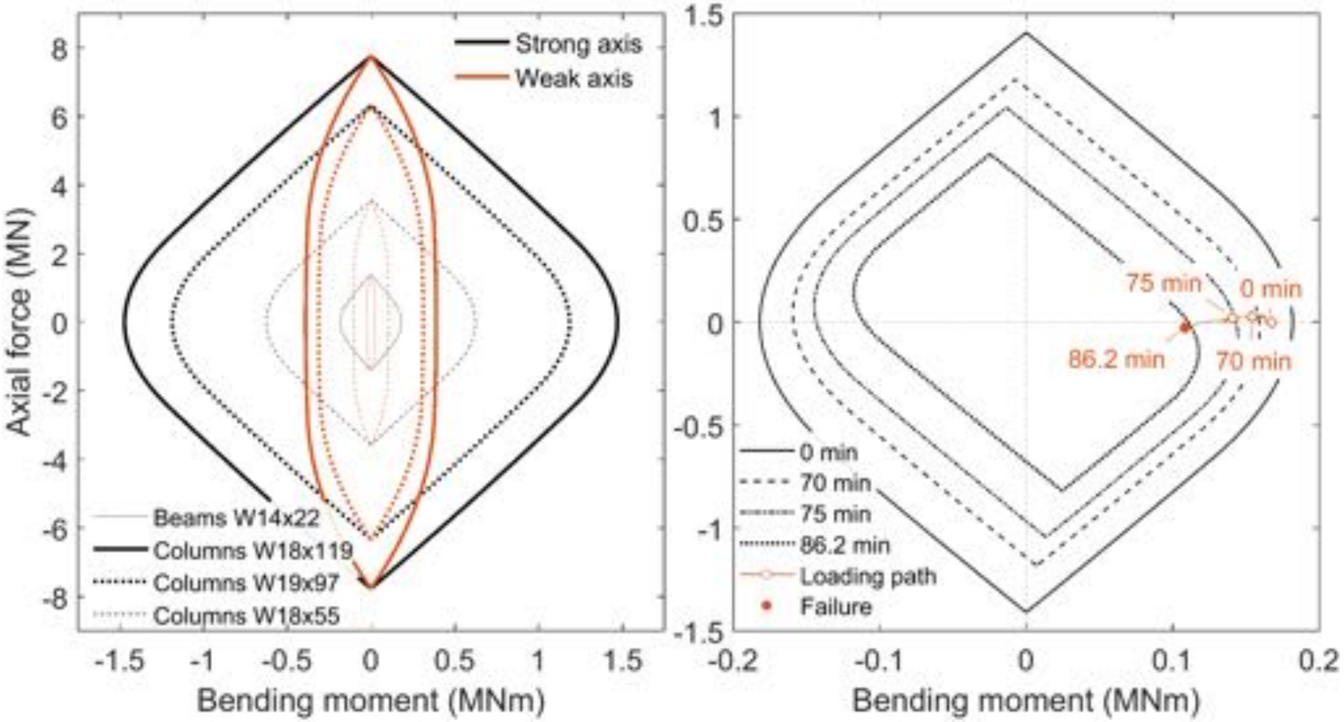
FAILURE CRITERIA

Thermal:

- Critical temperature of 550°C

Structural:

- Utilization



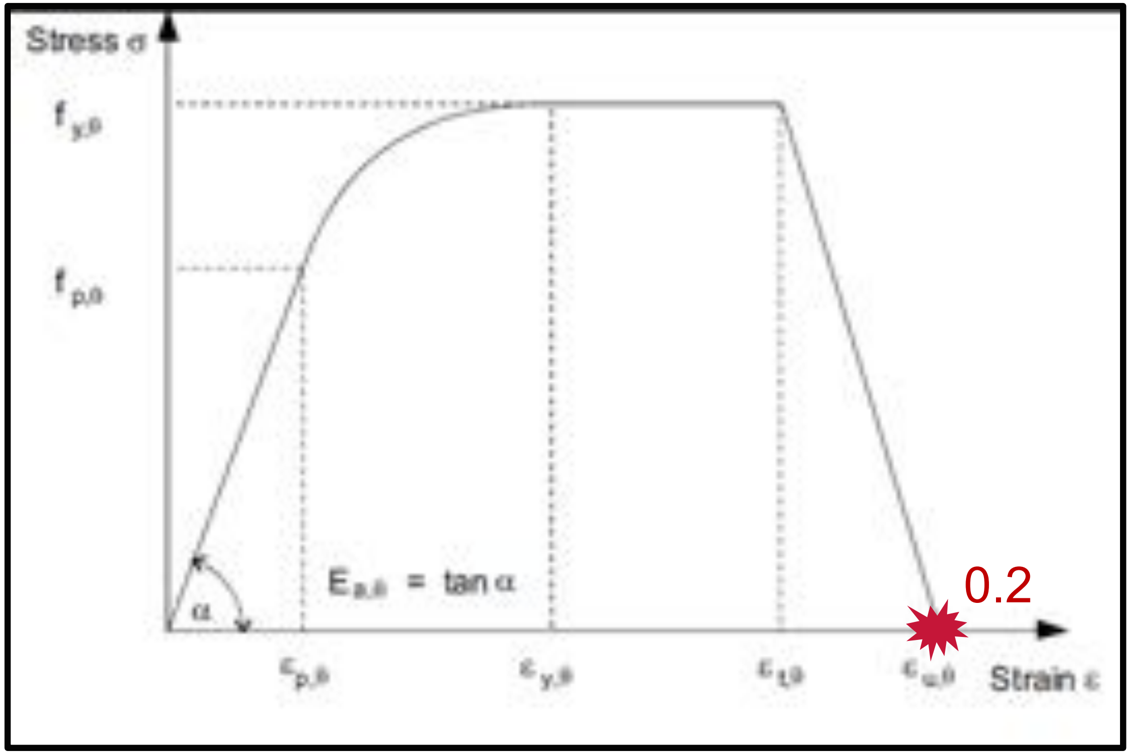
FAILURE CRITERIA

Thermal:

- Critical temperature of 550°C

Structural:

- Utilization
- Stability



FAILURE CRITERIA

Thermal:

- Critical temperature of 550°C

Structural:

- Utilization
- Stability
- Deflection
  - Ryan and Robertson criterion

    Mid-span deflection - $L^2/800d$

    Rate of deflection - $L^2/9000d$ over 1 min
  - L/20

FAILURE CRITERIA

Thermal:

- **Critical temperature of 550°C**

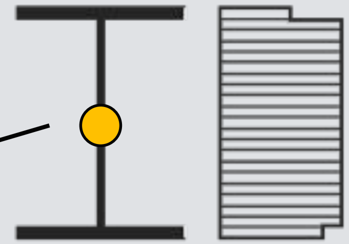
Structural:

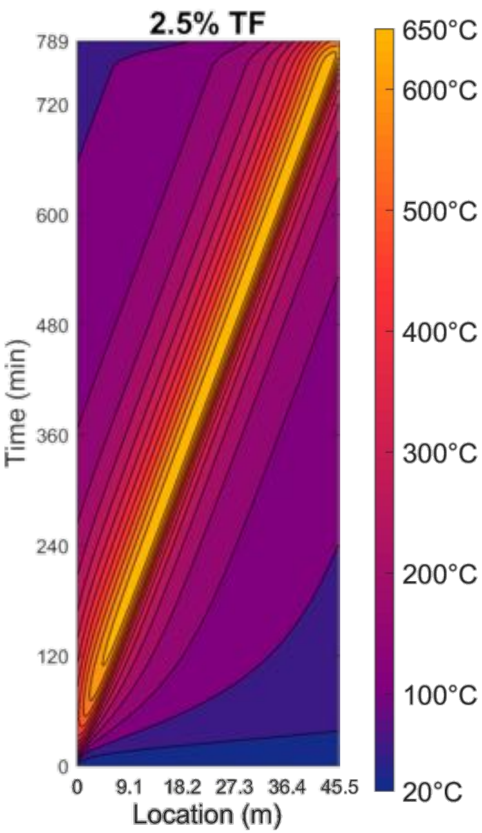
- Utilization
- **Stability**
- **Deflection**
  - Ryan and Robertson criterion

    Mid-span deflection - $L^2/800d$

    Rate of deflection - $L^2/9000d$ over 1 min
  - **L/20**

THERMAL RESPONSE





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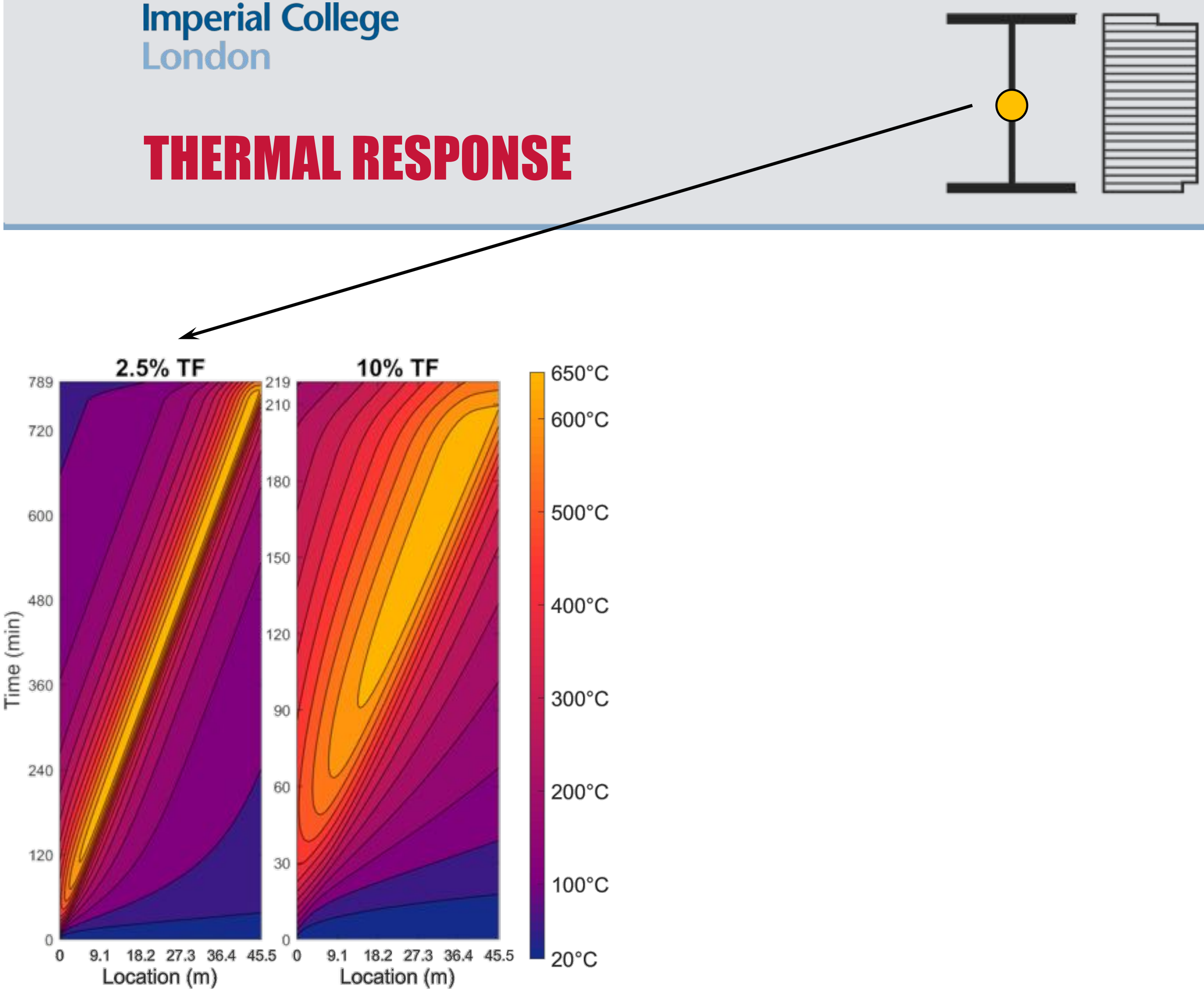

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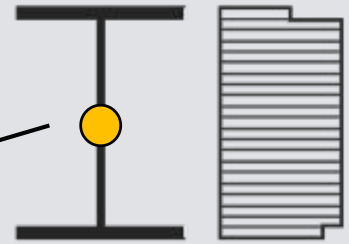
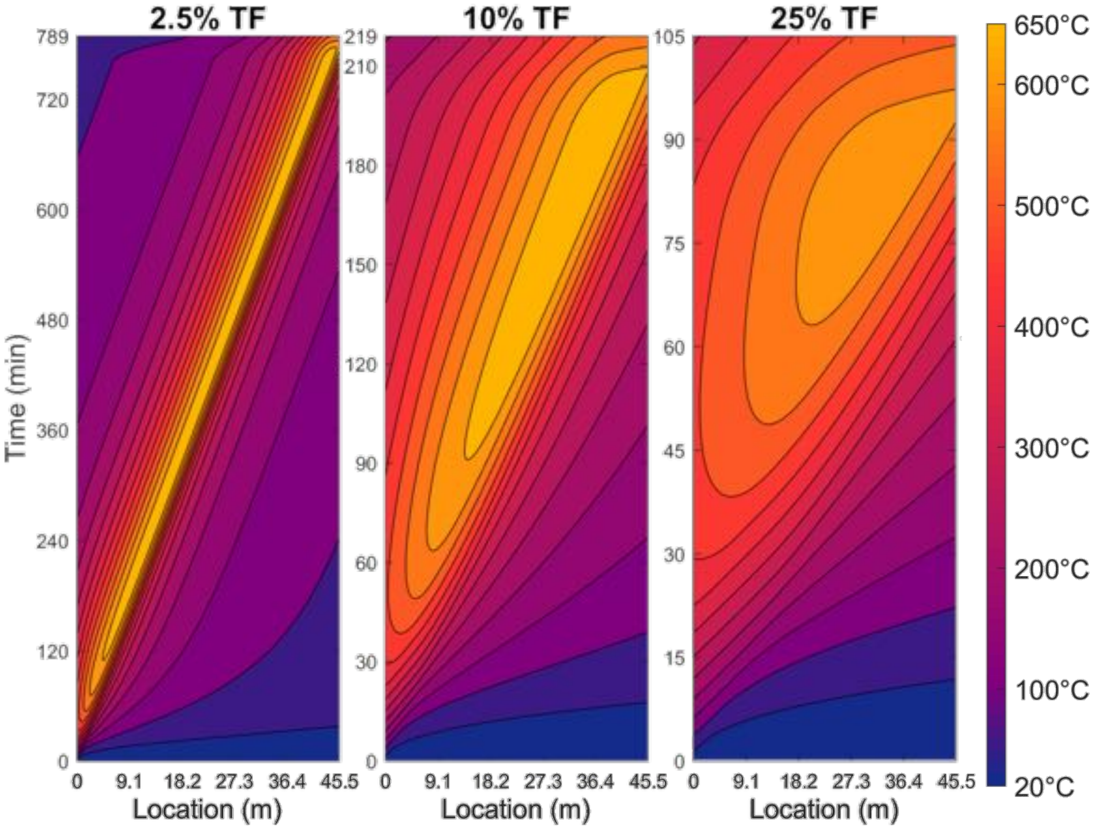
THERMAL RESPONSE





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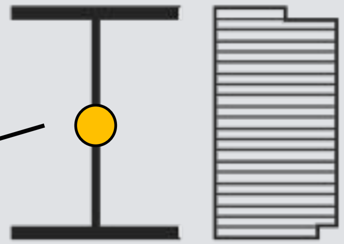

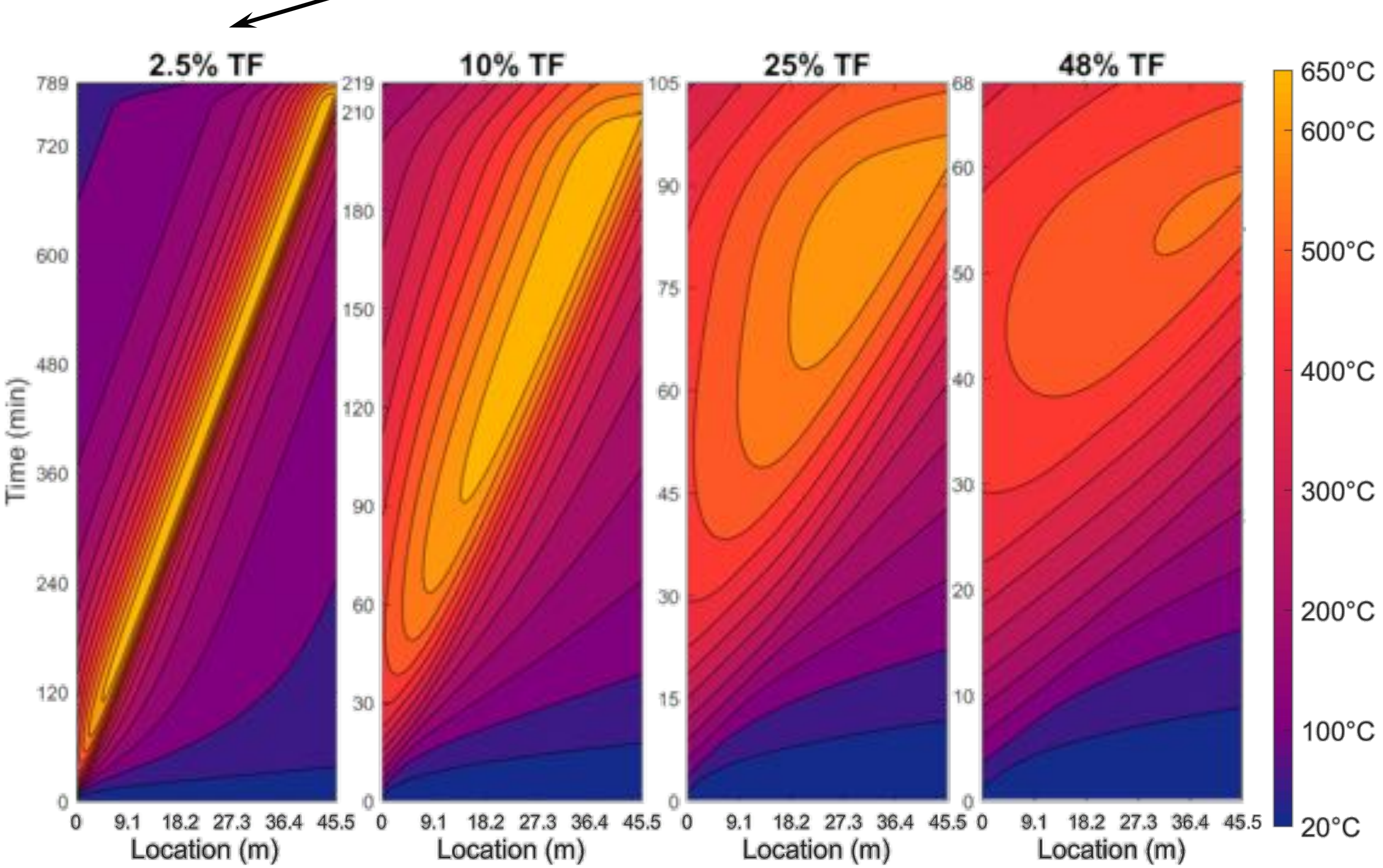

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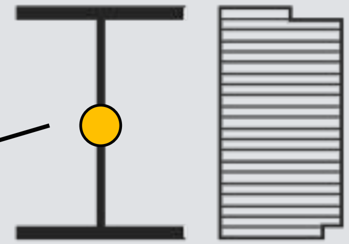

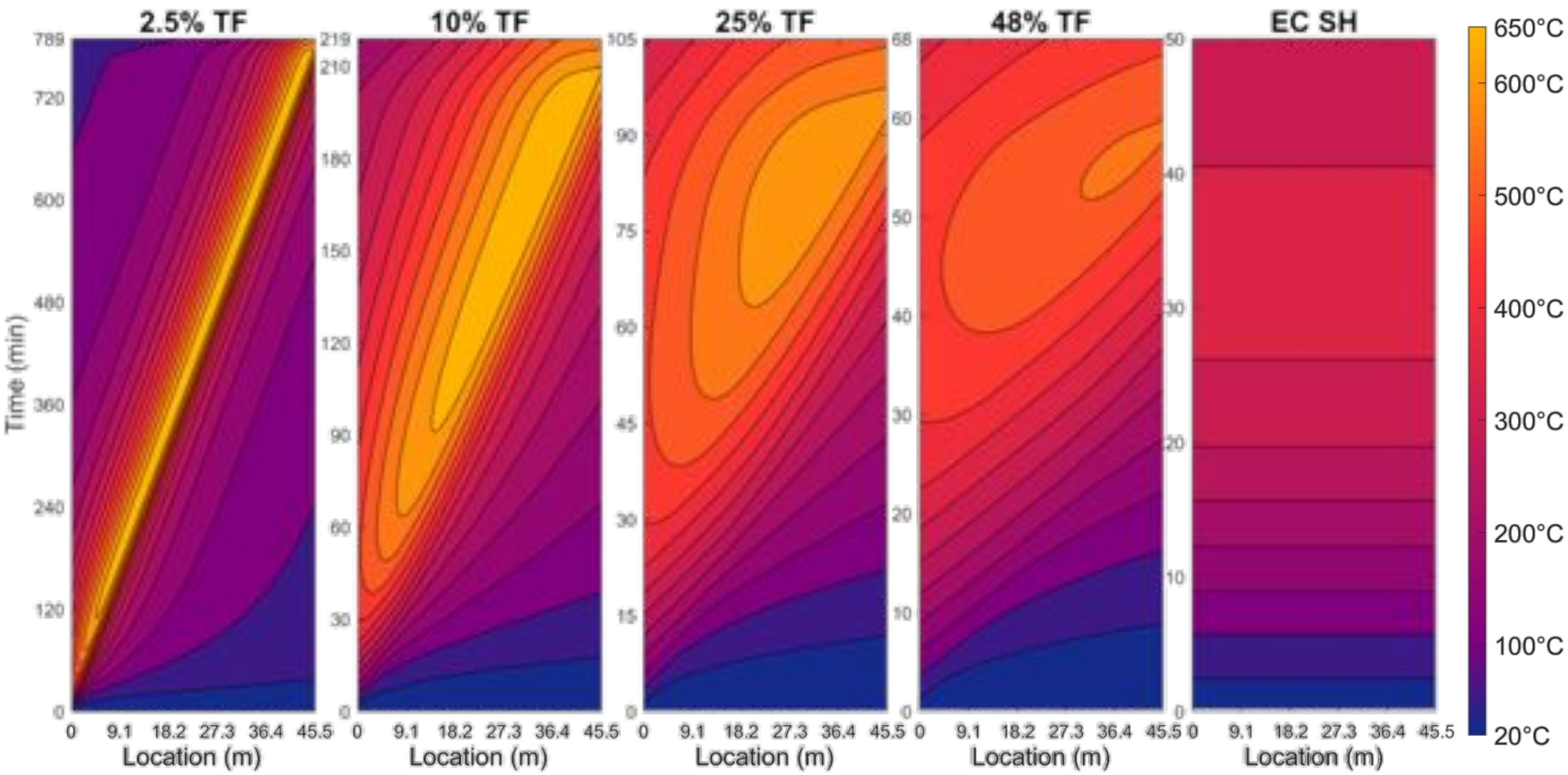

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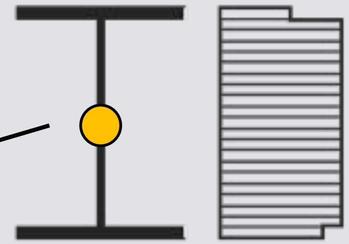
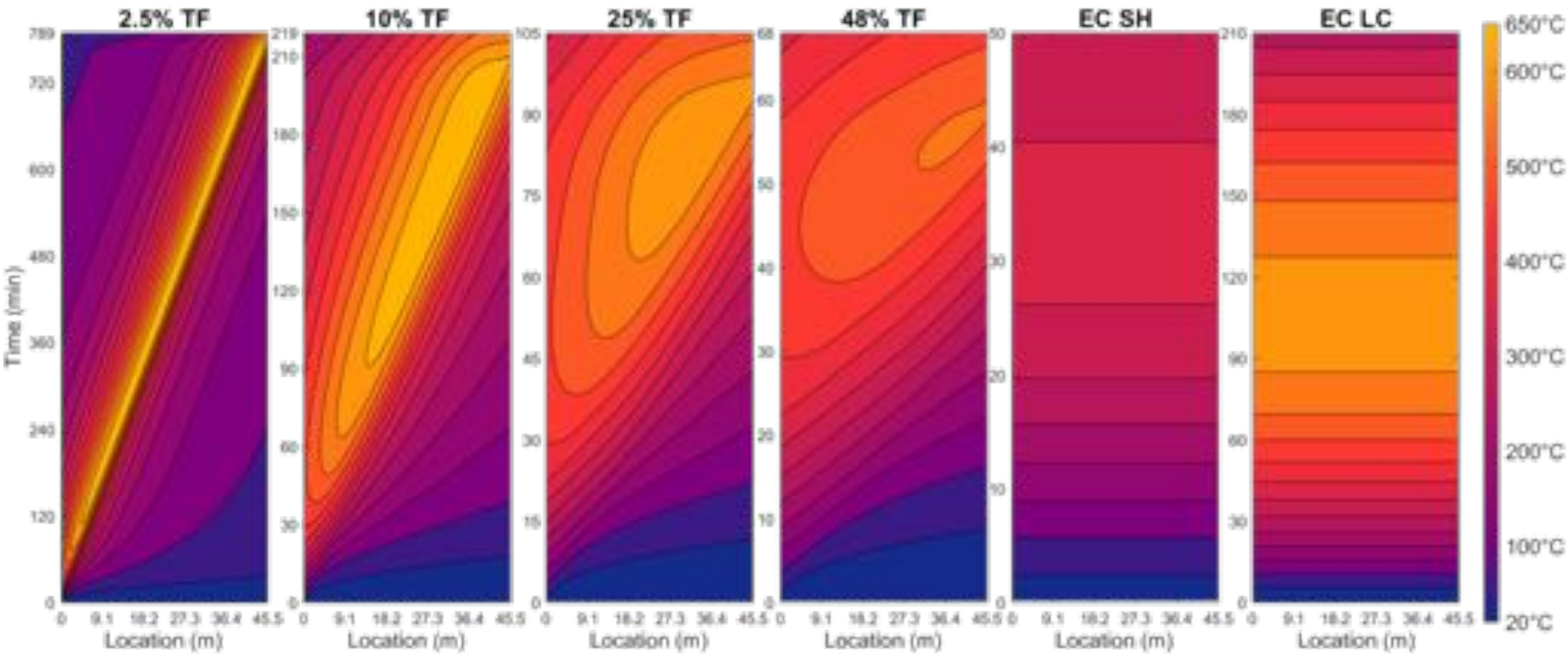
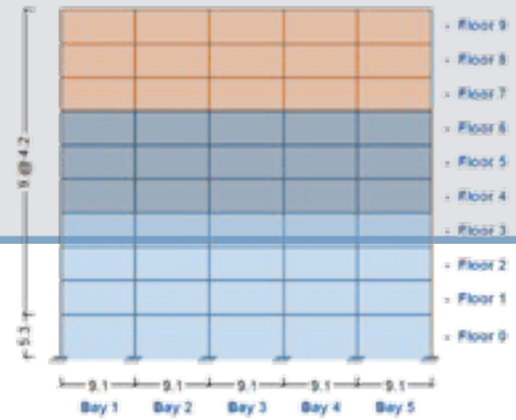
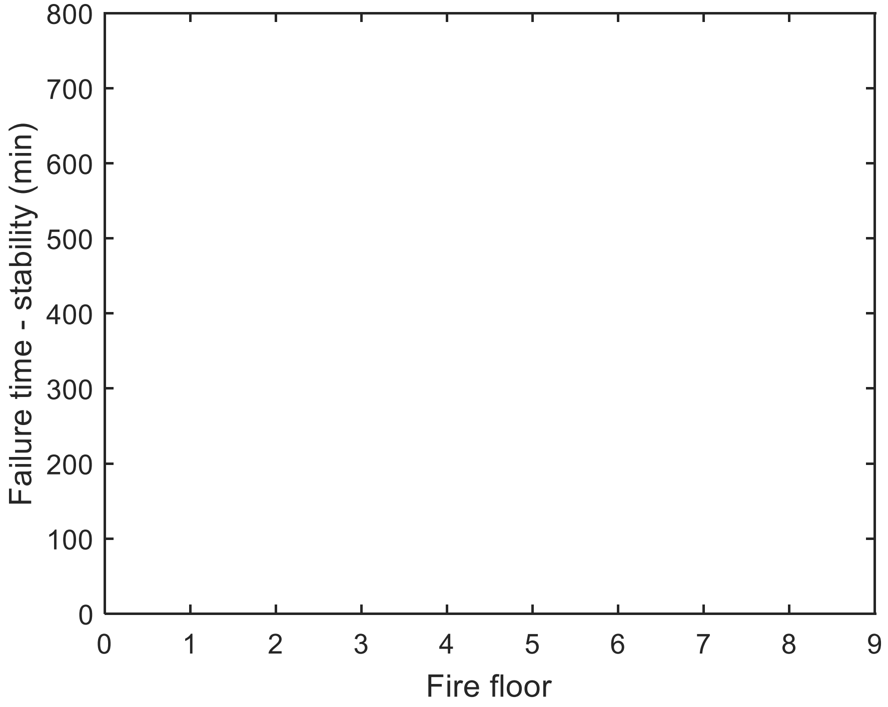




680°C 690°C 635°C 560°C 370°C 620°C

STRUCTURAL FAILURE





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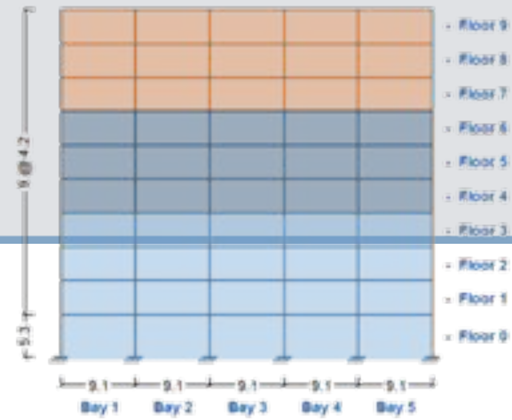

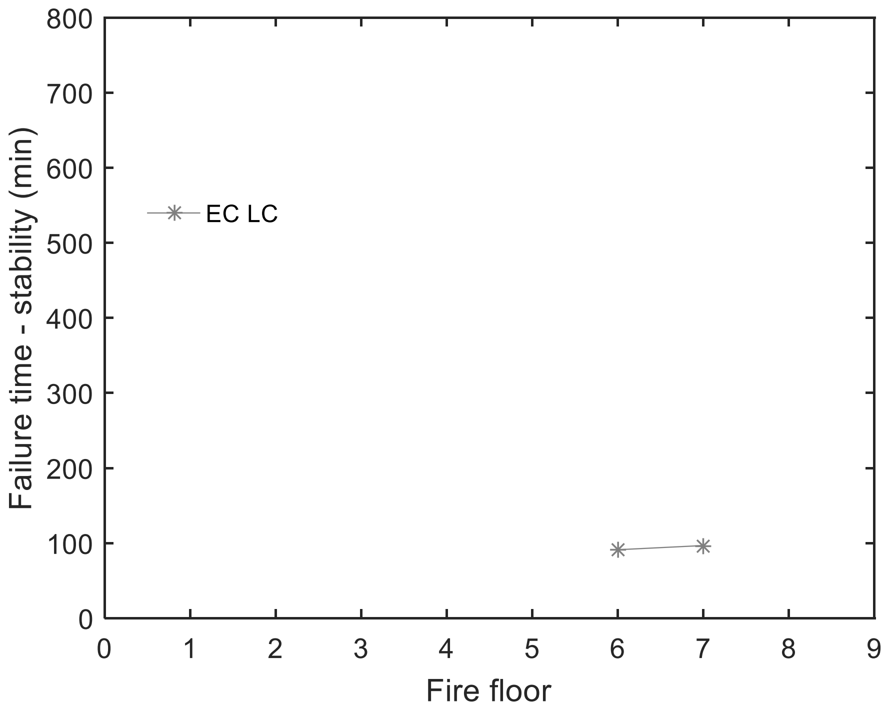

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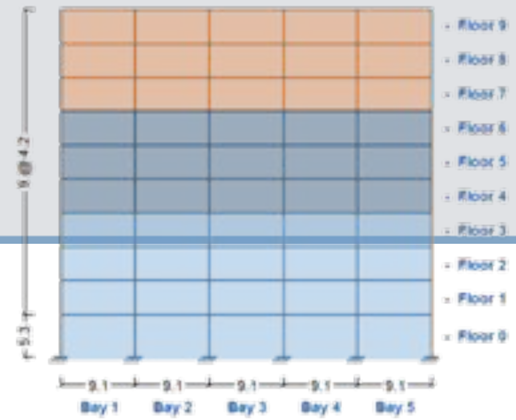

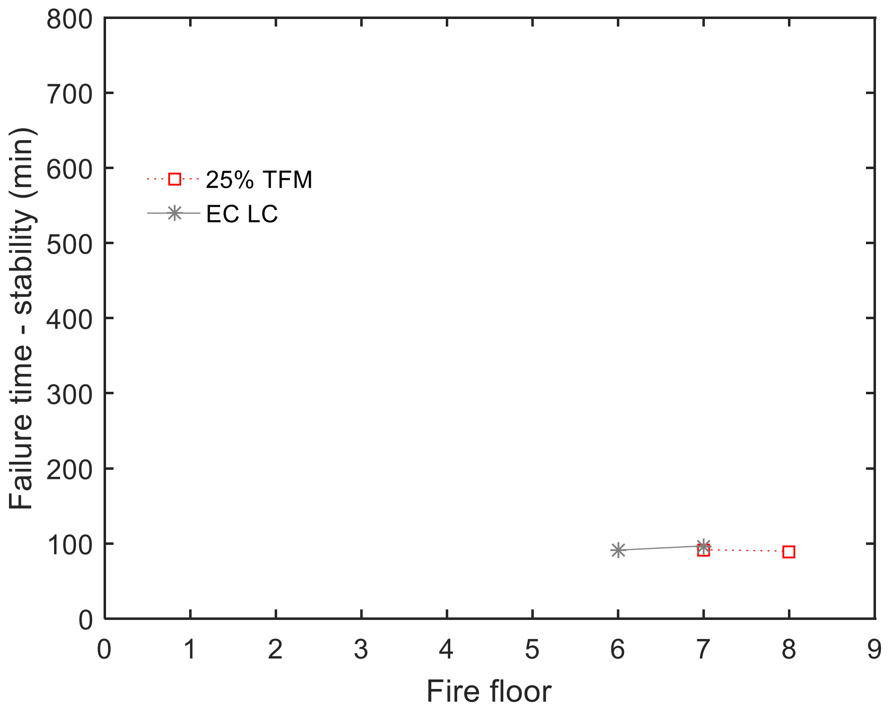

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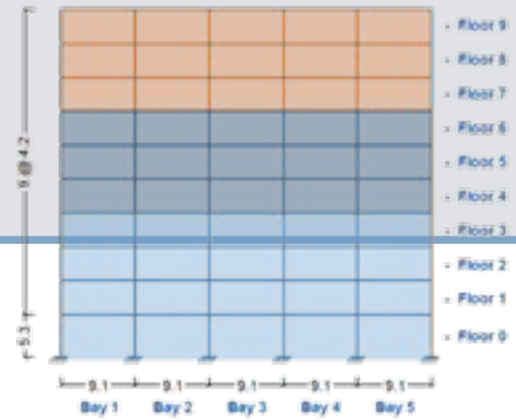

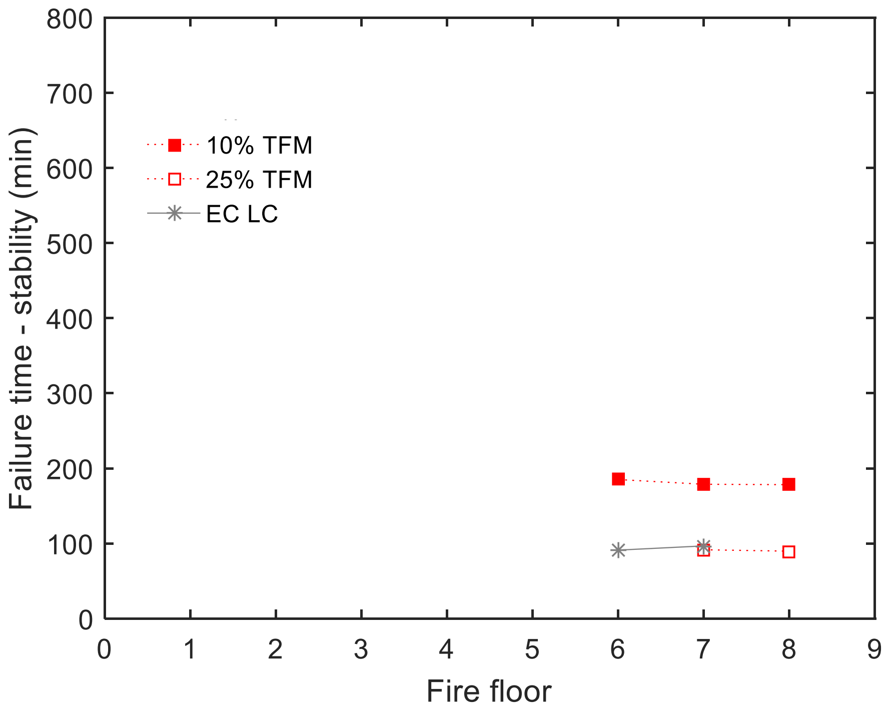

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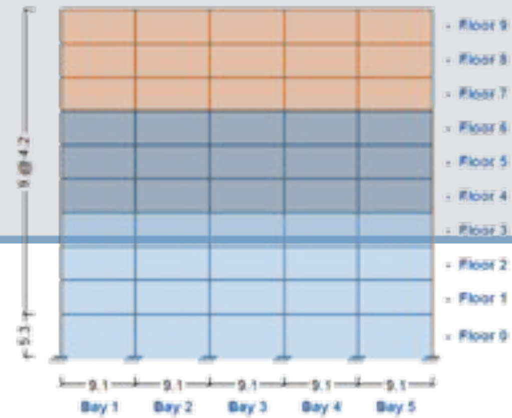

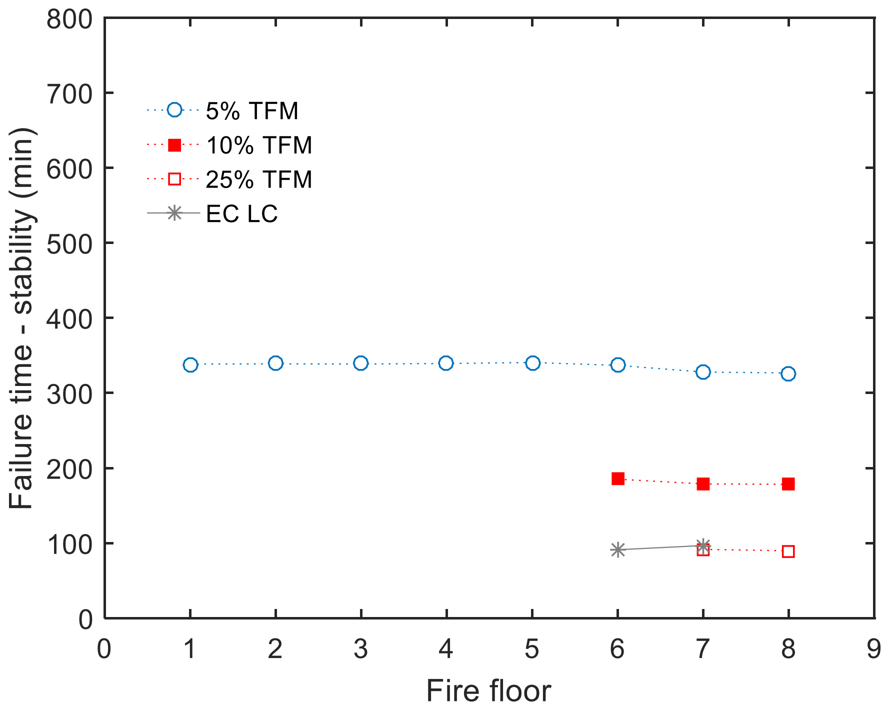

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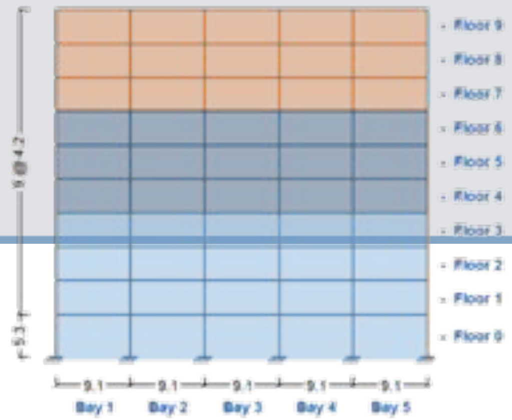

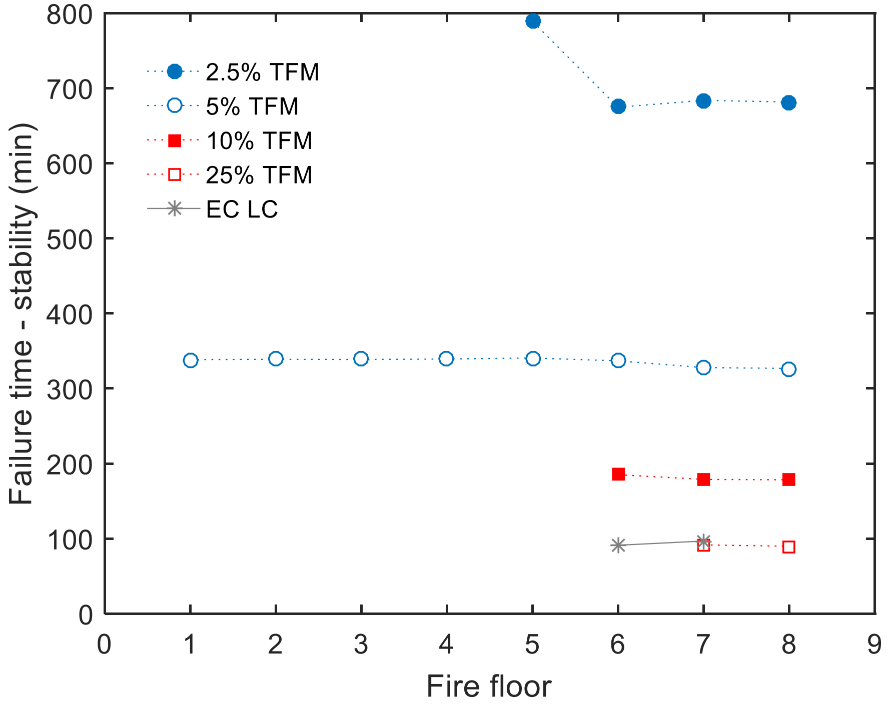

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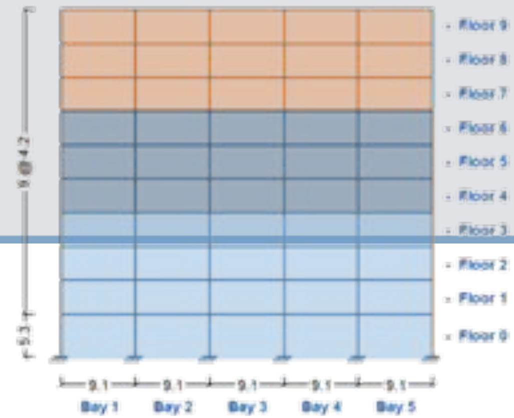

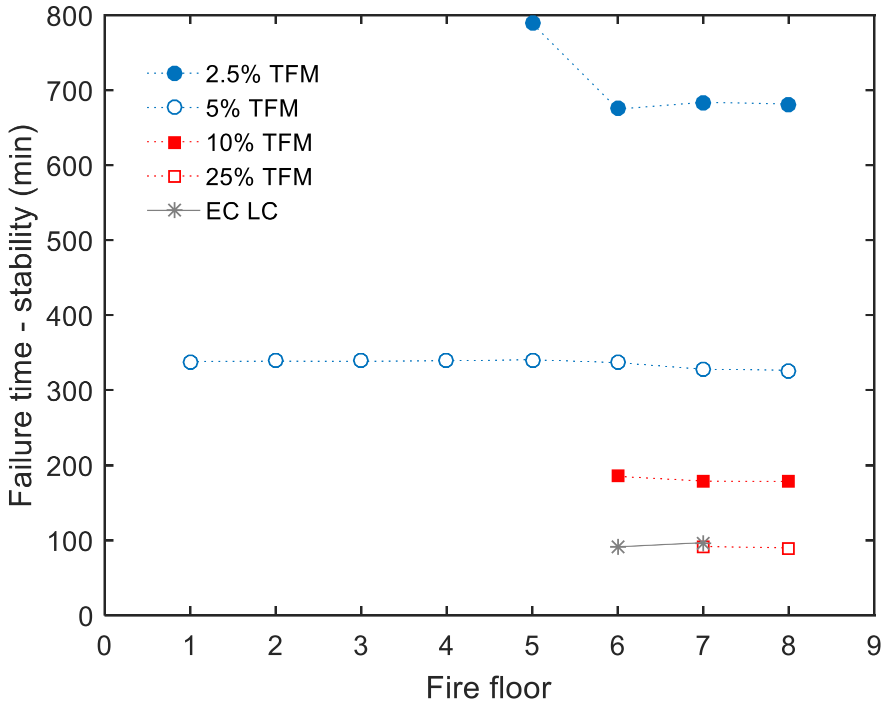

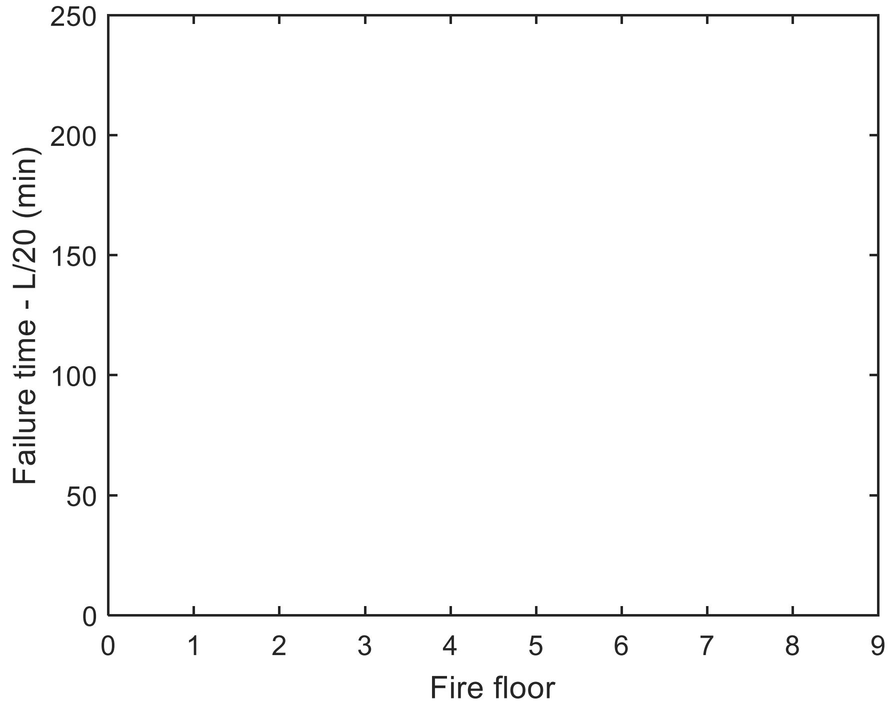

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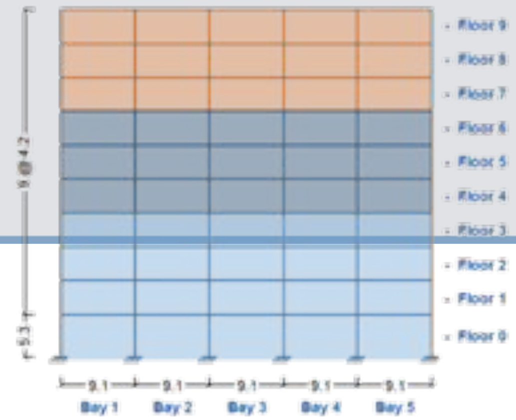

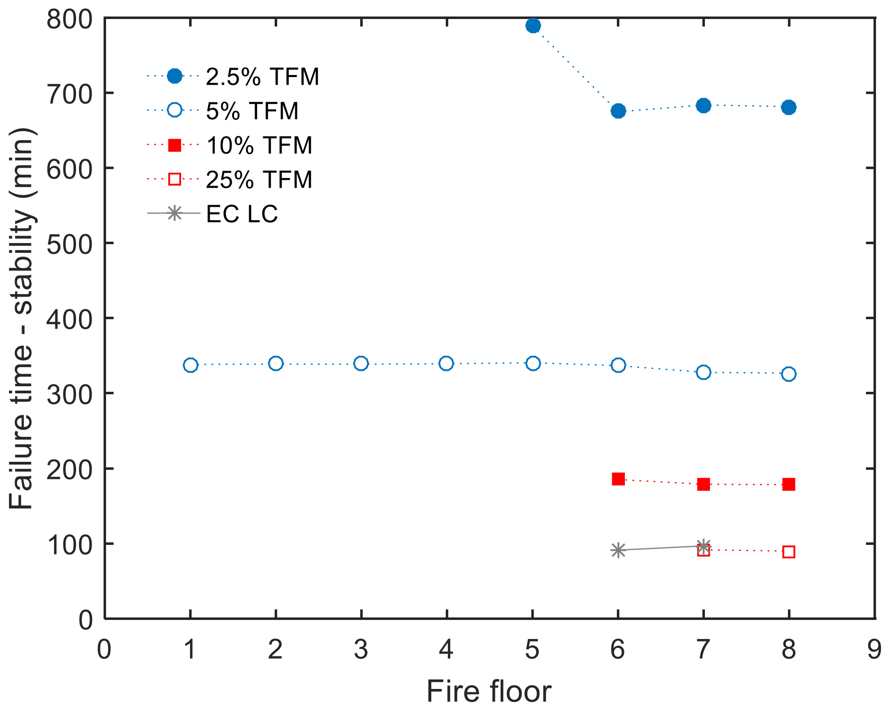

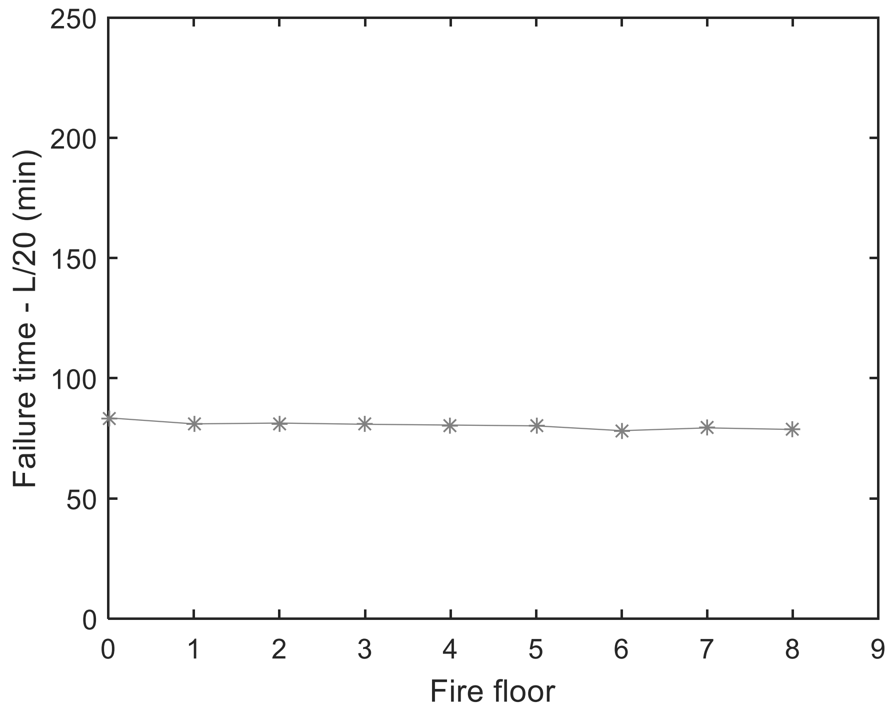

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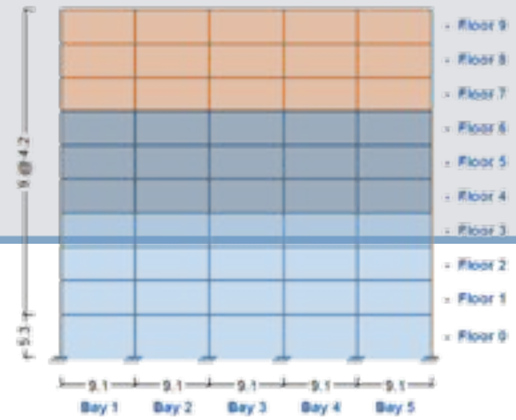
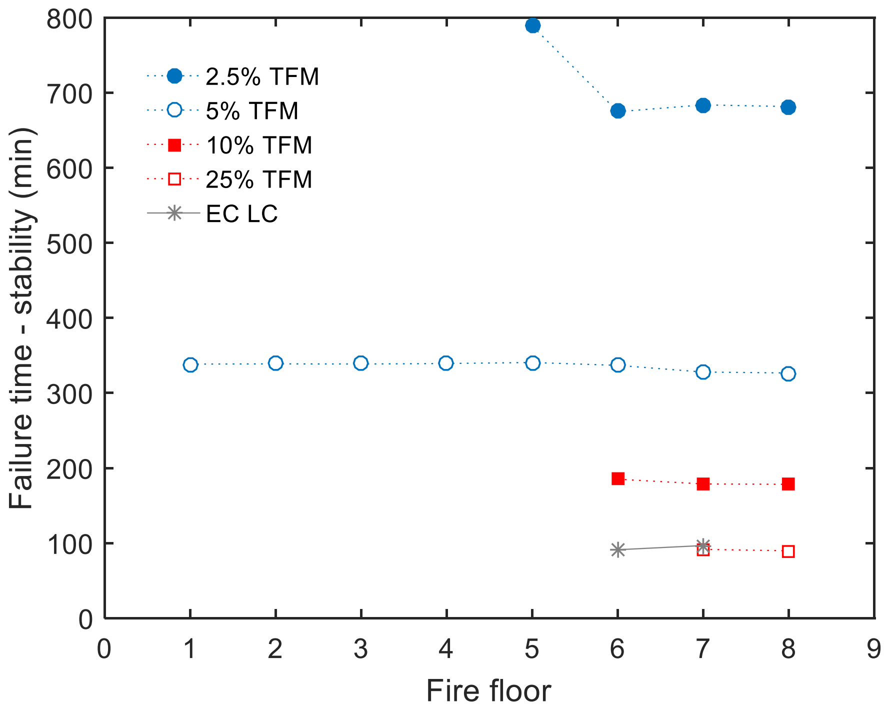
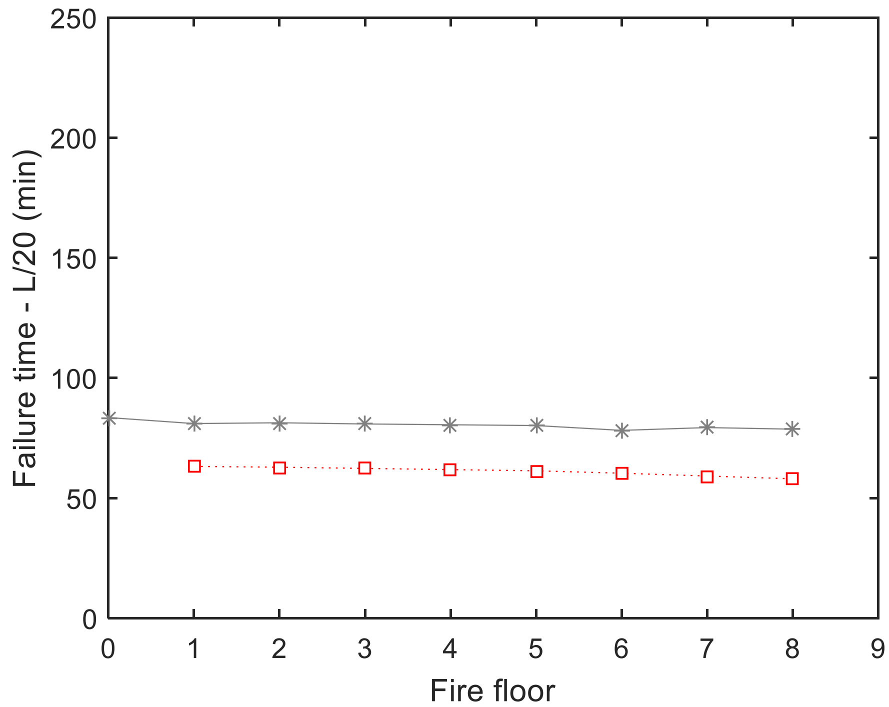
STRUCTURAL FAILURE







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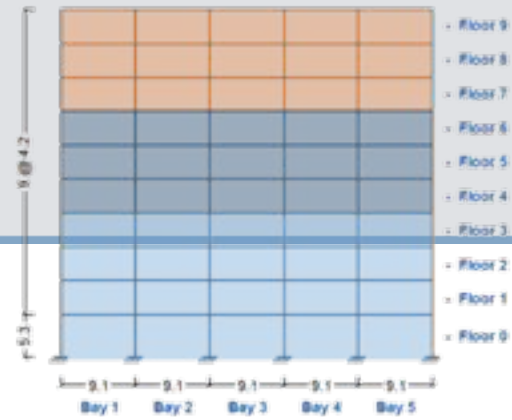

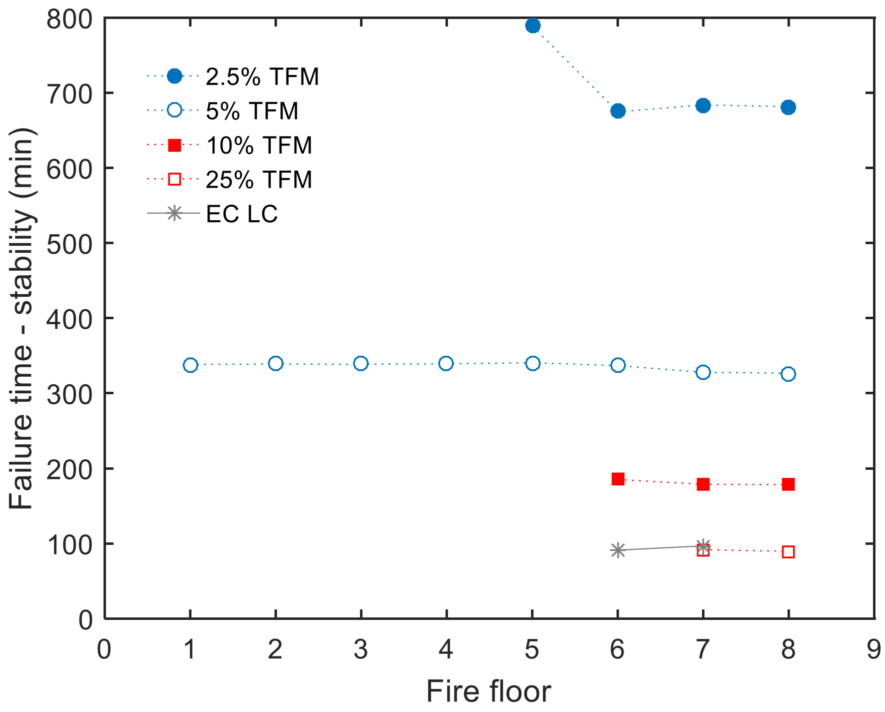

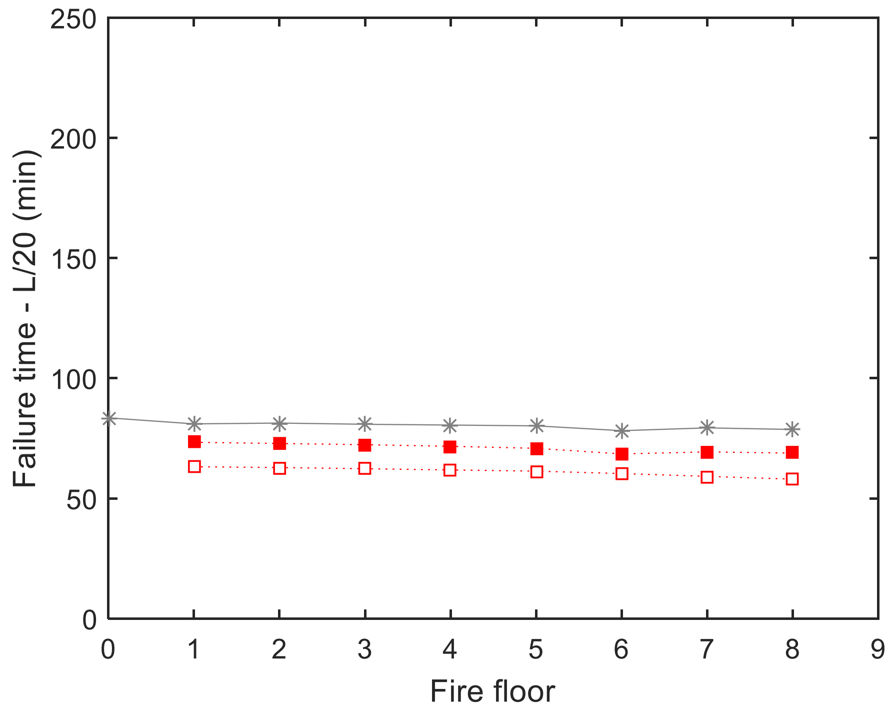

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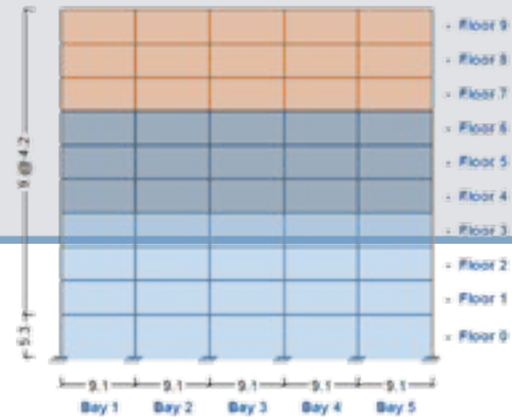
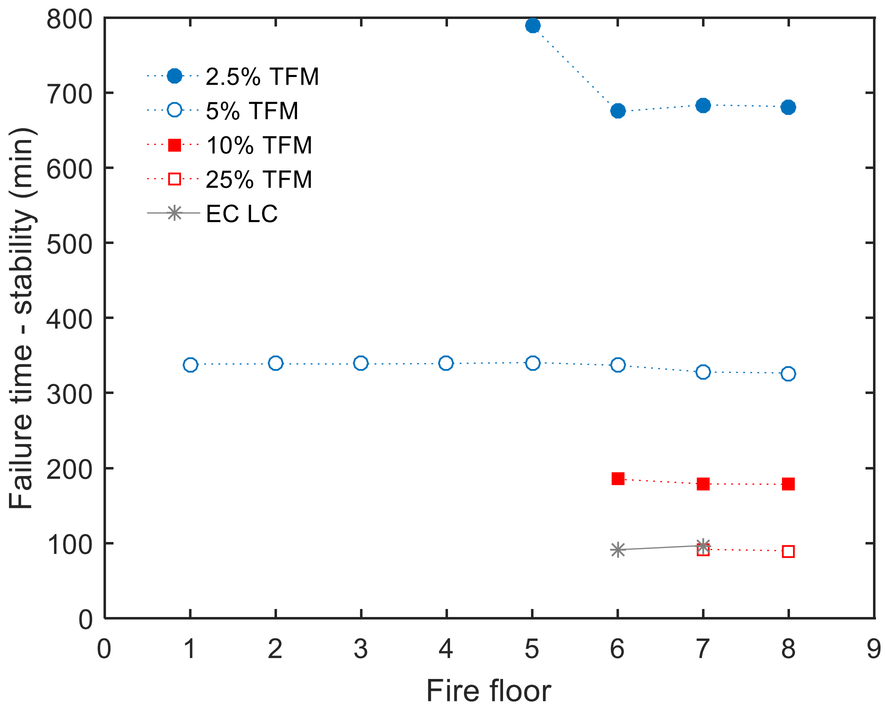
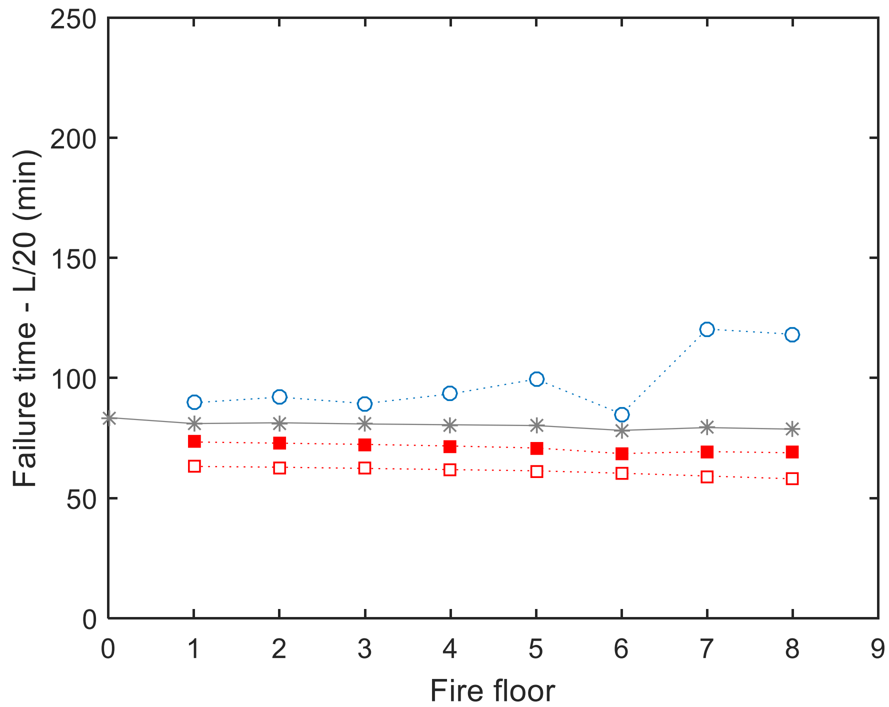
STRUCTURAL FAILURE







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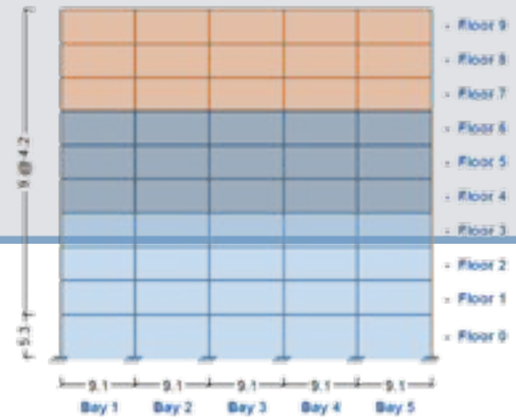

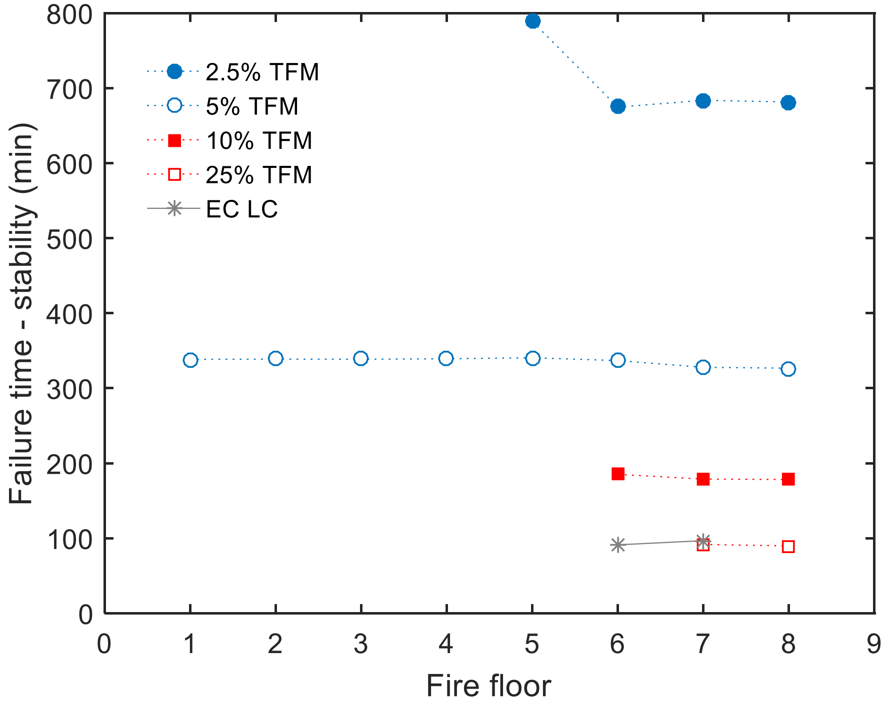

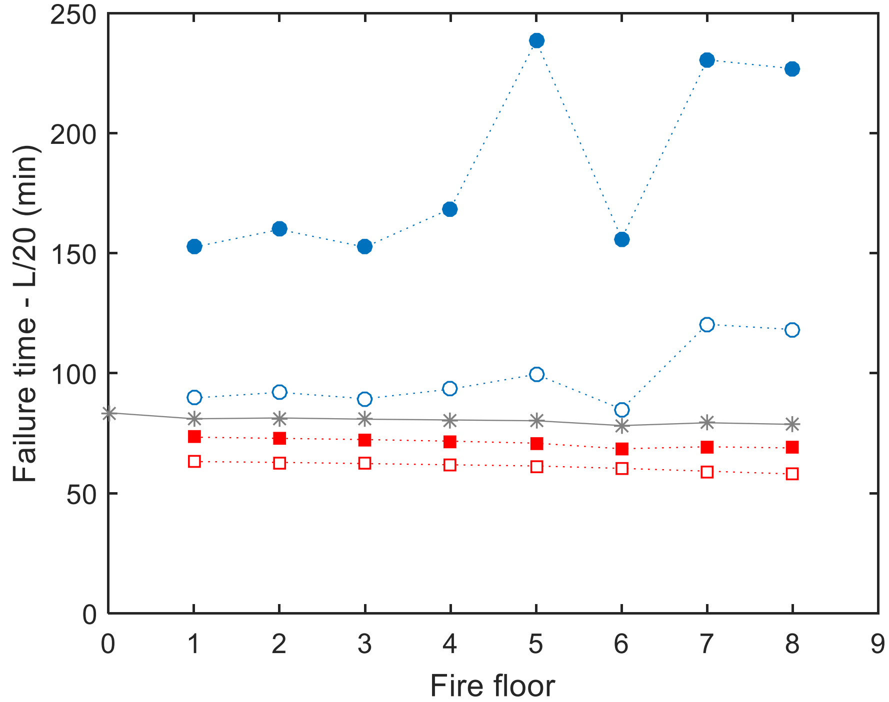

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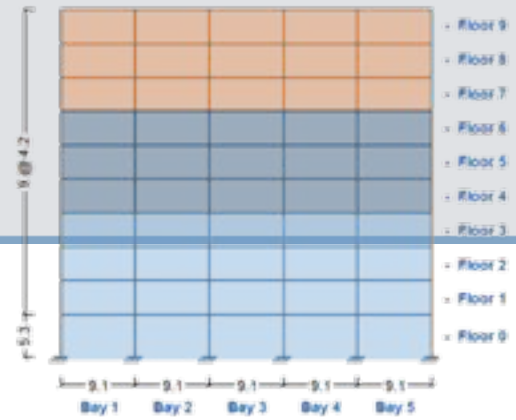

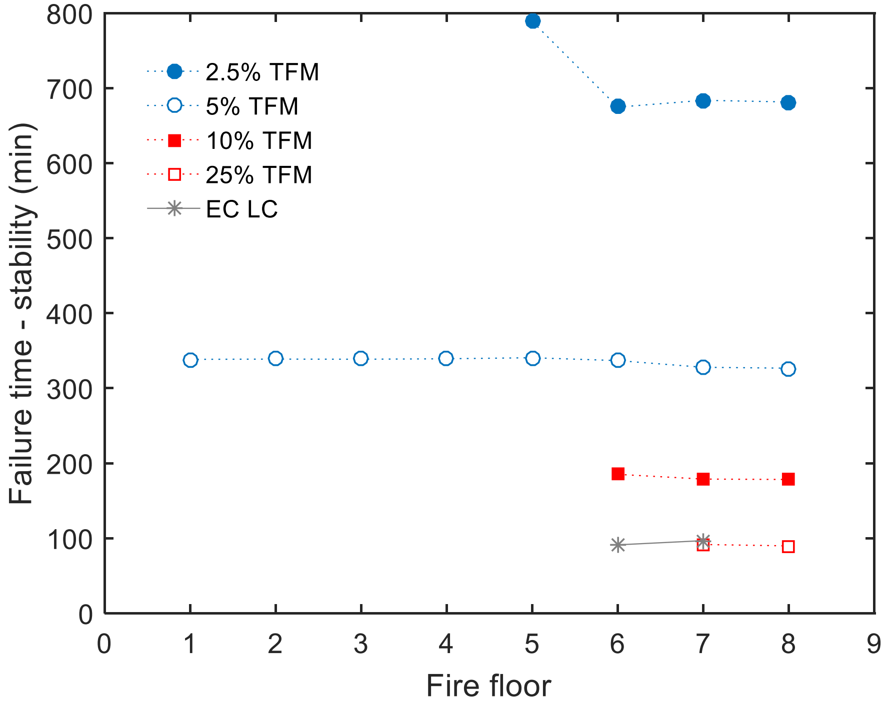

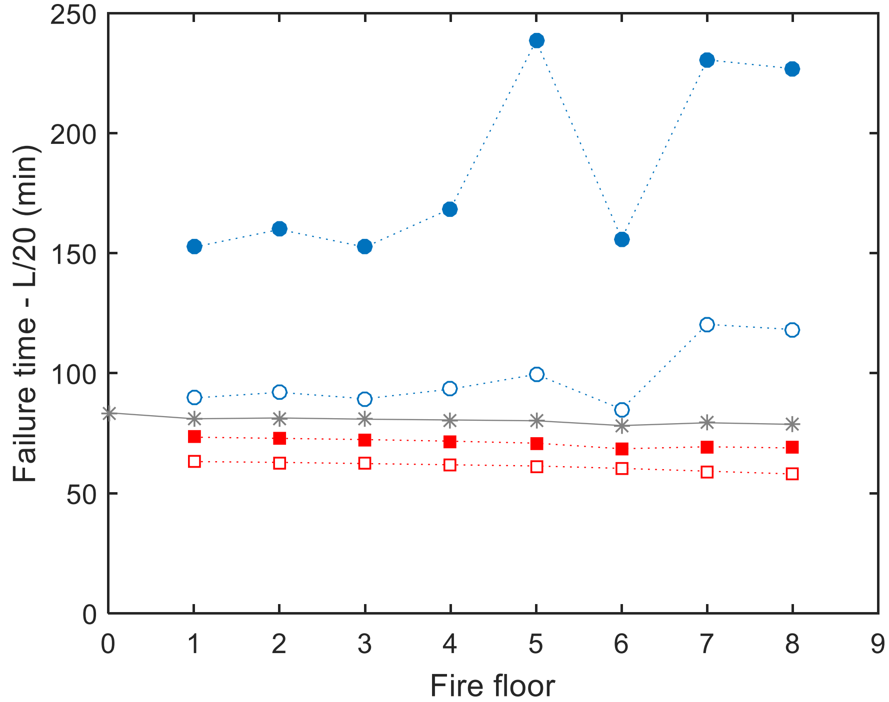

- There is no single fire scenario which would represent the worst case

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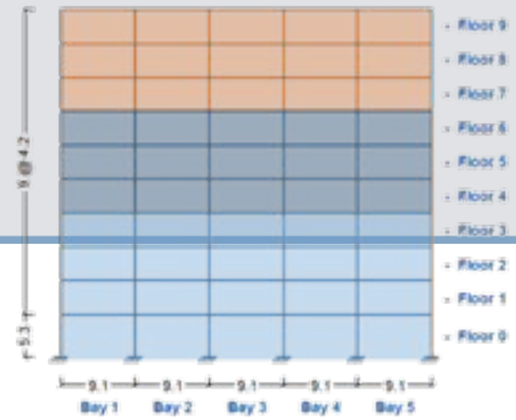
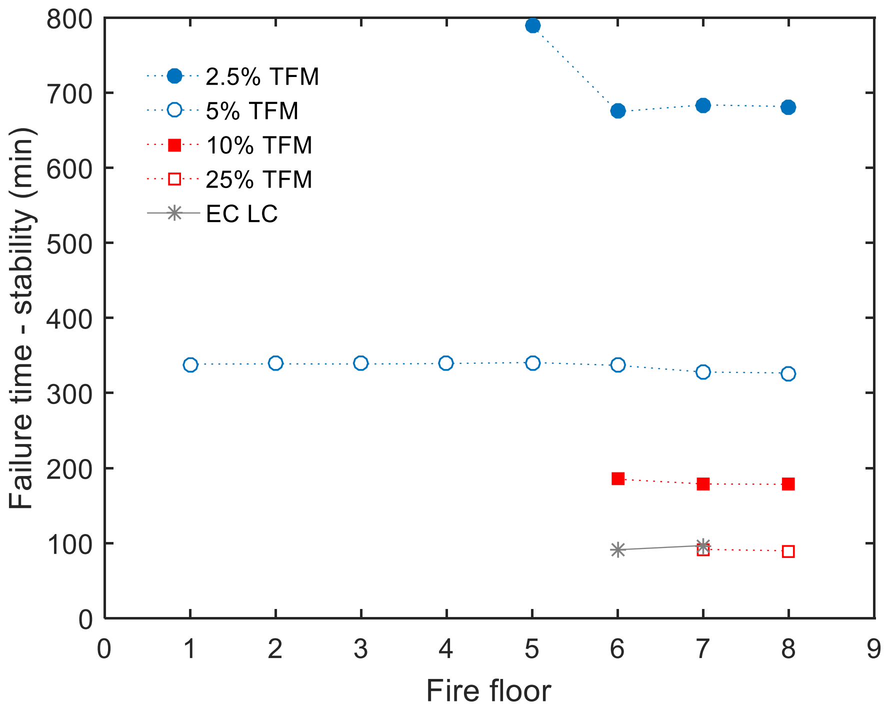
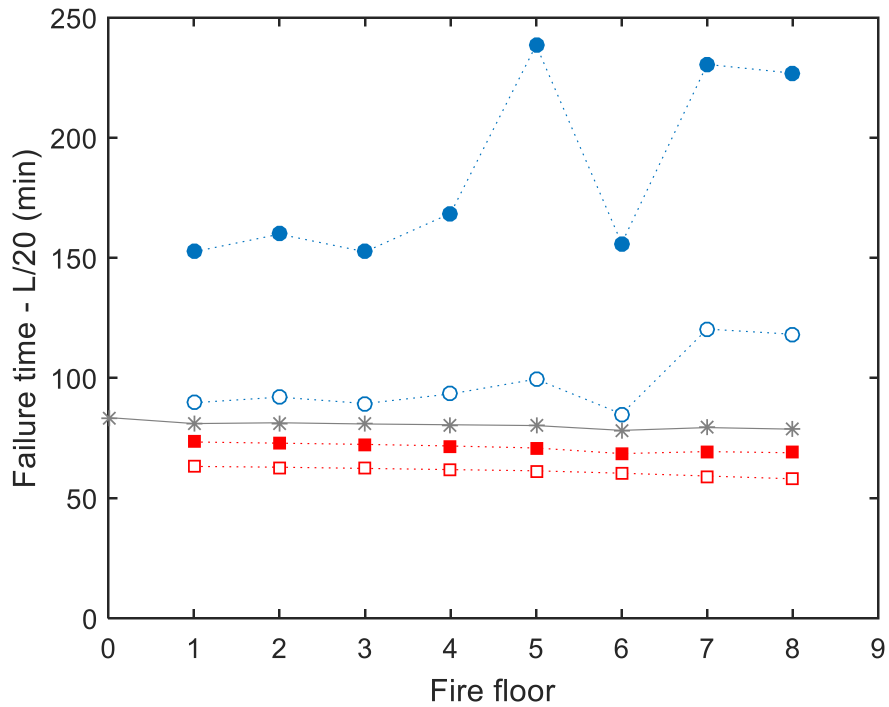
STRUCTURAL FAILURE







- There is no single fire scenario which would represent the worst case
- For different fire exposure failure occurs on different floors

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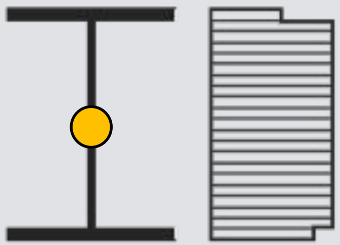
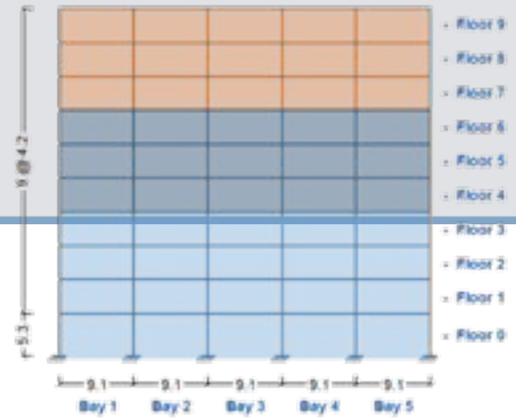
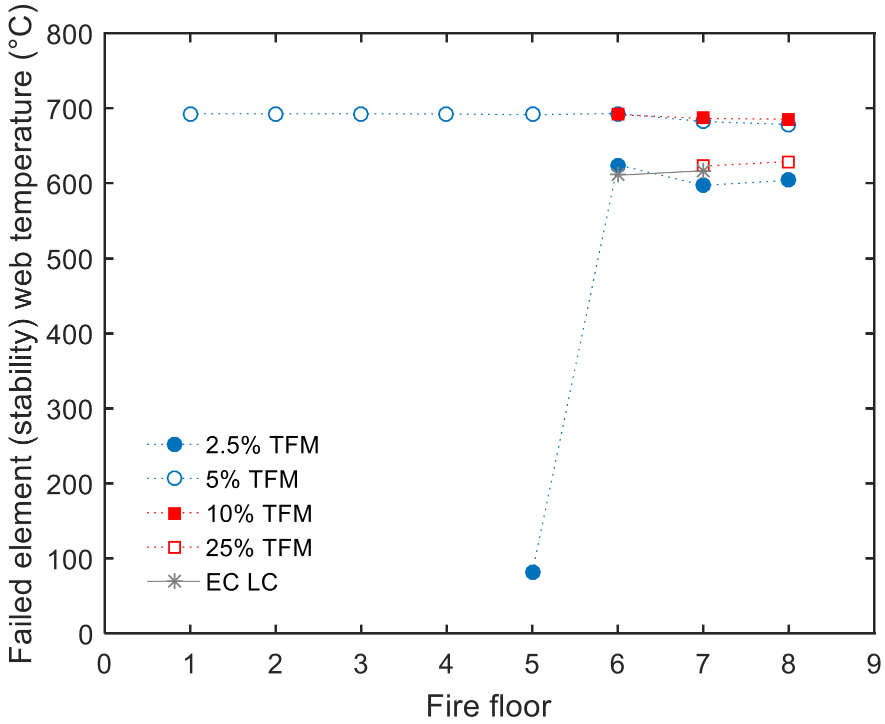
WEB TEMPERATURE AT FAILURE







- Stability criterion - 600–740°C

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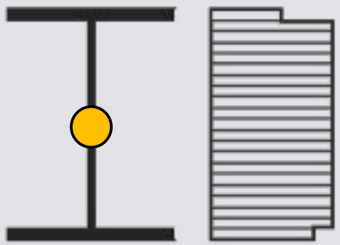
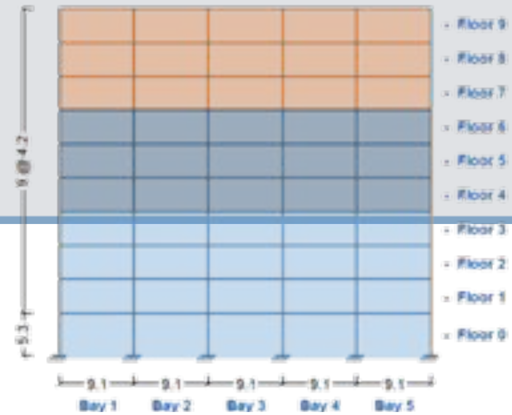
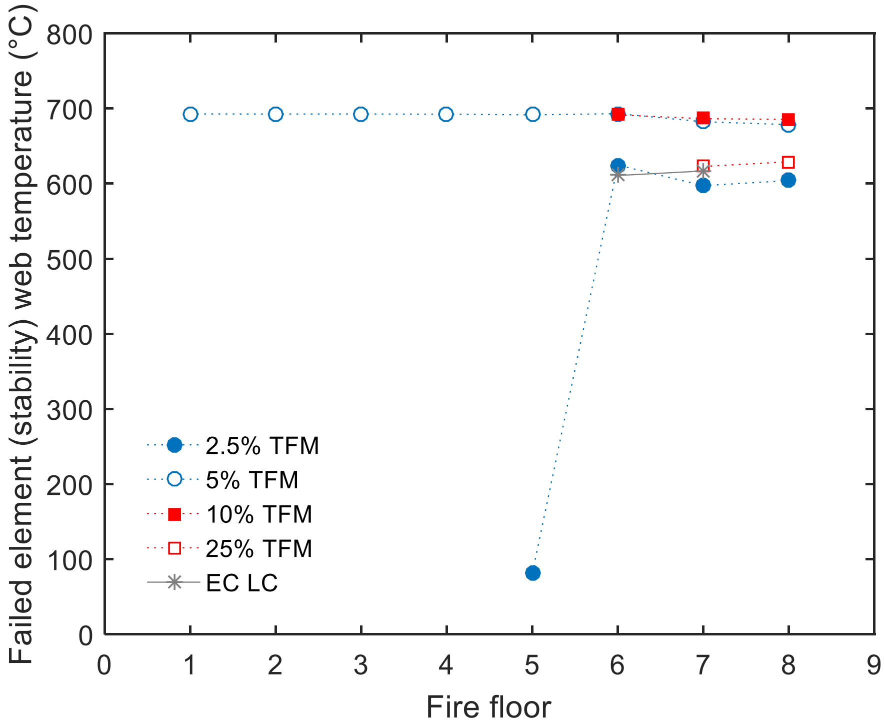
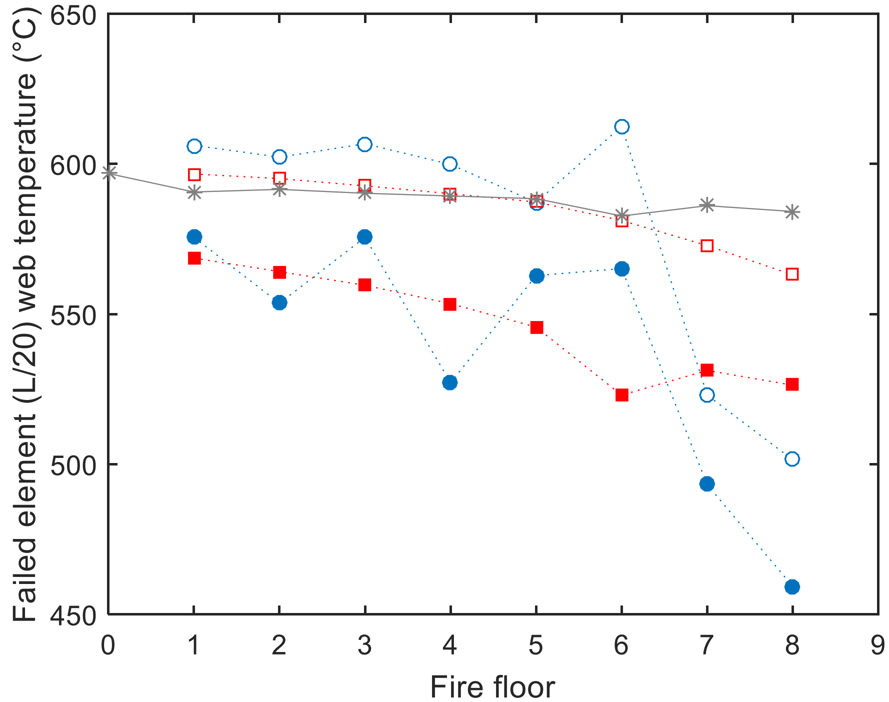
WEB TEMPERATURE AT FAILURE









- Stability criterion - 600–740°C
- Deflection criterion - 450–620°C

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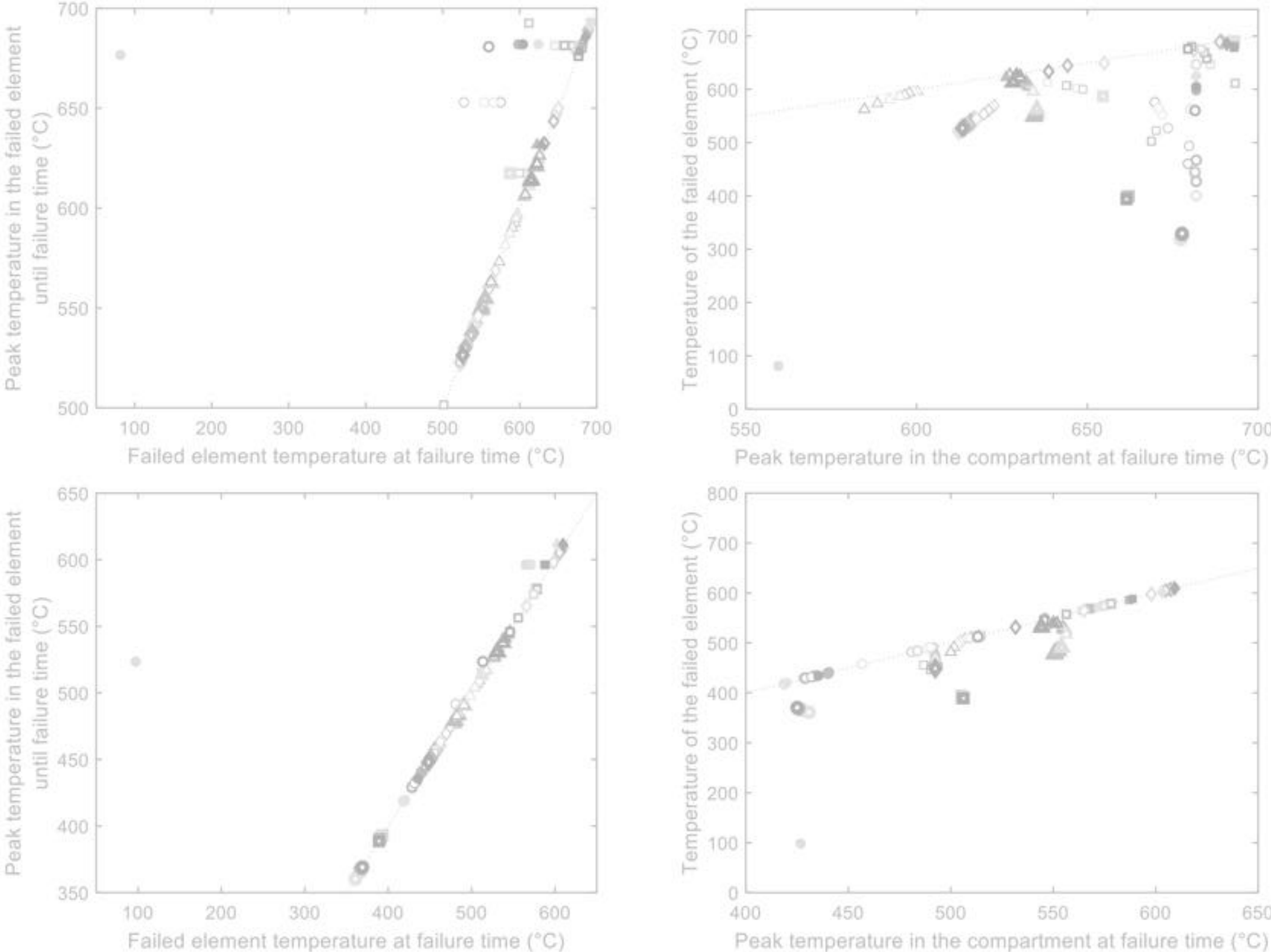
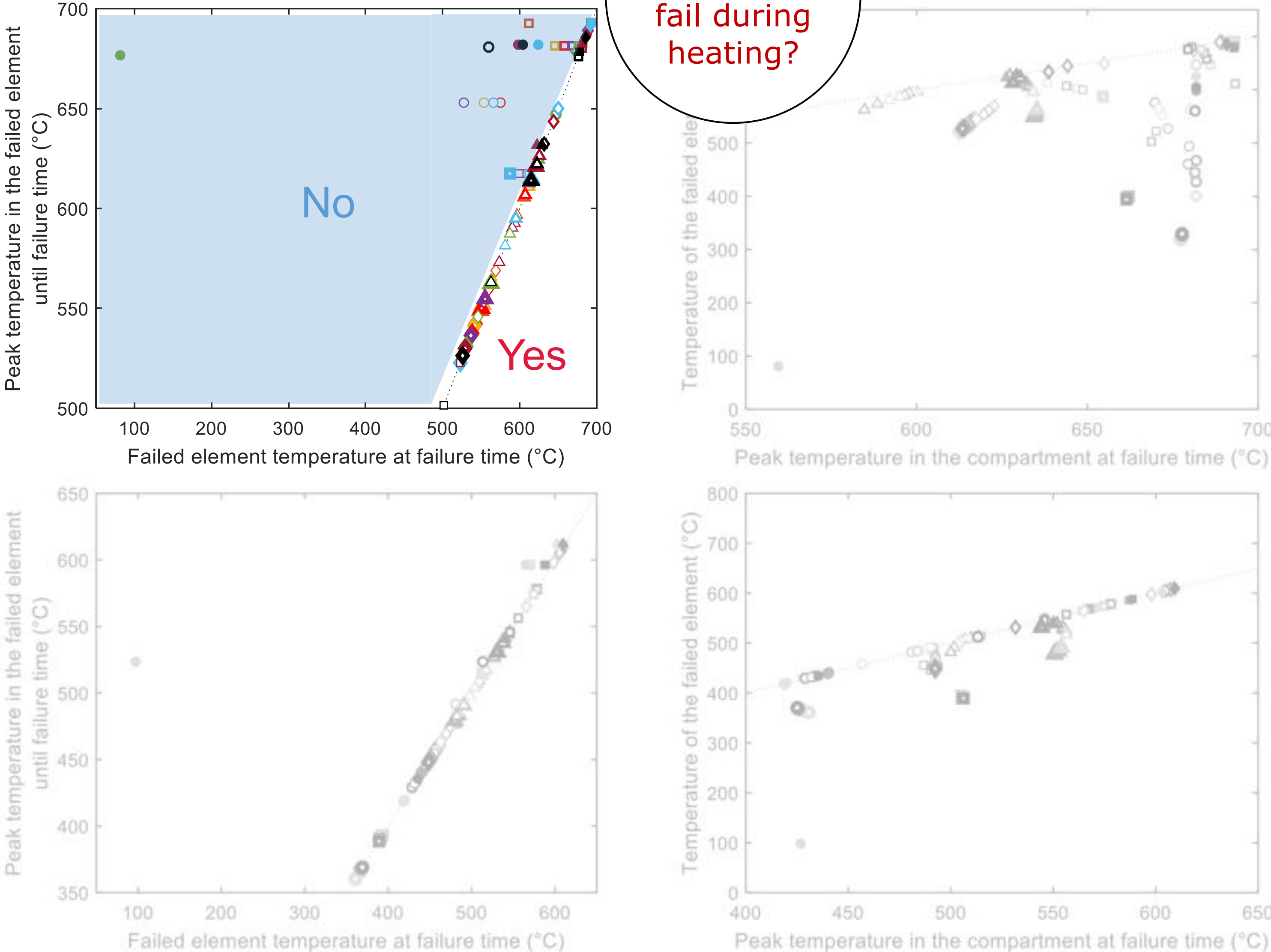
FAILURE TEMPERATURE



FAILURE TEMPERATURE

Does the element fail during heating?



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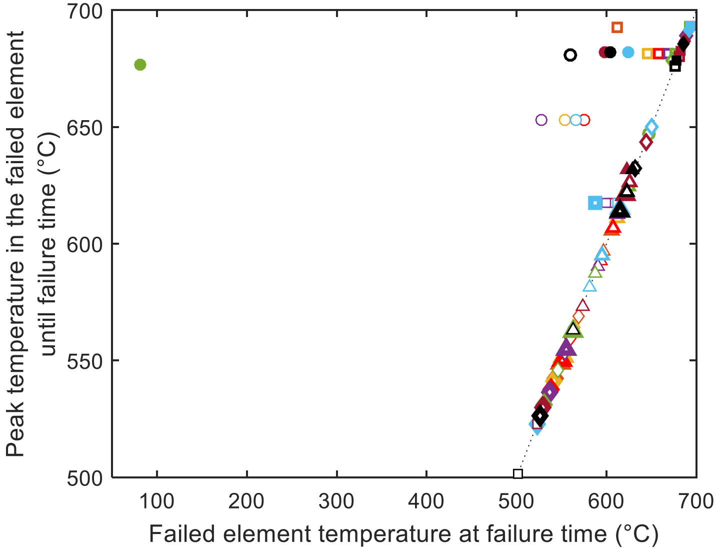
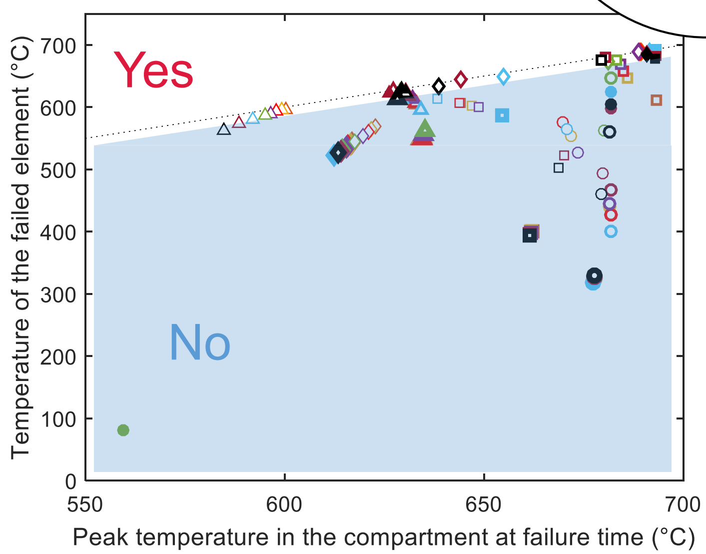
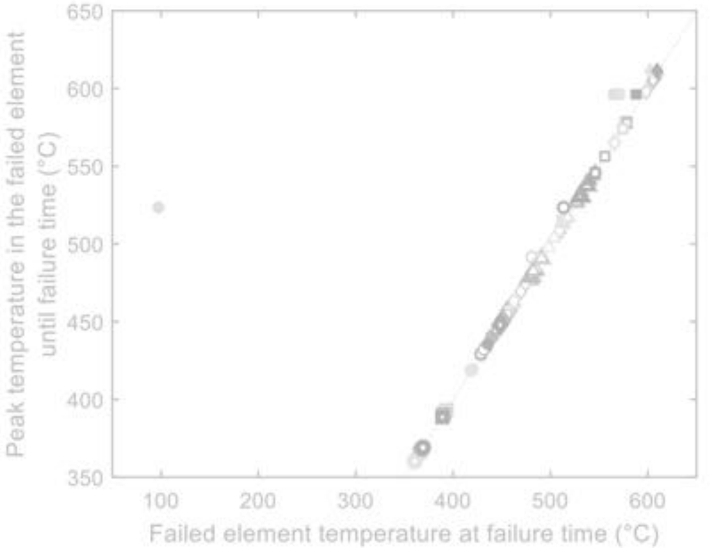
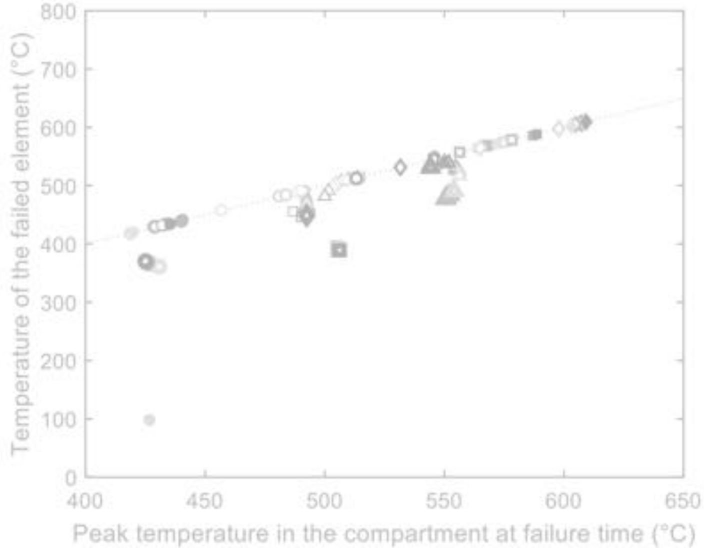
FAILURE TEMPERATURE

Is element at the location of peak temperature?









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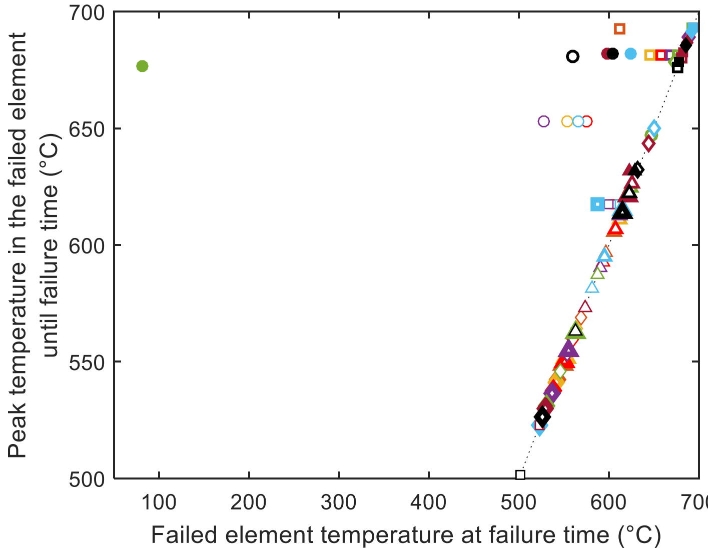
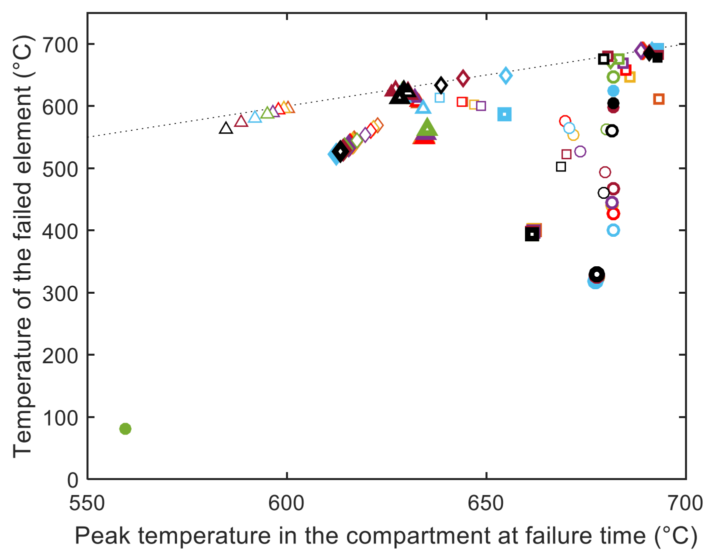
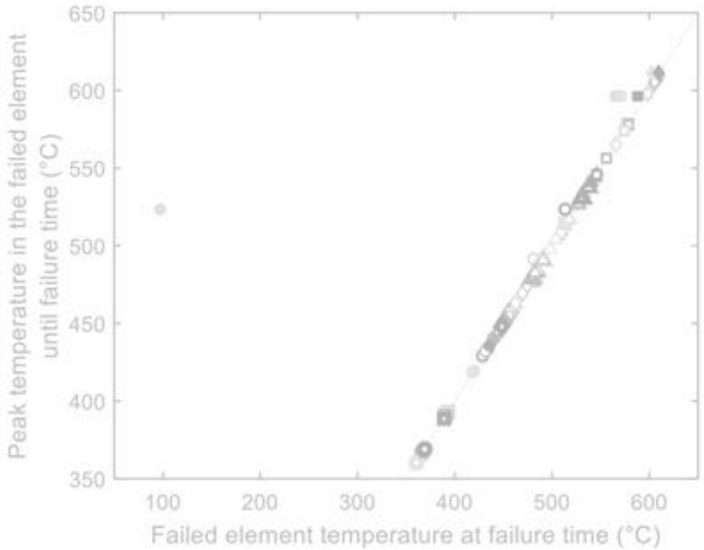
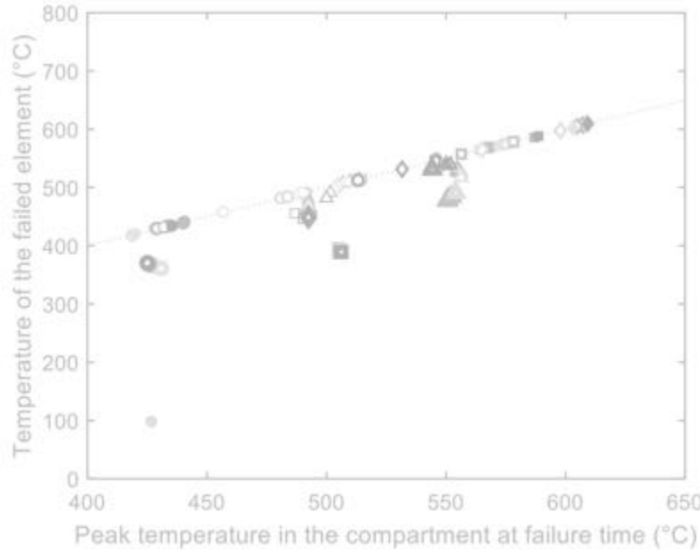
FAILURE TEMPERATURE





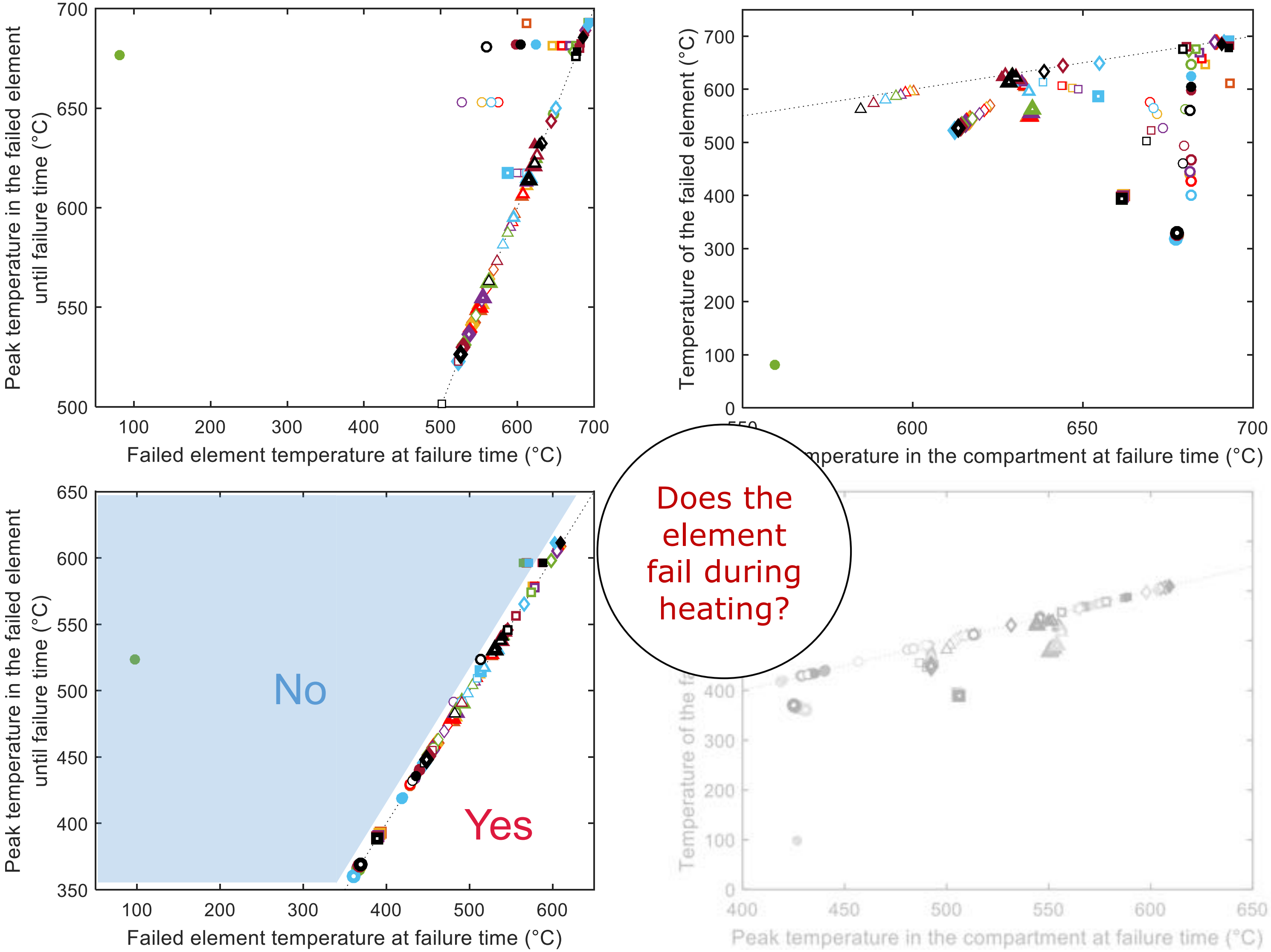
Average Bay temperatures





FAILURE TEMPERATURE

Average Bay temperatures



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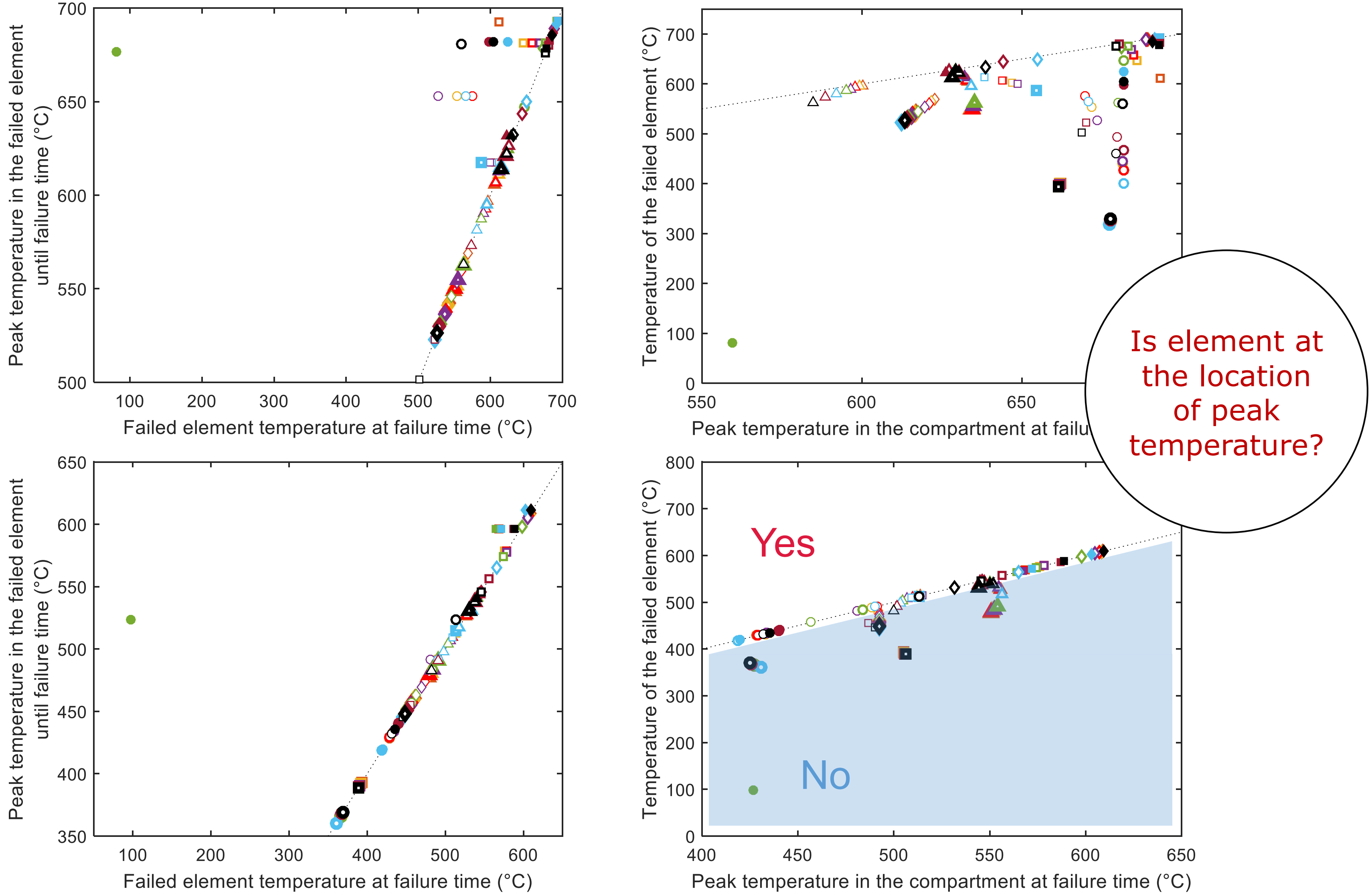
FAILURE TEMPERATURE

Average Bay temperatures



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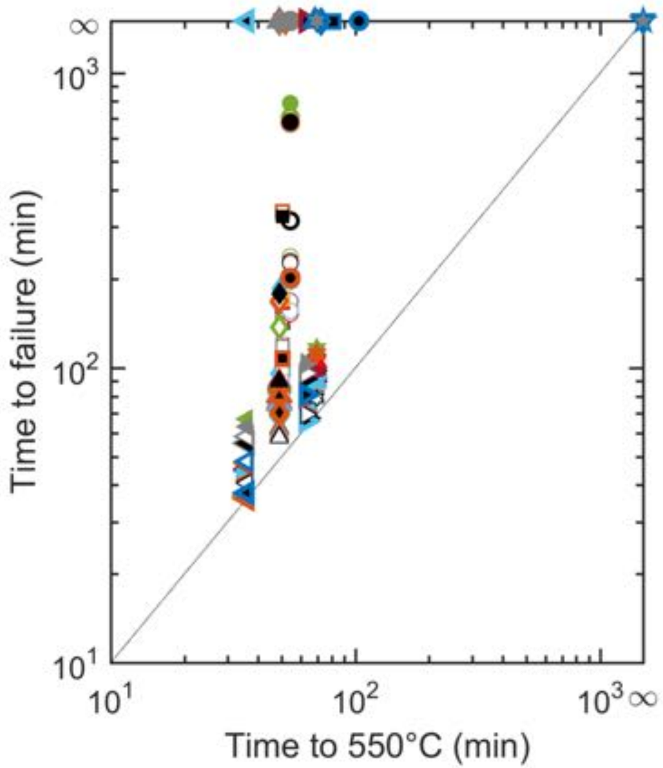
TIME TO FAILURE



- No relationship between the time to reach the critical temperature in the compartment and the failure time.

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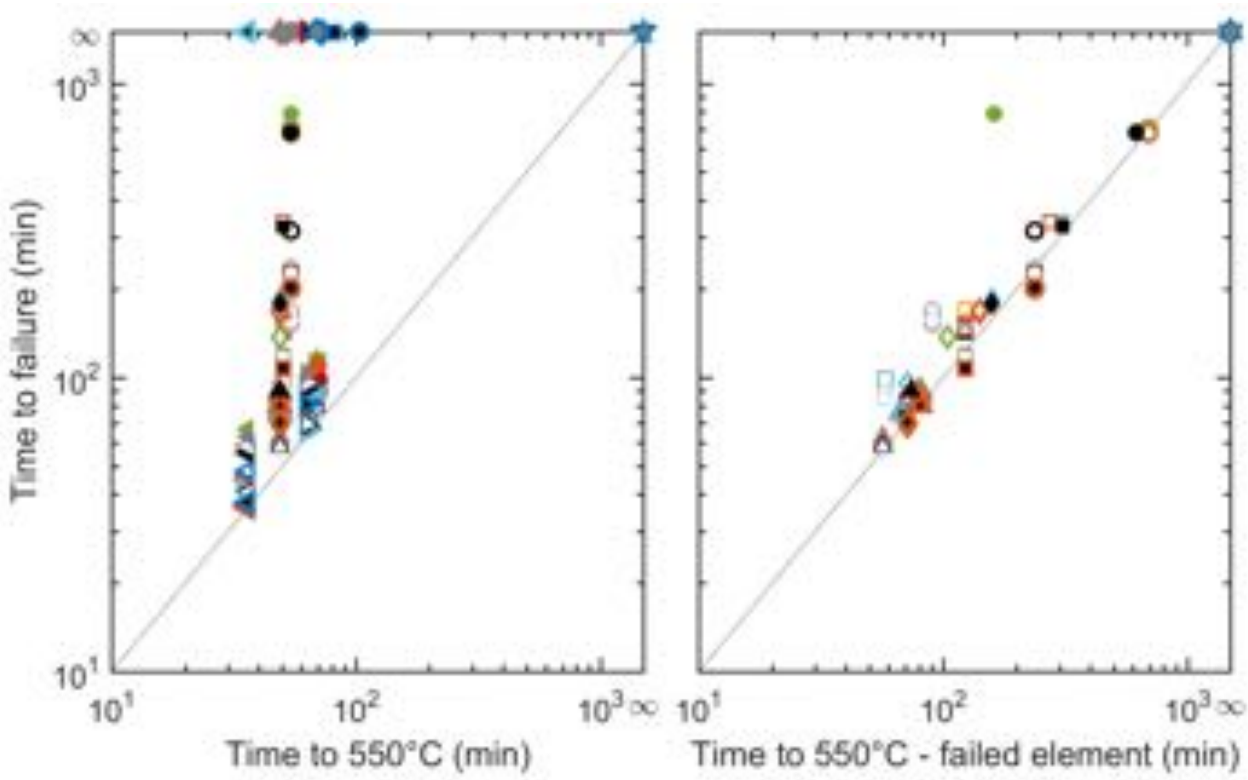
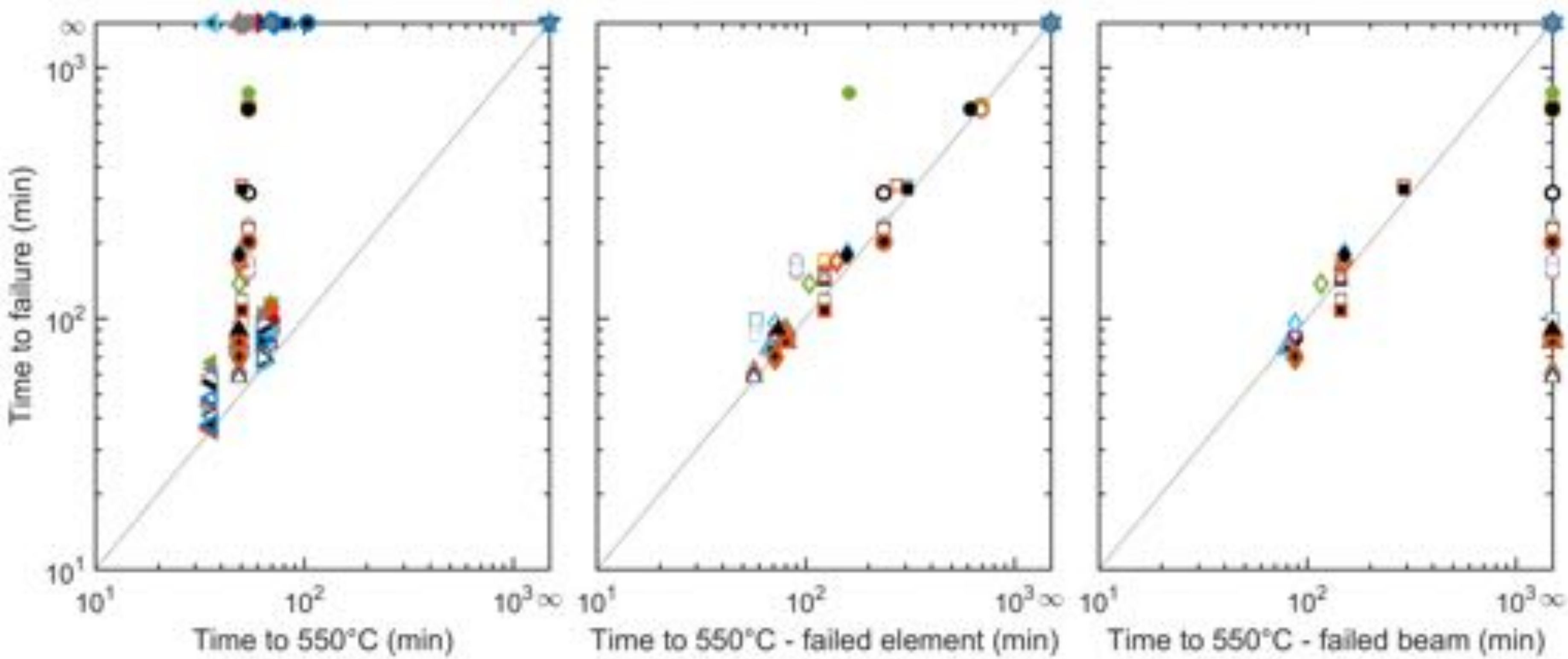
TIME TO FAILURE



- No relationship between the time to reach the critical temperature in the compartment and the failure time.

TIME TO FAILURE



- No relationship between the time to reach the critical temperature in the compartment and the failure time.
- Best correlation between the times to reach the critical temperature in the failed element and times to failure.

CONCLUSIONS

- In large compartments, post-flashover fire cannot occur, but a travelling fire would develop
- Critical fire scenarios occur on the upper levels of the building.
- There is no single fire scenario which would represent the worst case.

➡ There is no relationship between the time to reach the critical temperature in the compartment and the failure time.

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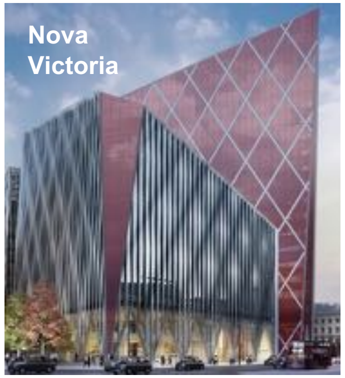
THANK YOU!

39 iconic buildings in UK



IMPERIAL HAZELAB | SFPE Engineering A Fire Safe World | CERIB | ARUP | EPSRC Engineering and Physical Sciences Research Council

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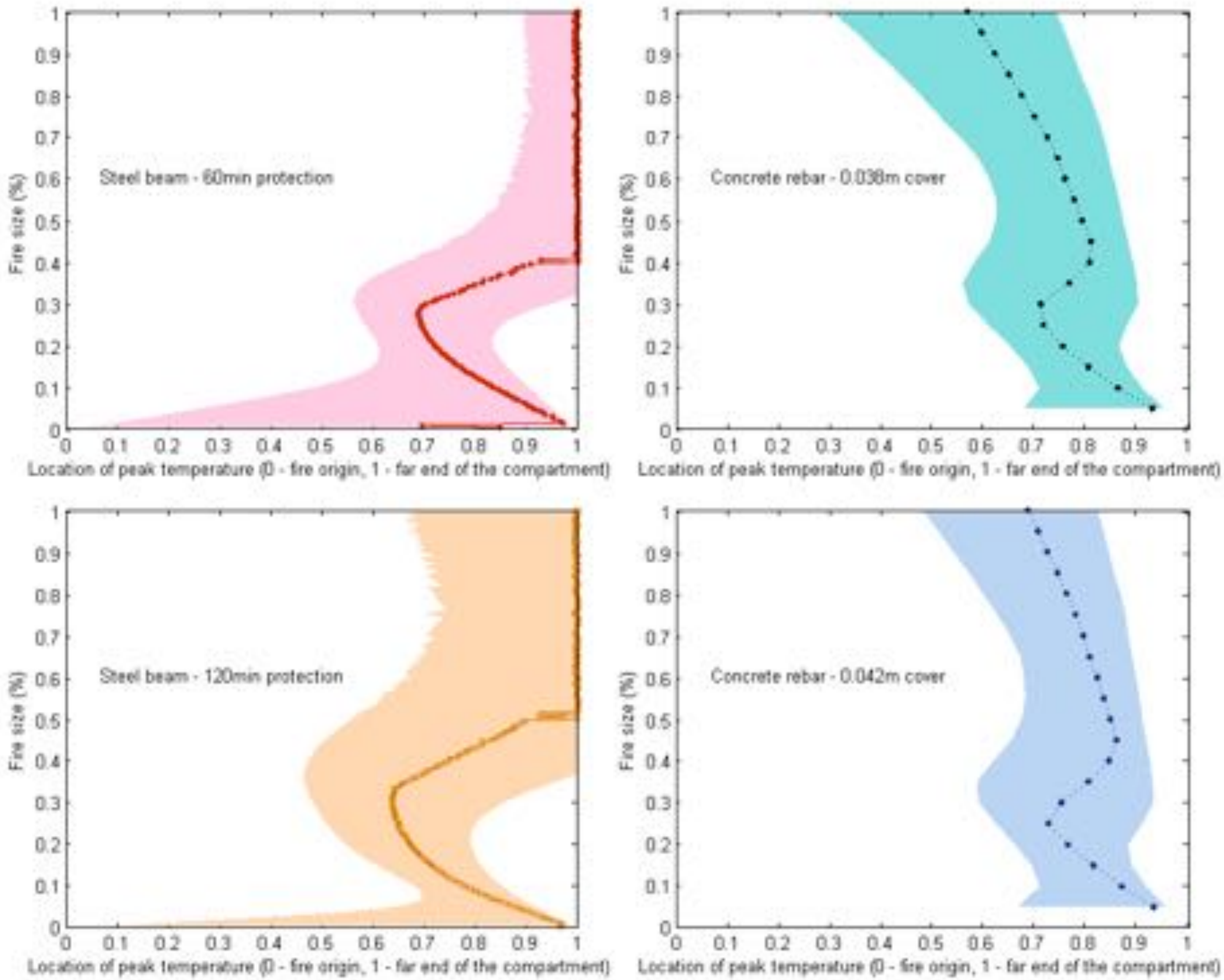
LOCATION OF PEAK TEMPERATURE



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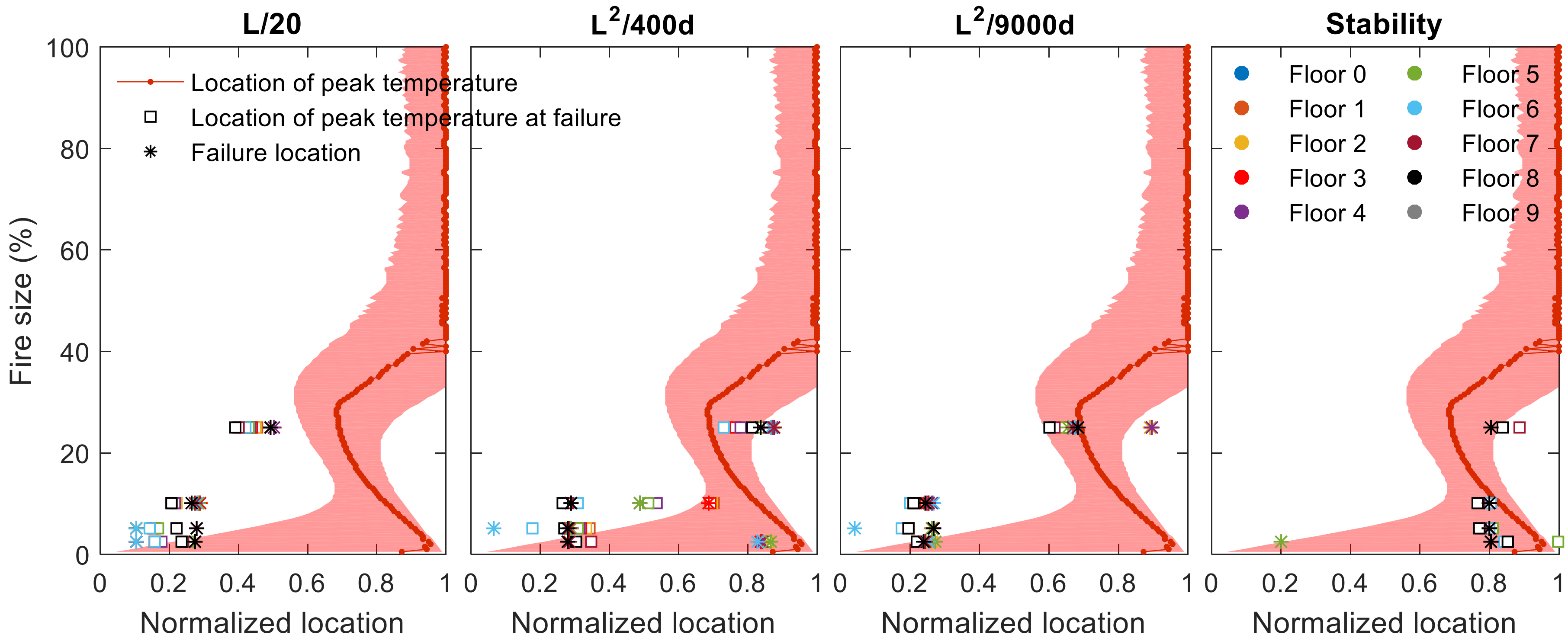
LOCATION OF PEAK TEMPERATURE



- Deflection criteria - no correlation with the location of the peak temperature.
- Stability - failure tends to occur towards the end of the fire path within the region where peak temperatures in the compartment develop.

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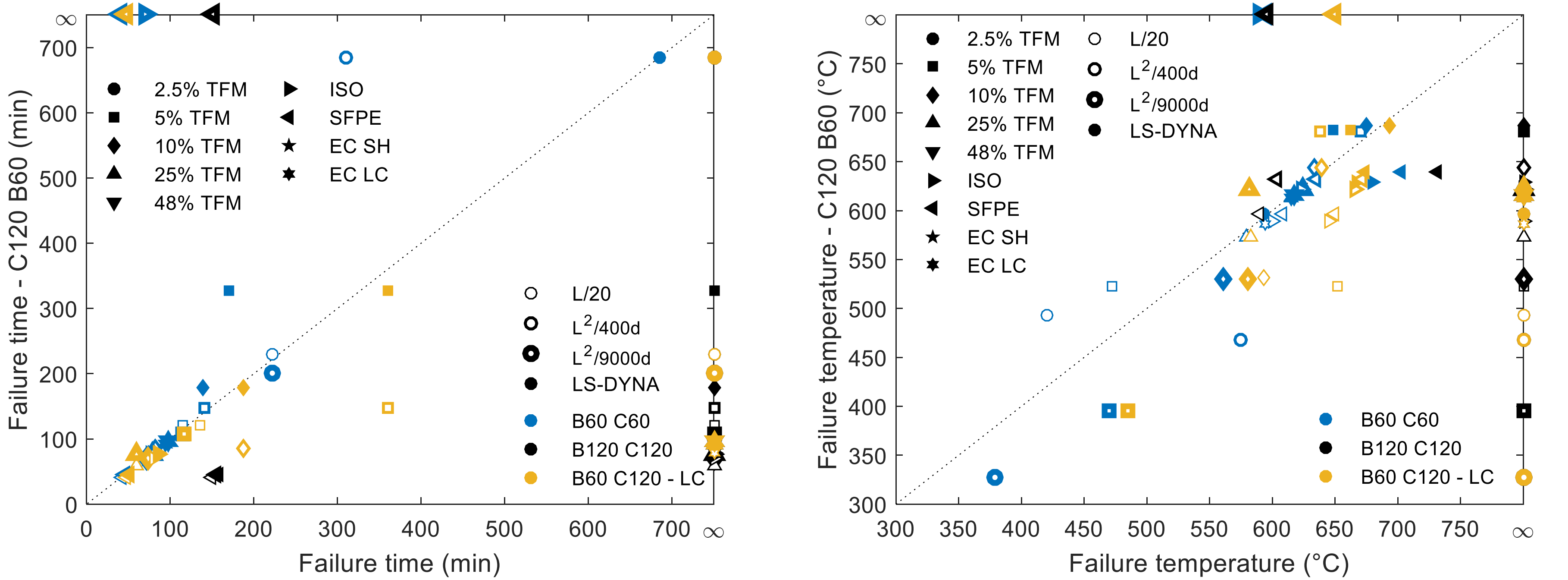
EFFECT OF FIRE PROTECTION AND BEAM SECTION SIZE



- B120 C120 – 3 times higher fire resistance..
- B60 C60 – lower fire resistance.
- B60 C120 – higher fire resistance.

only up to 20 min difference

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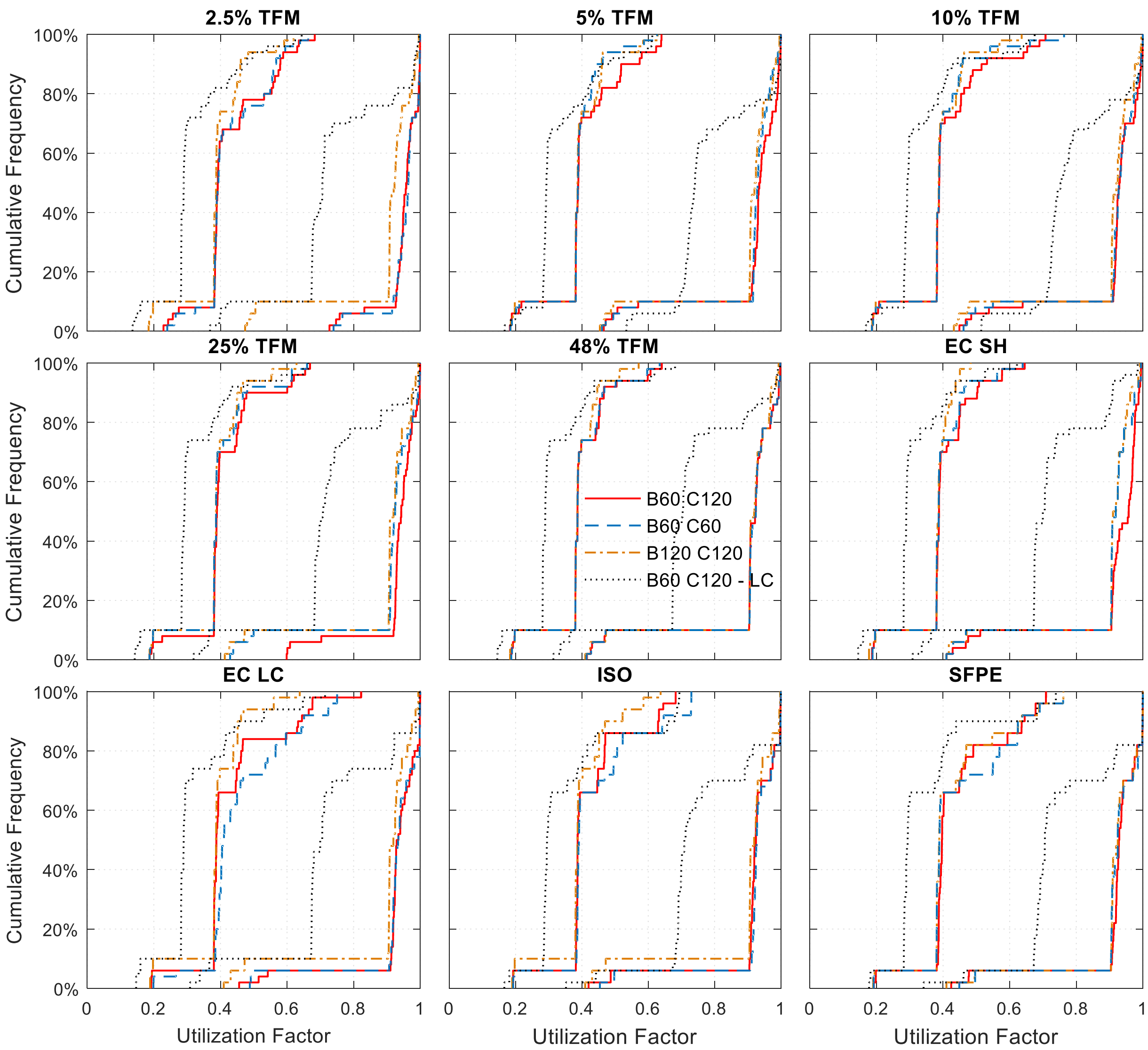
EFFECT OF FIRE PROTECTION AND BEAM SECTION SIZE



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UTILIZATION