

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

Egle Rackauskaite, Panagiotis Kotsovinos, and Guillermo Rein

WHY? – Real Fires



WHY? – Traditional Design

Traditional Design Fires

Standard Fire ~1880

Swedish Curves ~1972

Eurocode Parametric Curve ~1995

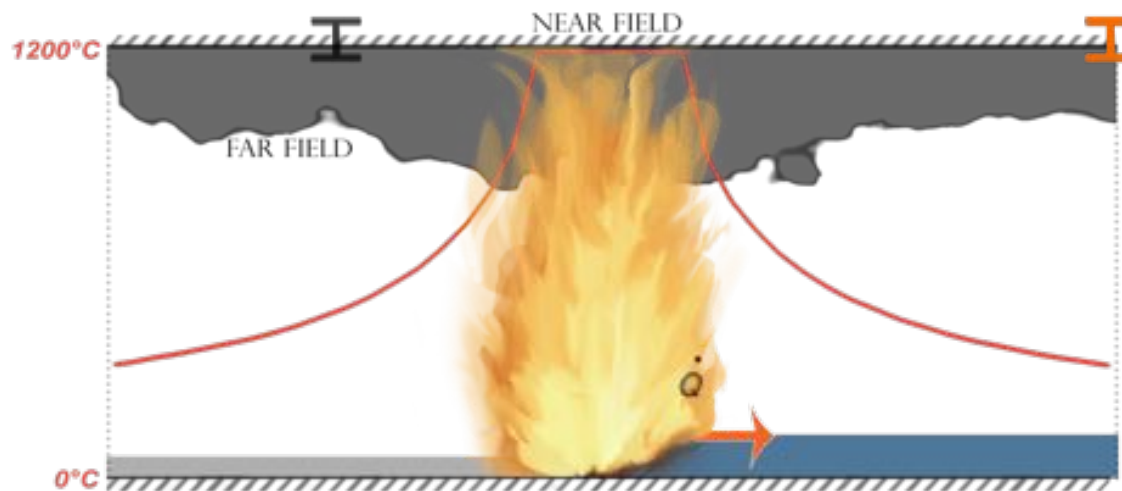
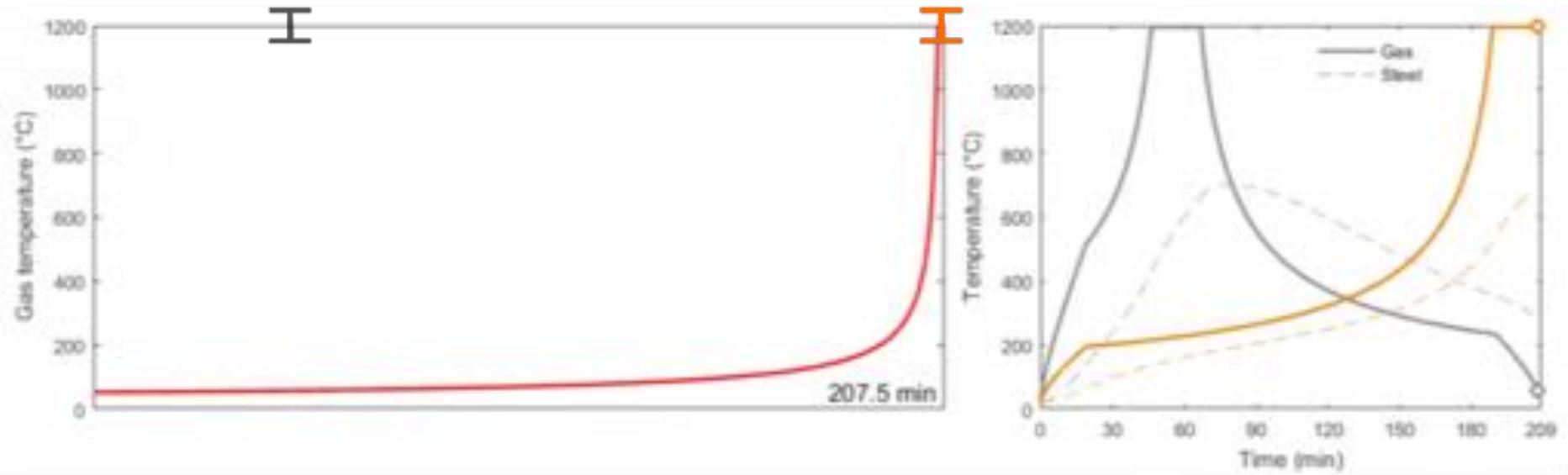
- Based on small scale tests (<100 m²)
- *Assume uniform temperatures within the compartment*
- *Have strict limitations on the applicability to compartments*

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

e.g., only 8% of volume within limitations

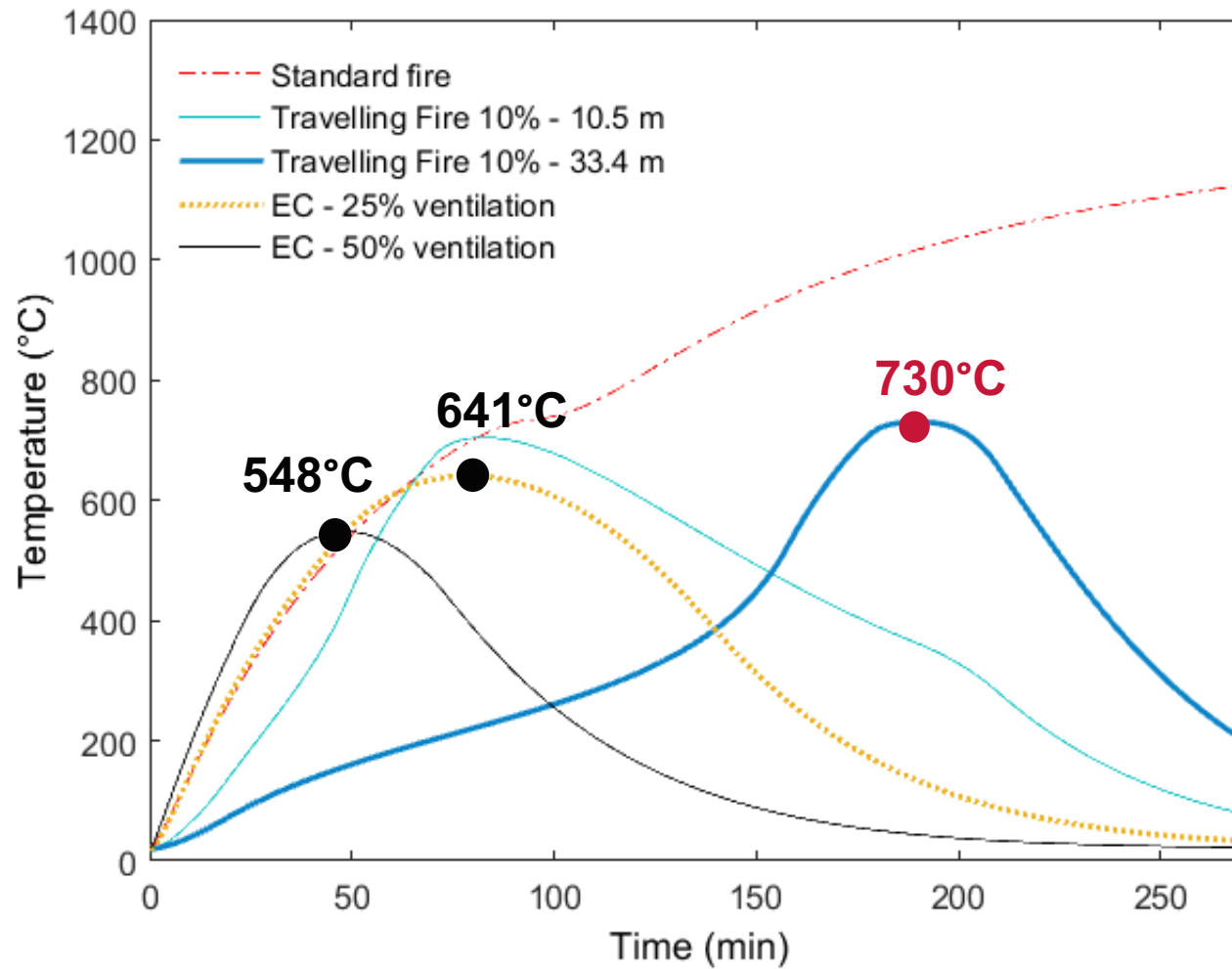
in survey at Edinburgh

Travelling Fires Methodology (iTFM)



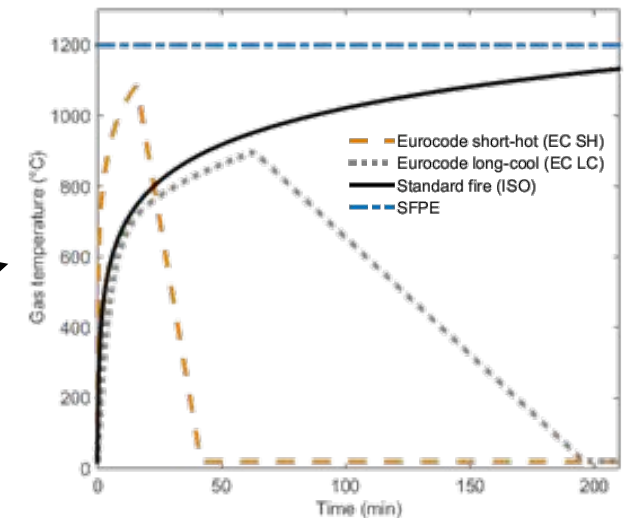
- TFM - Stern-Gottfried, Law and Rein (2007-2012)
- iTFM - Rackauskaite, Hamel, Law and Rein (2015)
- Considers a **family of fires** → different % of floor areas engulfed in flames
- Takes into account highly **non-uniform** temperature distributions

Travelling Fires Methodology (iTFM)

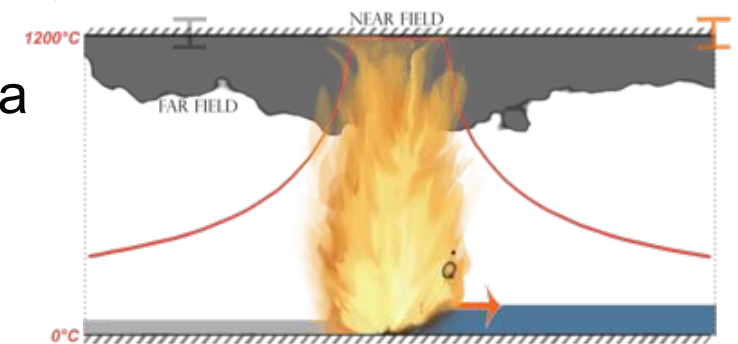


AIM OF THE STUDY

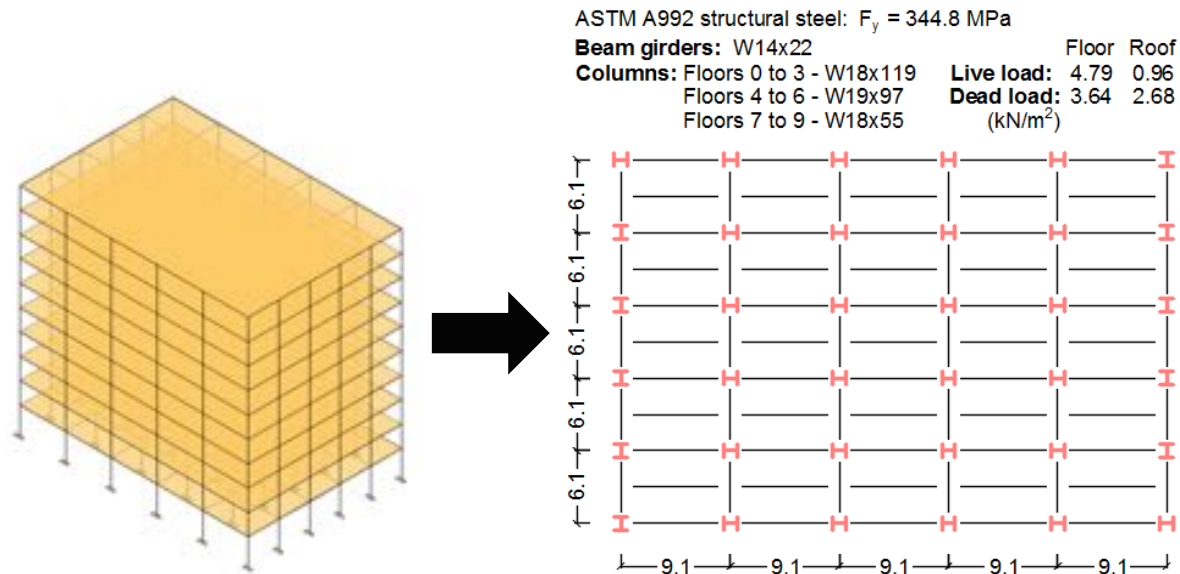
- Apply iTFM and **compare** the structural response of the steel frame subjected to **traditional fires** and **travelling fires**



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

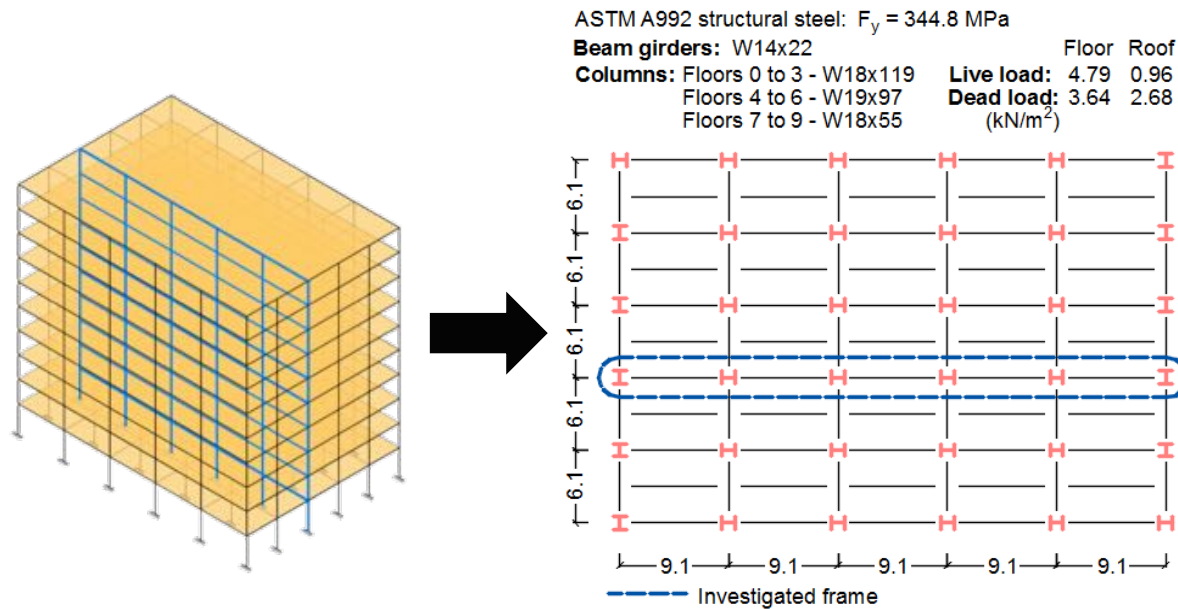


INVESTIGATED STEEL FRAME



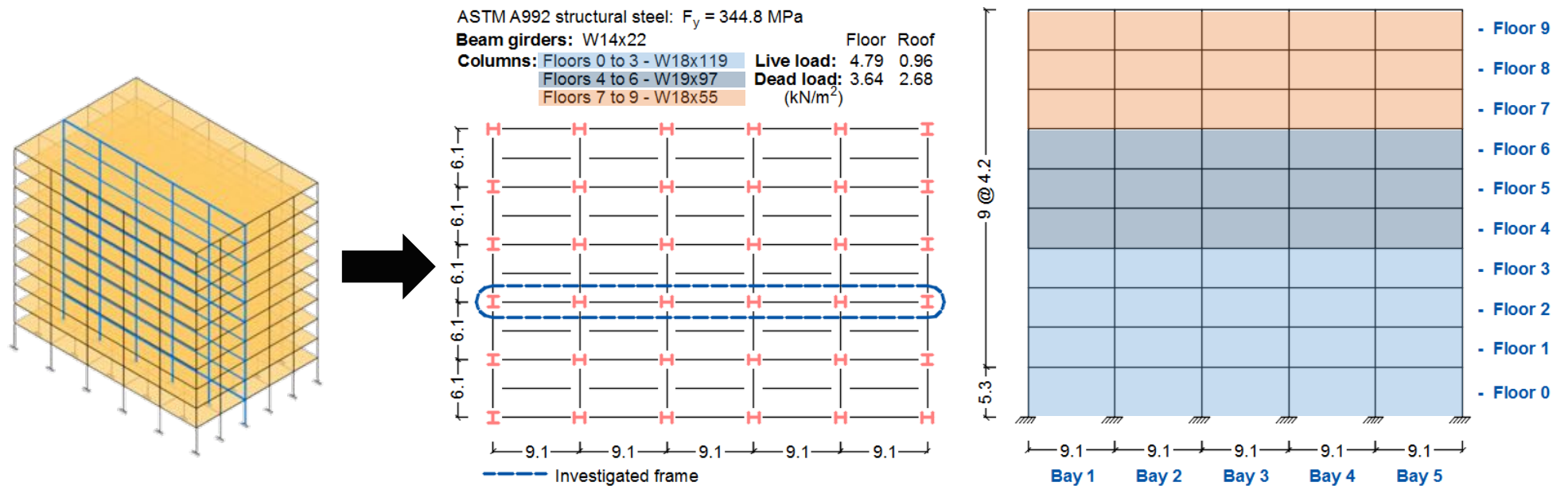
- Design (in accordance to ASCE 7-02 standard) published by NIST

INVESTIGATED STEEL FRAME



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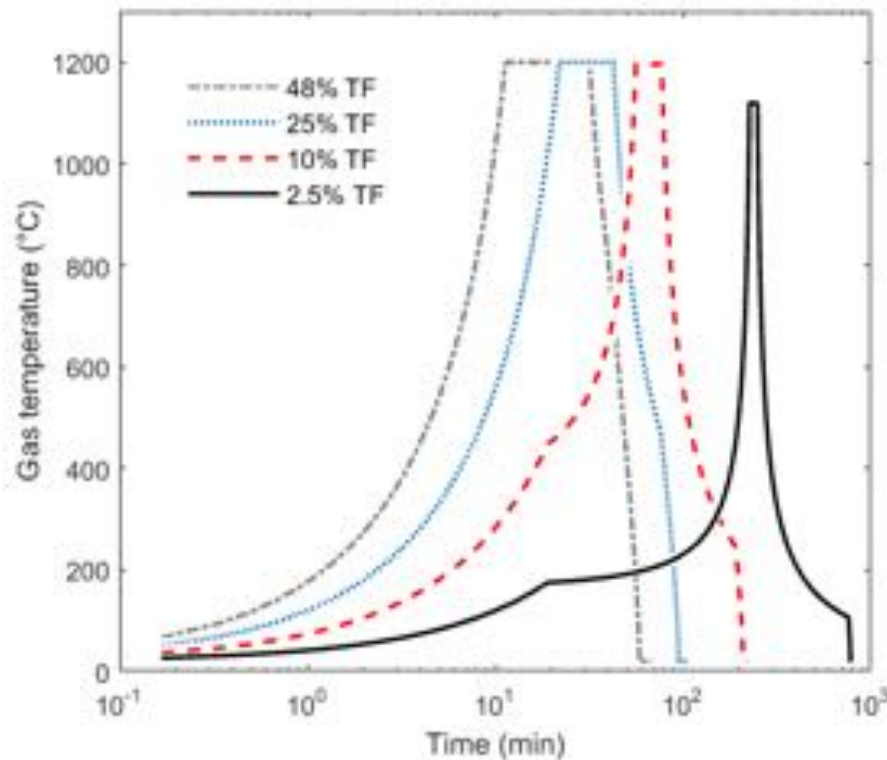
INVESTIGATED STEEL FRAME



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

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*}

^a Department of Mechanical Engineering, Imperial College London, UK
^b Department of Fire Protection Engineering, University of Maryland, College Park, USA
^c Arup, UK

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ABSTRACT

Current design codes and consequently most of the understanding of behaviour of structures in fire are based on the often unrealistic assumption of uniform fire within the enclosure. This assumption is especially wrong in the case of large open-plan compartments, where non-uniform travelling fires have been observed instead. An innovative concept called the Travelling Fire Methodology (TFM) has been developed to take into account this non-uniform fire behaviour. In this study, TFM has been improved to account for better fire dynamics. Equations are introduced to reduce the range of possible fire sizes taking into account fire spread rates and flow. The analytical equations used to represent the fire field temperatures are presented in continuous form. The concept of flame flapping is introduced to account for variation of temperatures in the near-field region due to natural fire oscillations. These updated near-field temperatures cover a range of temperatures between 600 and 1200 °C, depending on fire size and compartment characteristics. These temperature changes are based on a fire model which can be used flexibly and adjusted to fit experimental data when it becomes available in the near future. Improved TFM (ITFM) is applied to generic concrete and steel compartments to study the effect of non-uniform heating associated with the travelling fire by investigating the location of the peak temperature along the fire path. It is found to be mainly dependent on the fire spread rate and the heat release rate. Location of the peak temperature in the compartment mostly occurs towards the end of the fire path.

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1. Introduction

Accidental fire can be disastrous, especially in buildings. Most fire deaths occur due to the toxic effects of smoke before any structural collapse [1]. However, the effect of fire on structural stability is critical in regard to safe evacuation and safe access for fire fighters, financial losses, and lost business. This is particularly the case in tall buildings where extended evacuation times are required due to planned evacuation practices [2].

Innovative architectural designs of modern buildings already provide a challenge to structural engineers. This is shown all the case in structural fire engineering [3,4]. Understanding of fundamental mechanisms of whole building behaviour in fire has significantly increased in the last decades, especially after full-scale tests of various multi-storey buildings were carried out in Cambridge between 1994 and 1996 [5, 6]. However, most of this understanding and current design codes are based on the assumption of uniform fire in a compartment. An extensive recent work [7,8] has shown that while the uniform fire assumption may be suitable for small enclosures, fires in large, open-plan compartments, typical of modern architecture, do not cover the full area of compartment but rather travel from one part of it to another with non-uniform temperature distribution. These fires are referred to as travelling fires.

Current design standards (e.g. Eurocodes) do not account for such fires. The standard fire and parametric time-temperature curves are based on small scale tests (<100 m³) [9], and assume uniform heating of fire and homogeneous temperature distributions in the compartment. In large accidental events, fires have been observed to travel across floor plates and between stories. Accidental events where fires were observed to travel include World Trade Centre Towers 1, 2 & 3 (2001); Windsor Tower fire in Madrid (2006); Society of Architecture building fire at TU Delft (2008); Inverstar Rank fire in Los Angeles (1988); and One Meridian Plaza fire in Philadelphia (1991). In all of these accidents, the fires lasted for up to 7 or even 20 hours (i.e. Windsor Tower and Meridian Plaza fires). Such long fire durations are not considered now can be understood by current design codes. It has been shown in the WTC Towers study by NIST [10,11] that such prolonged periods of heating may result in even protected structural elements reaching temperatures in excess of 600 °C. They also concluded that using average uniform gas temperatures rather than travelling fires would have led

* Corresponding author.
 E-mail address: guillermo@imperial.ac.uk (G. Rein).

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Behaviour of a small composite steel frame structure in a “long-cool” and a “short-hot” fire

S. Lamont^a, A.S. Usmani^{b,*}, M. Gillie^c

^a*Arup Fire, One Arup and Partners, 11 Finsbury Street, London W1T 4BQ, UK*

^b*School of Engineering and Electronics, University of Edinburgh, ABG Building, The King's Building, Edinburgh, Scotland EH8 9JN, UK*

^c*School of Civil Engineering, University of Nottingham, 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 Pittersson'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.

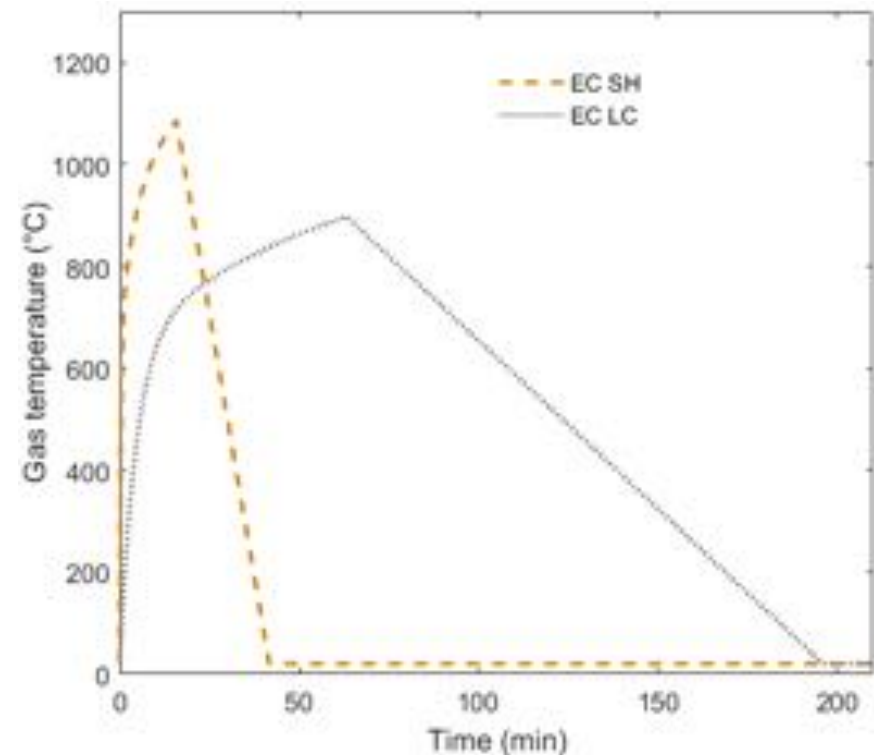
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Keywords: Steel frame; Composite construction; Natural fire; Structural behaviour in fire

*Corresponding author. Tel.: +44 131 650 5309; fax: +44 131 650 4702.

E-mail address: as.usmani@ed.ac.uk (A.S. Usmani).

2 Eurocode (EC) parametric curves - short-hot (SH) and long-cool (LC)



me → **117 fire scenarios** in total

THE MODEL

Heat transfer

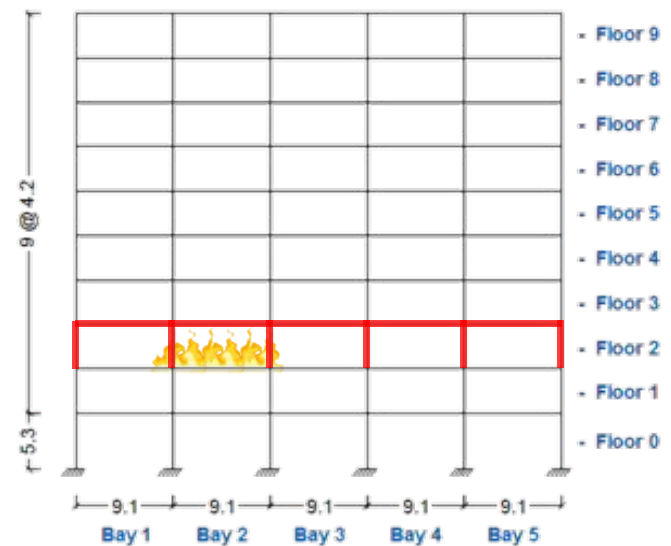
- Protected beams (60 min) and columns (120 min)
- Buchanan (2009):

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



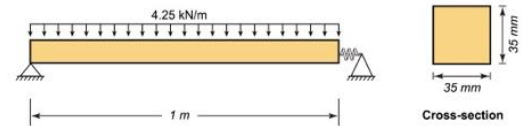
Structural analysis

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

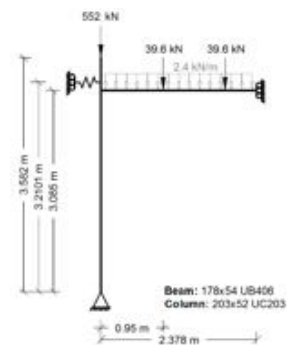


BENCHMARKING OF LS-DYNA

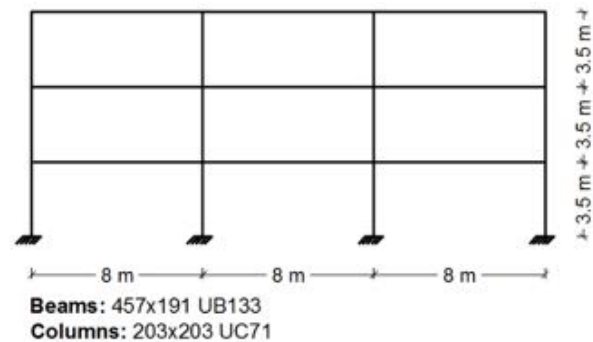
- BM1: Gillie (2009)



- BM2: Cooke
& Latham (1987)

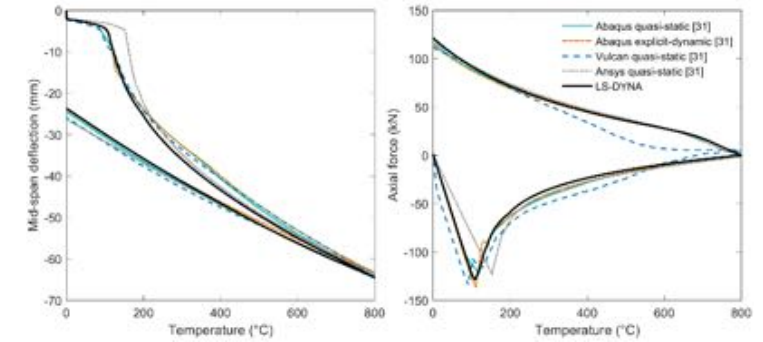
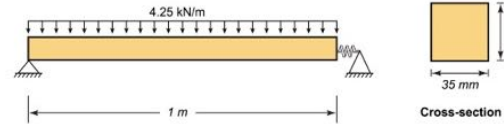


- BM3: Rackauskaite
& El-Rimawi (2015)

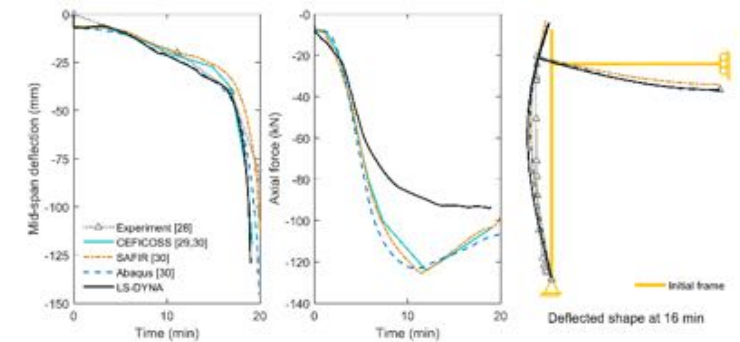
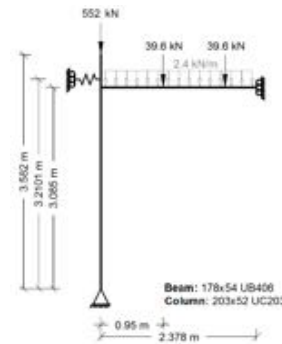


BENCHMARKING OF LS-DYNA

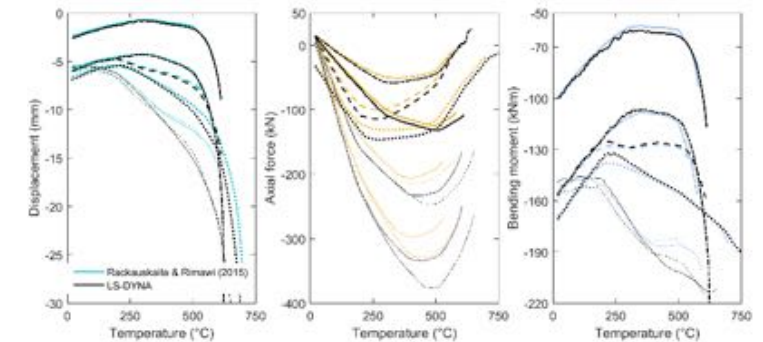
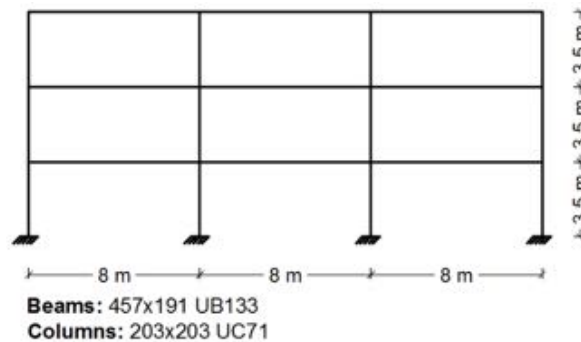
- BM1: Gillie (2009)



- BM2: Cooke & Latham (1987)



- BM3: Rackauskaite & El-Rimawi (2015)



FAILURE CRITERIA

Thermal:

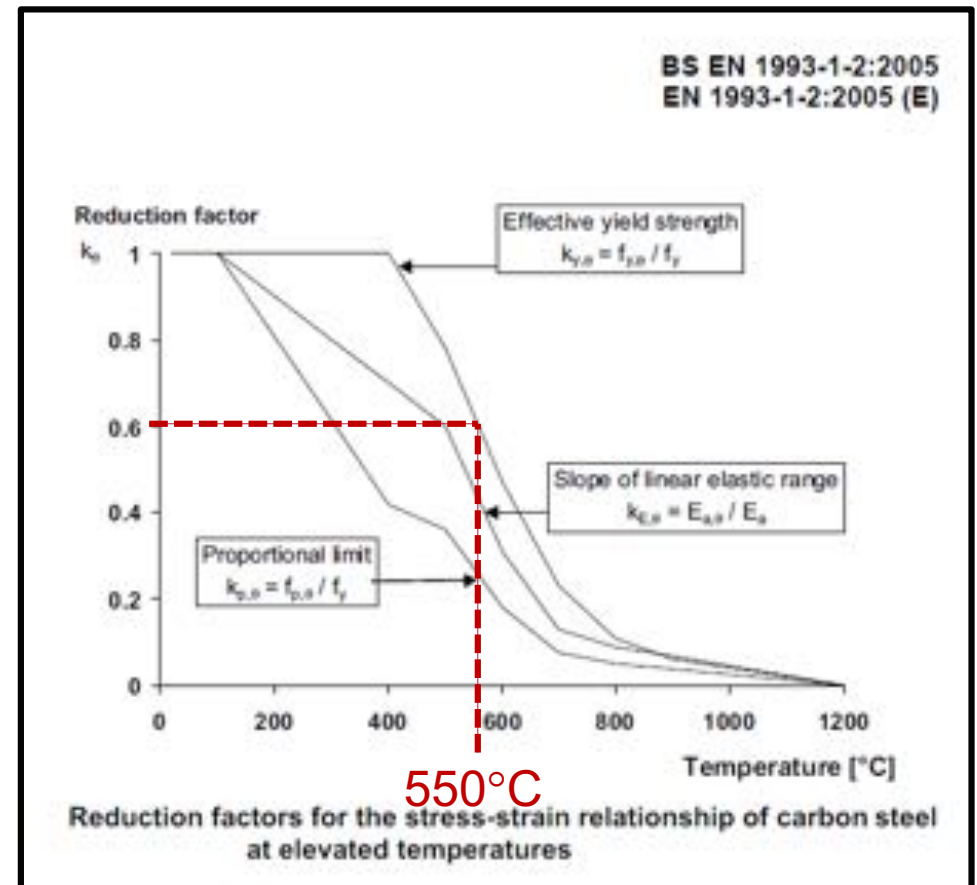
Structural:

FAILURE CRITERIA

Thermal:

- Critical temperature of 550°C

Structural:



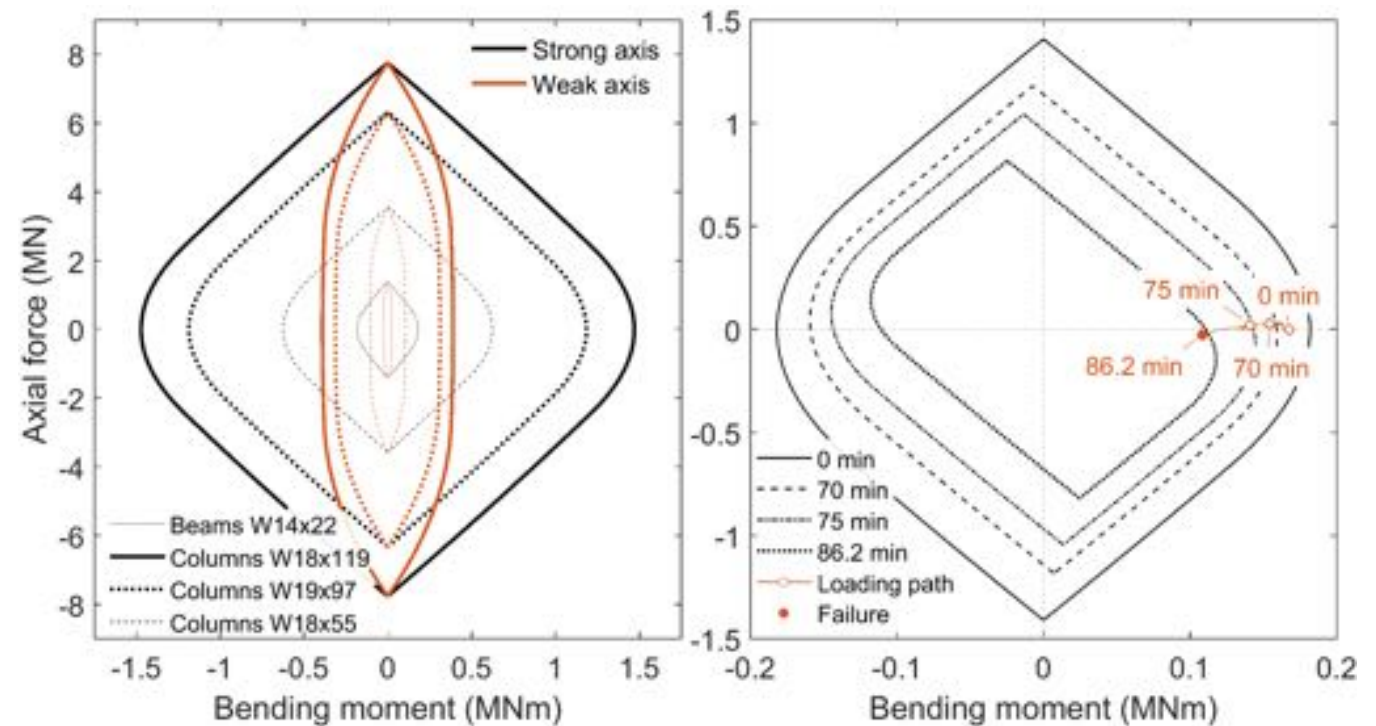
FAILURE CRITERIA

Thermal:

- Critical temperature of 550°C

Structural:

- Utilization



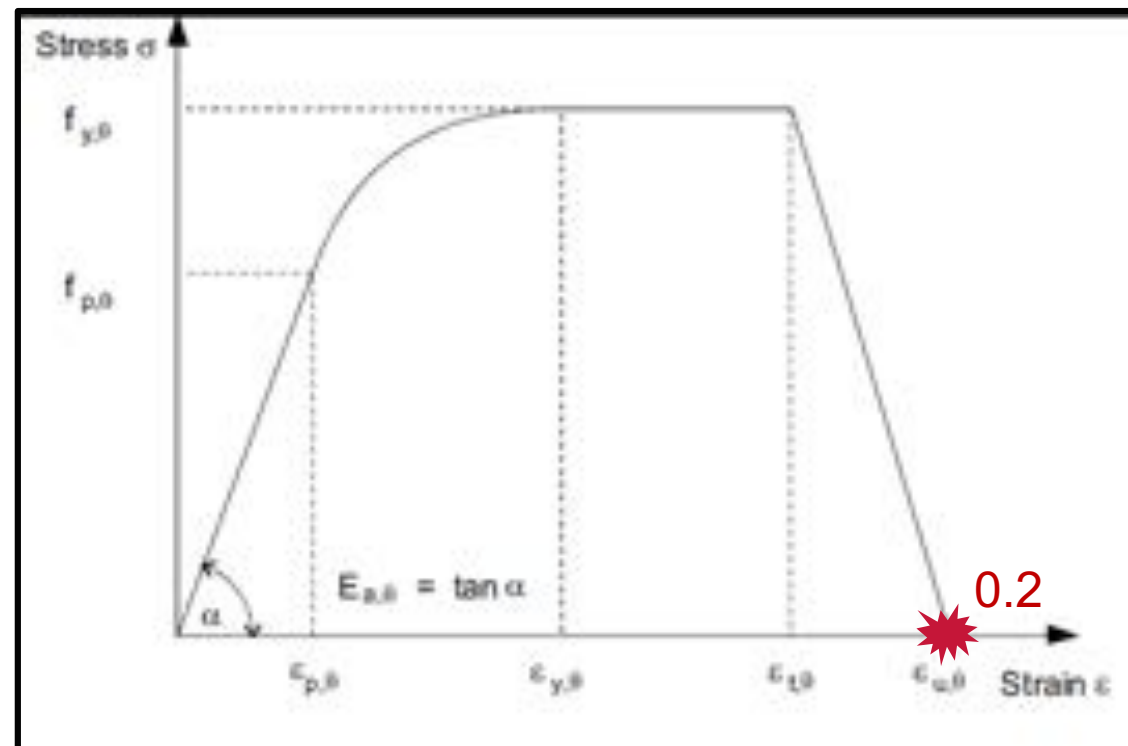
FAILURE CRITERIA

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

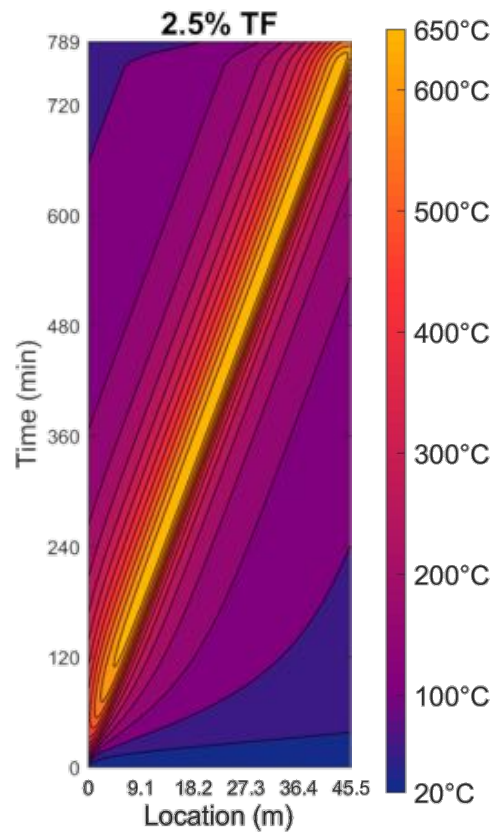
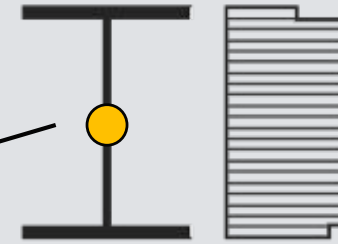
Thermal:

- **Critical temperature of 550°C**

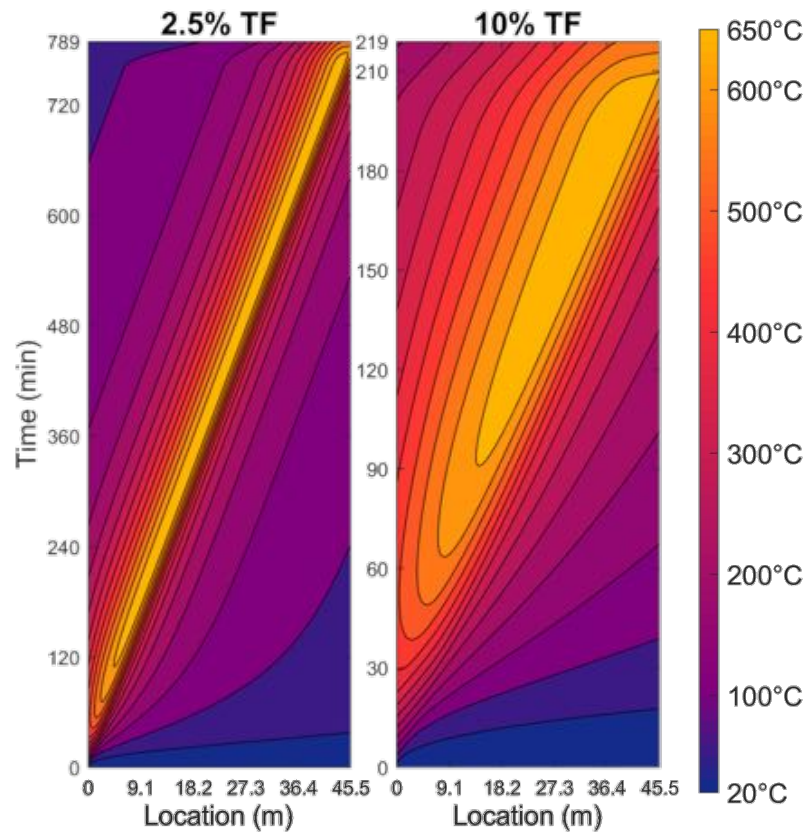
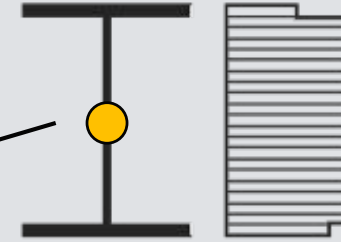
Structural:

- Utilization
- **Stability**
- **Deflection**
 - Ryan and Robertson criterion
 - Mid-span deflection - $L^2/800d$*
 - Rate of deflection - $L^2/9000d$ over 1 min*
 - **L/20**

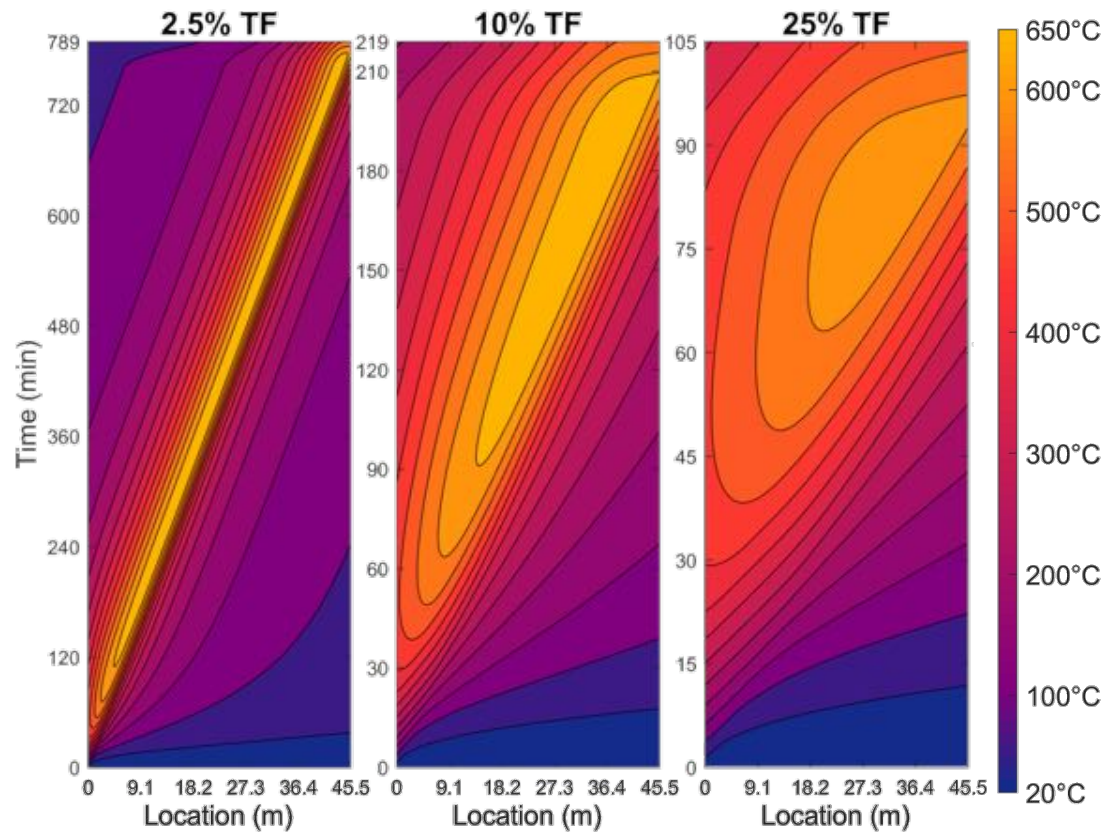
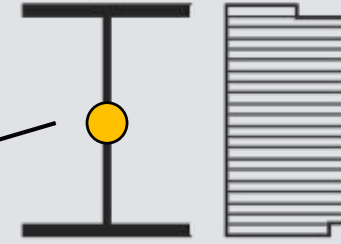
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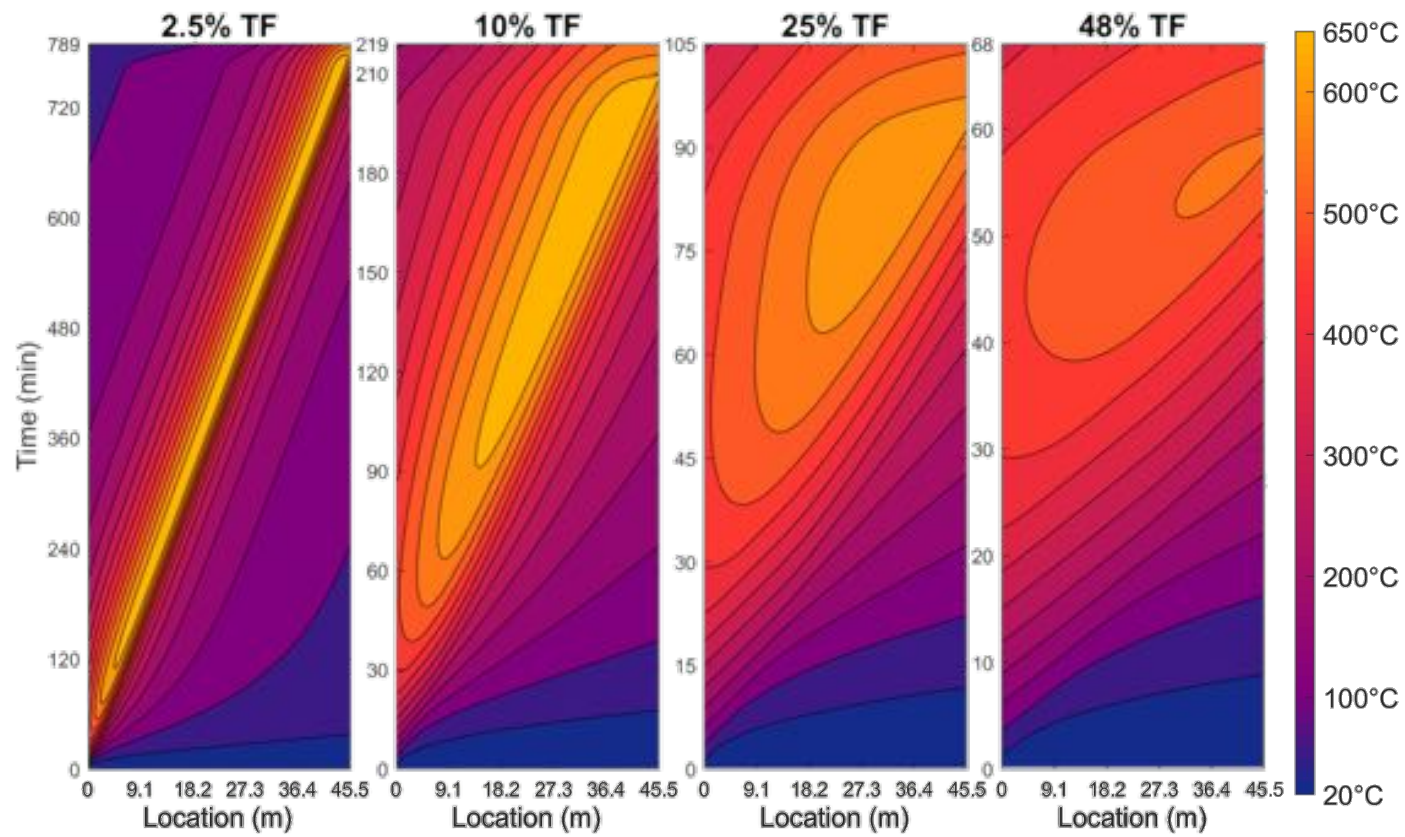
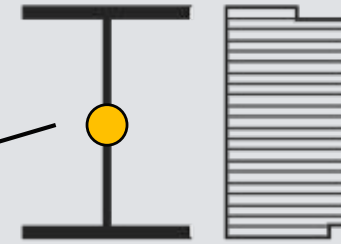
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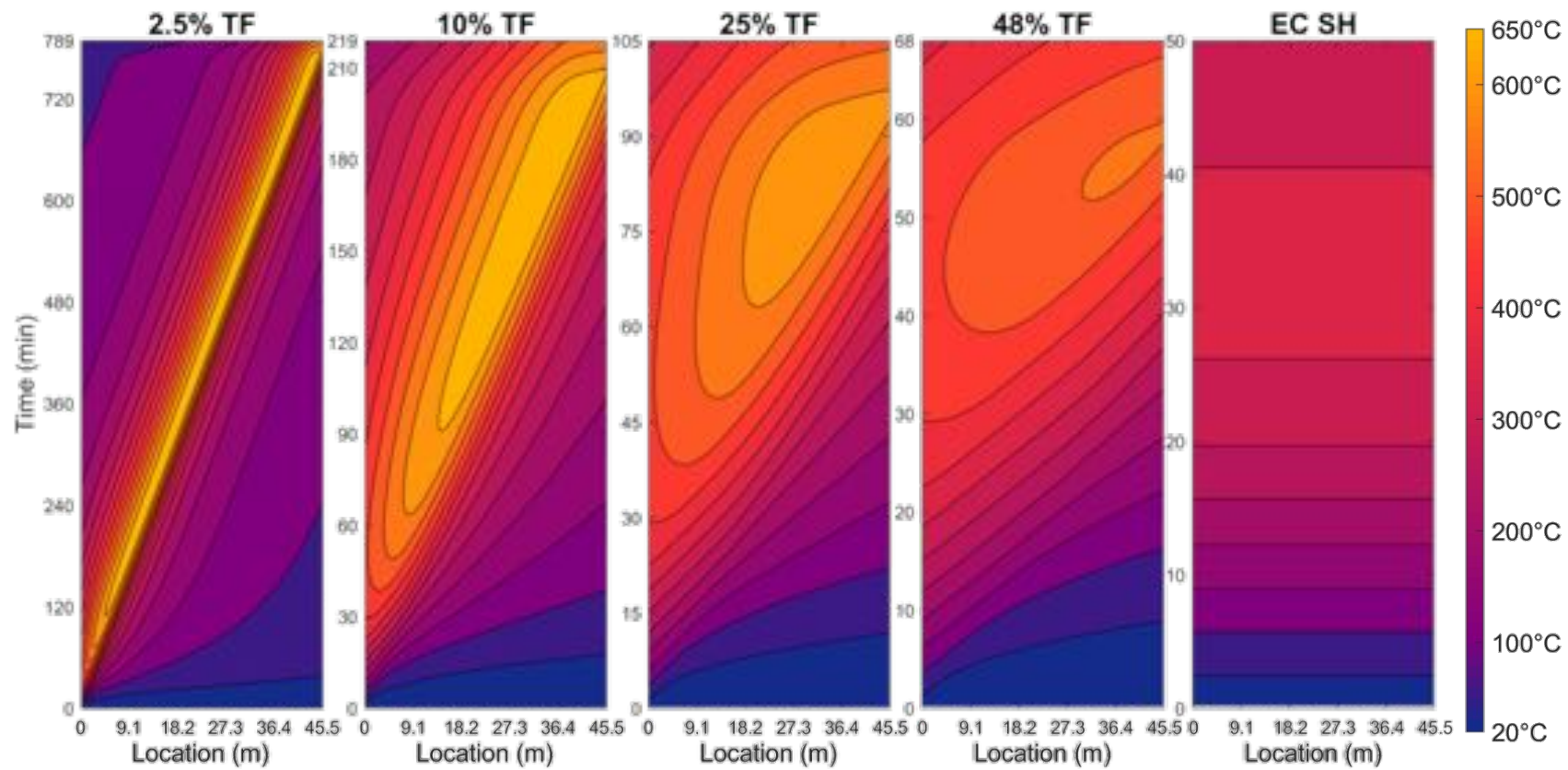
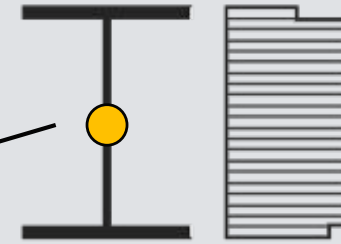
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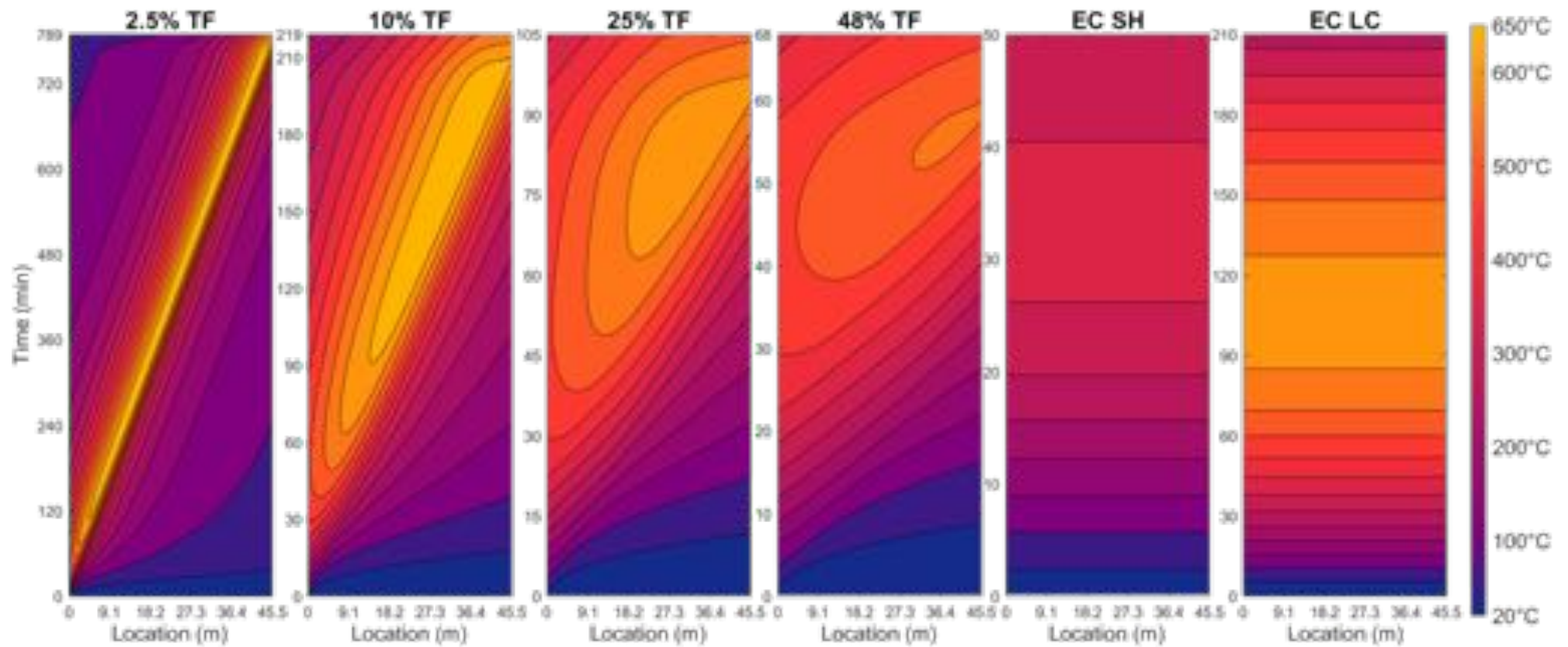
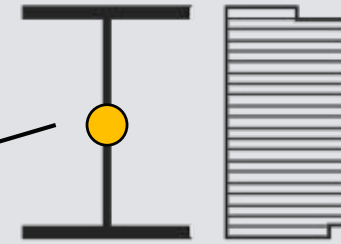
THERMAL RESPONSE



THERMAL RESPONSE



THERMAL RESPONSE



680°C

690°C

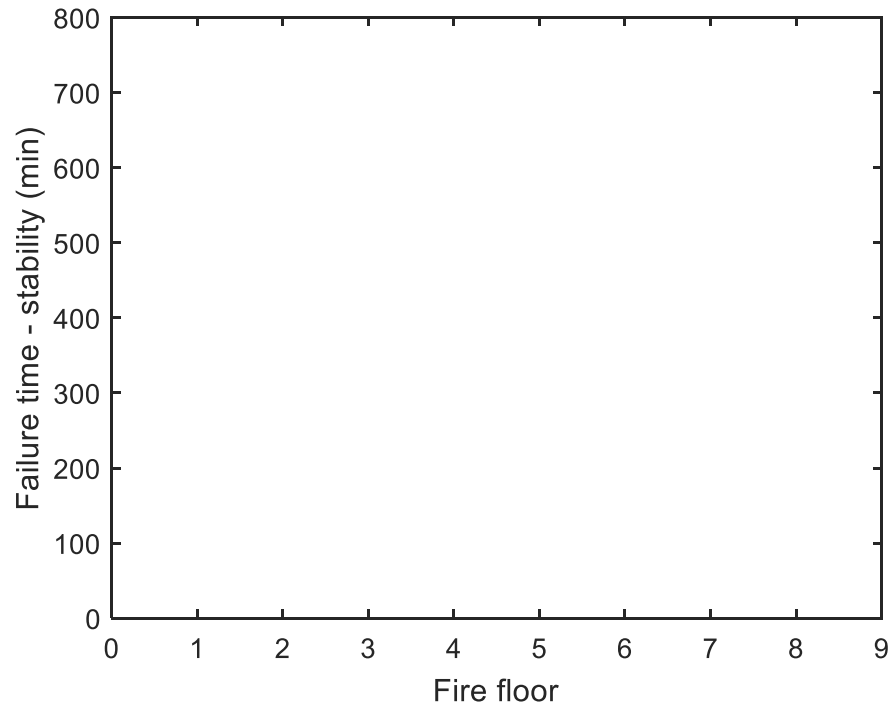
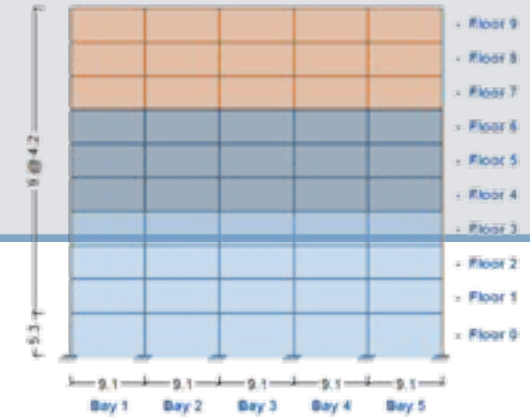
635°C

560°C

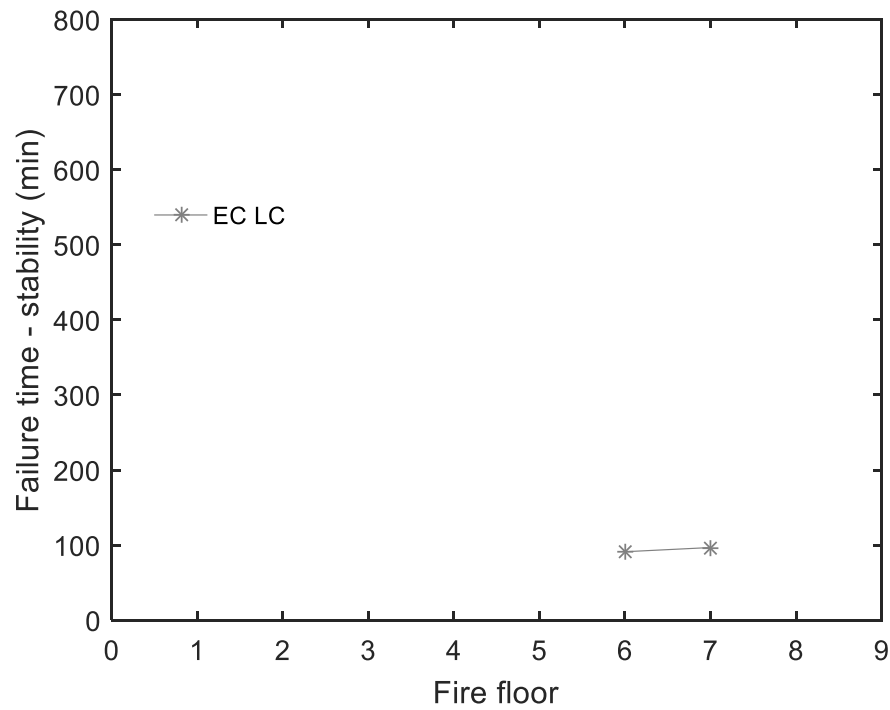
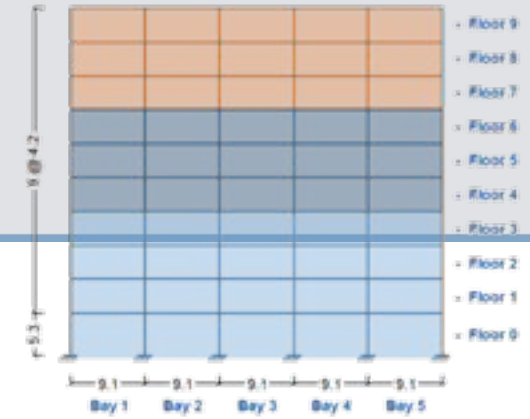
370°C

620°C

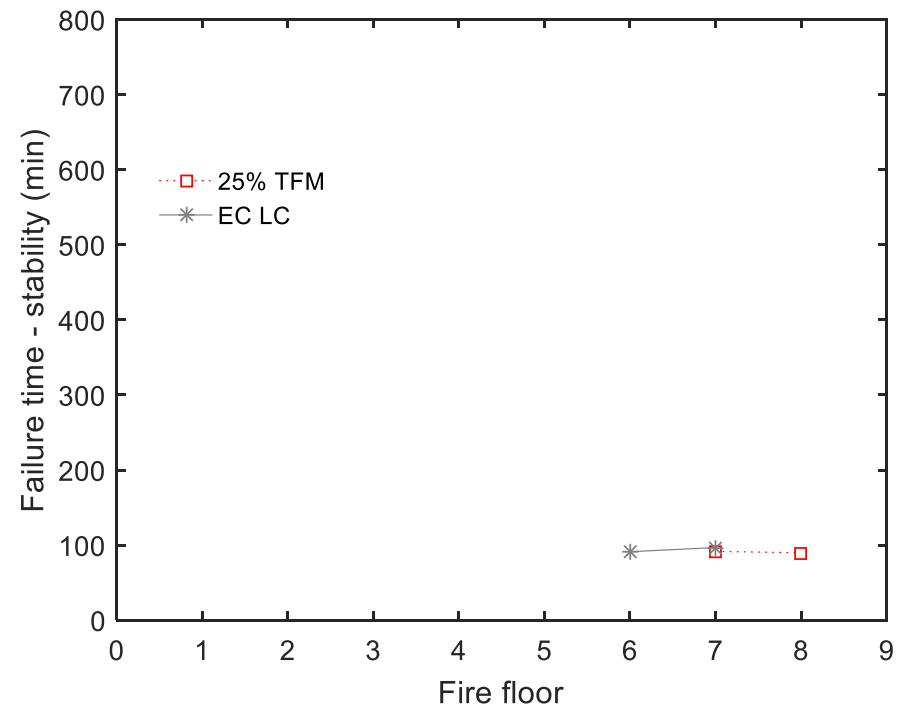
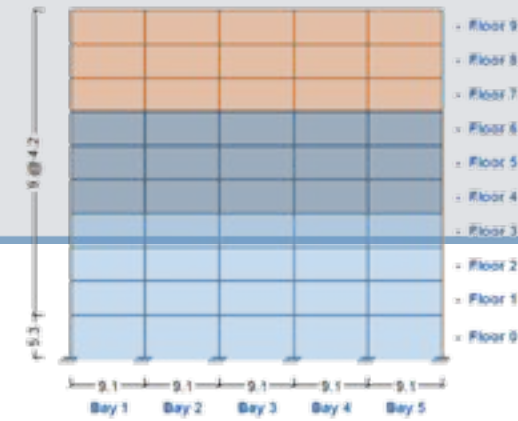
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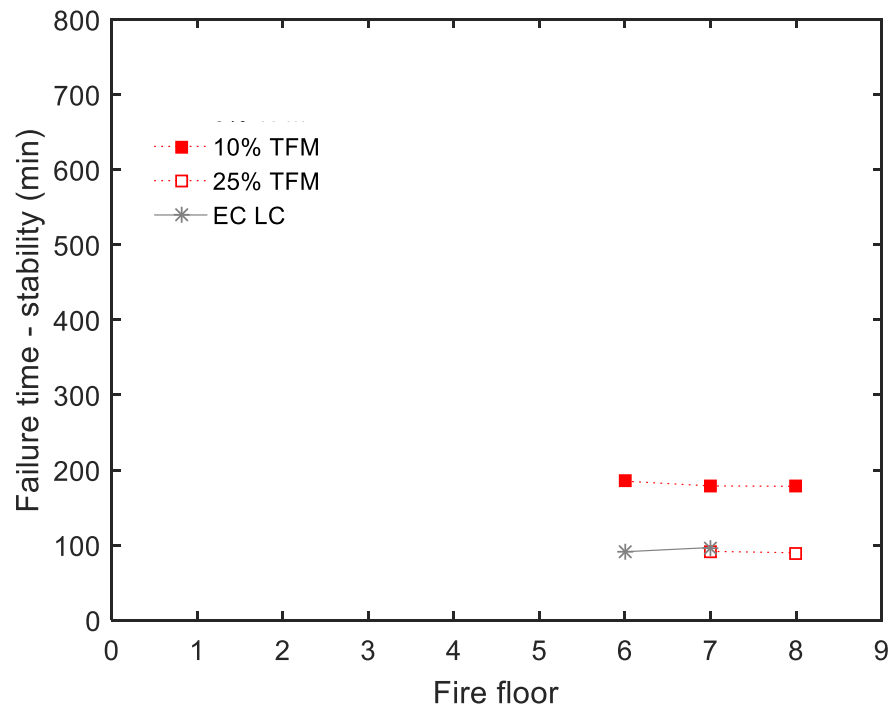
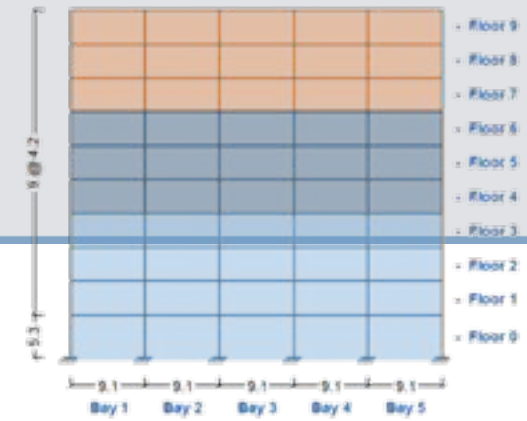
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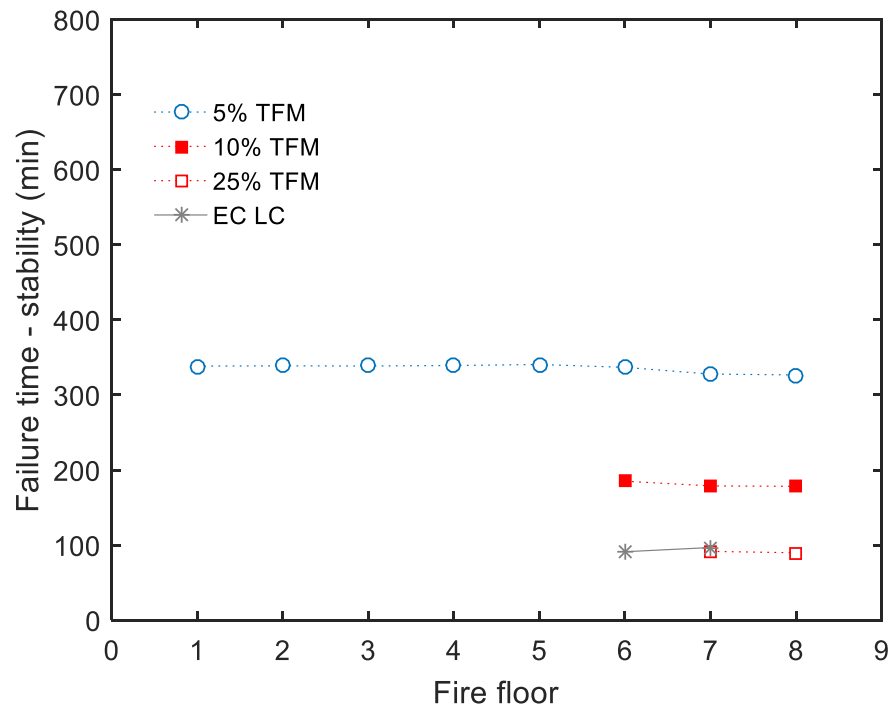
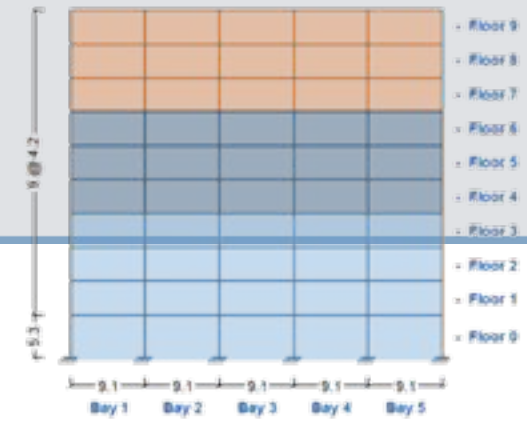
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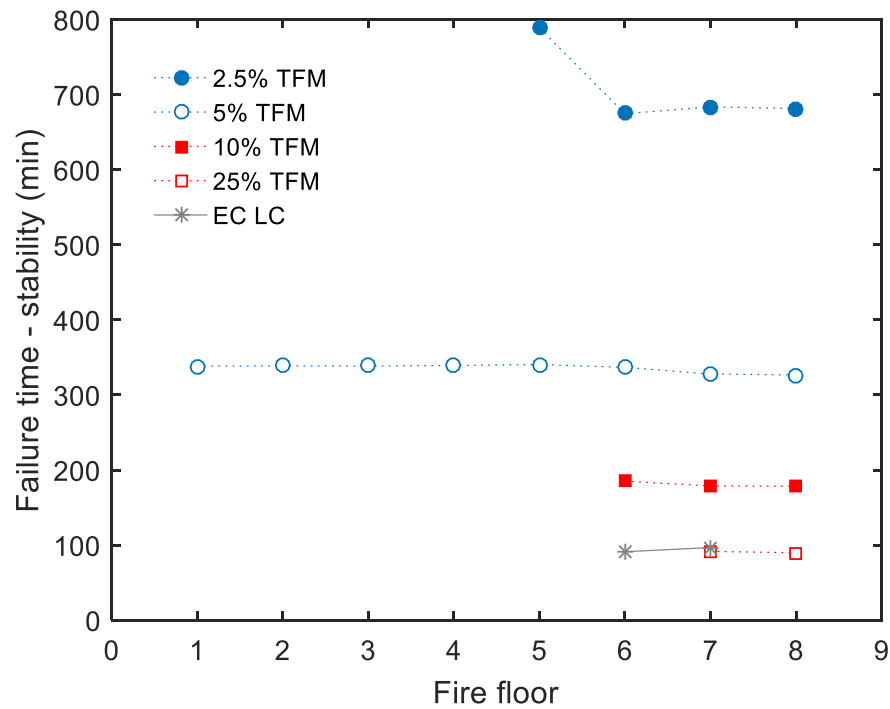
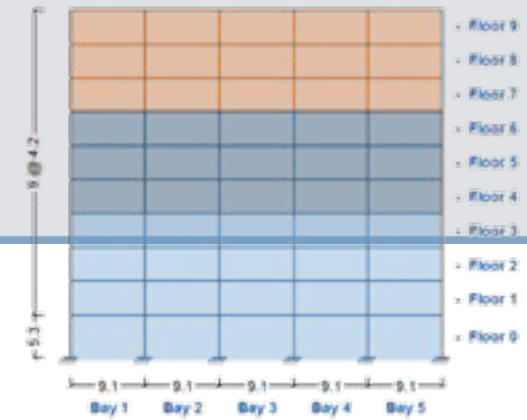
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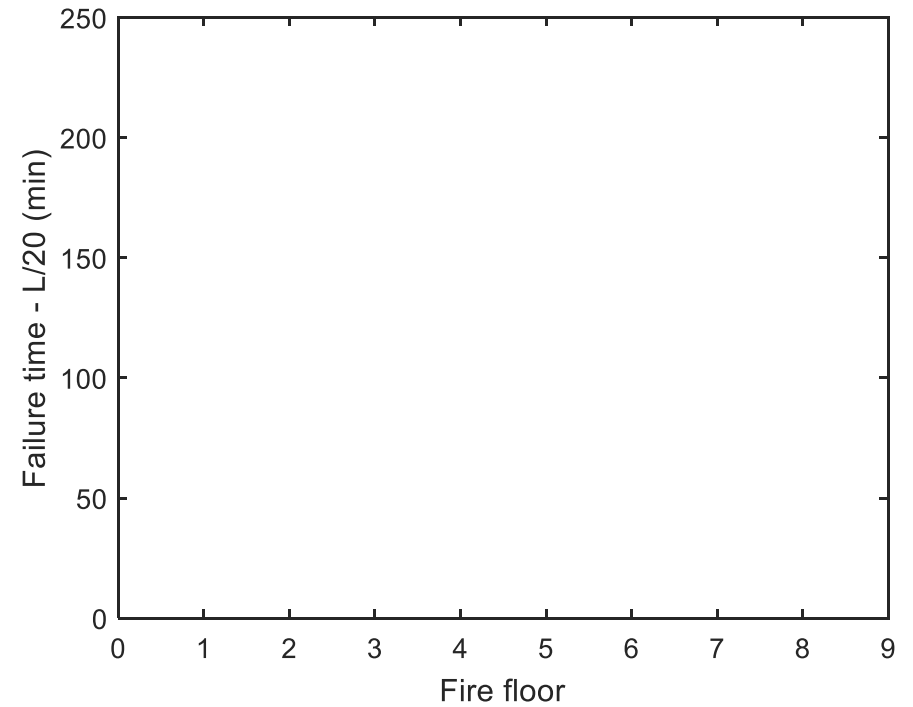
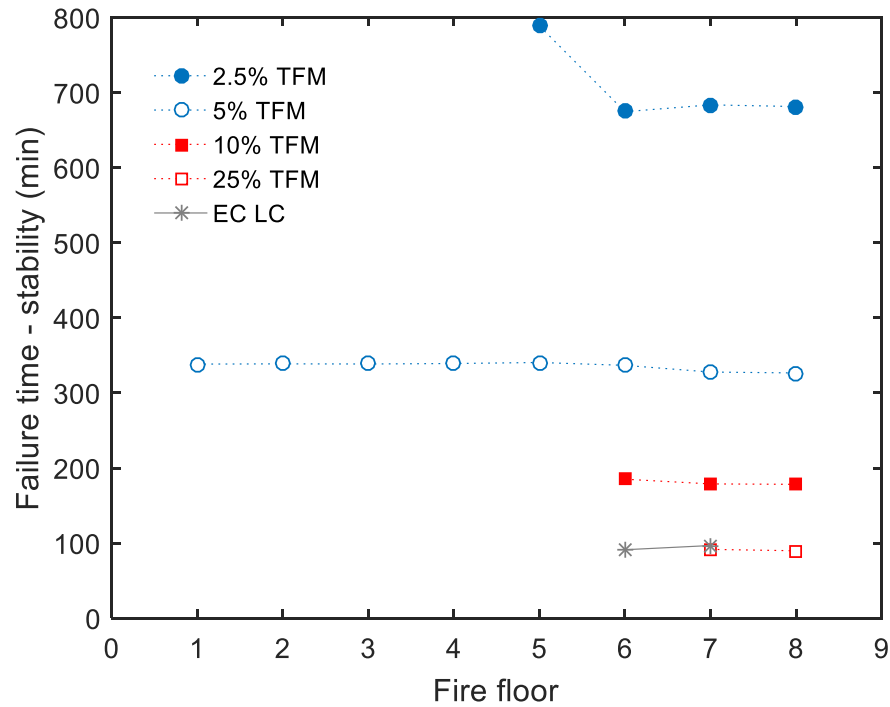
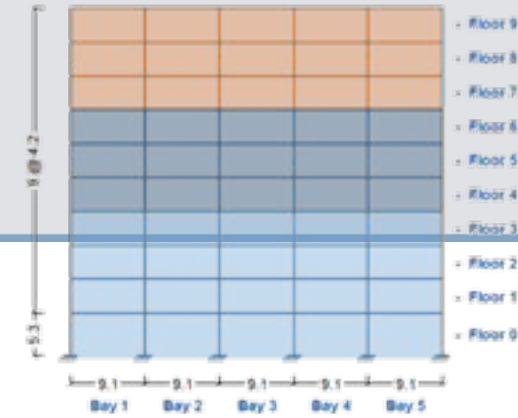
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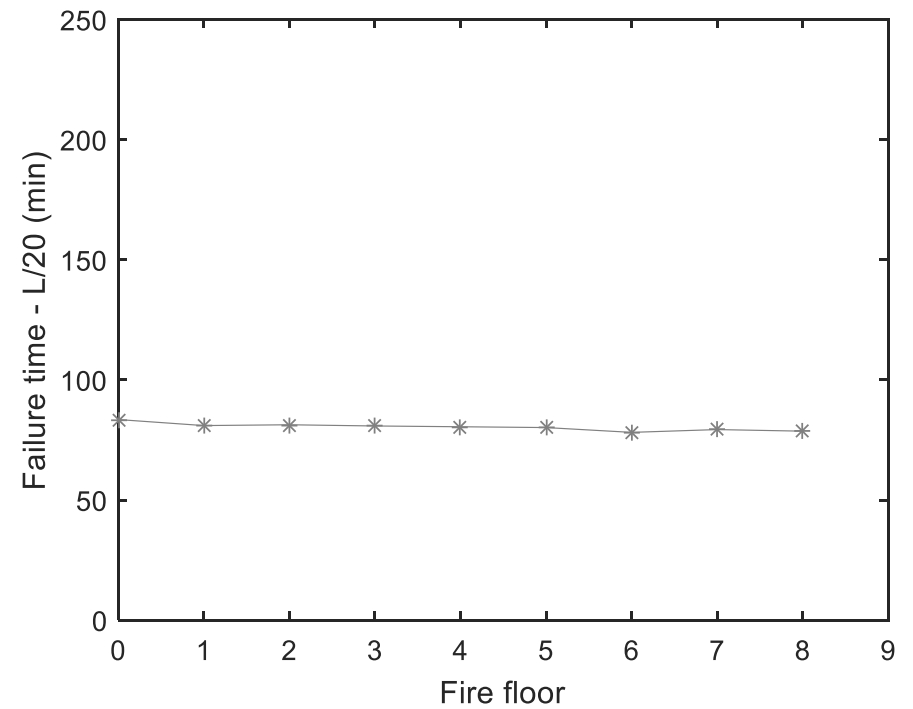
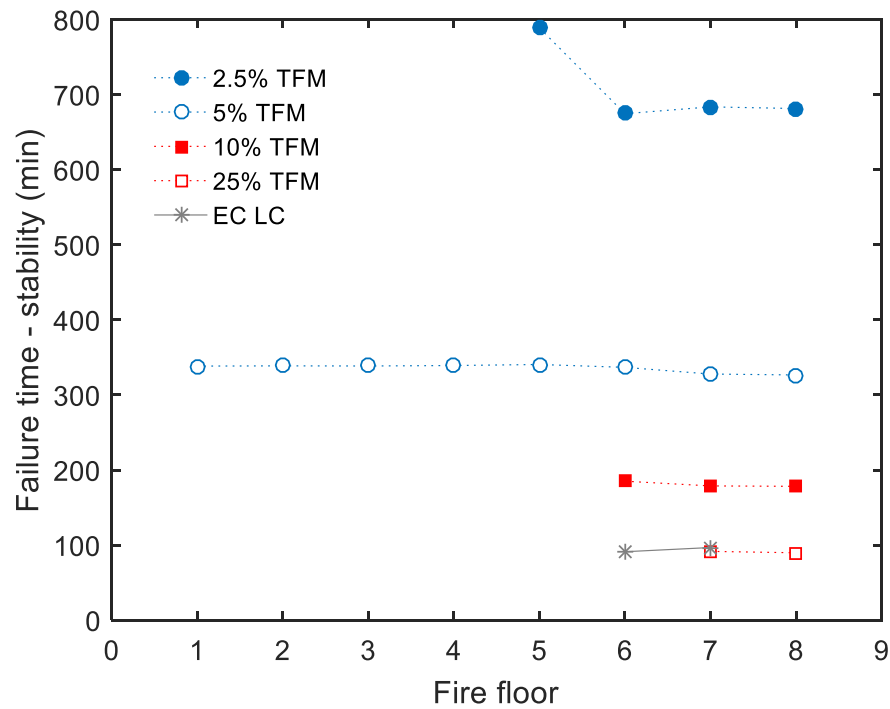
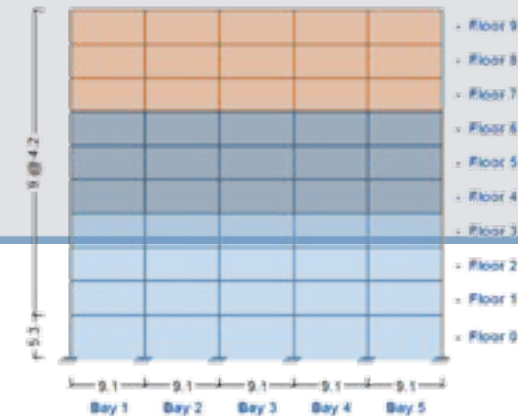
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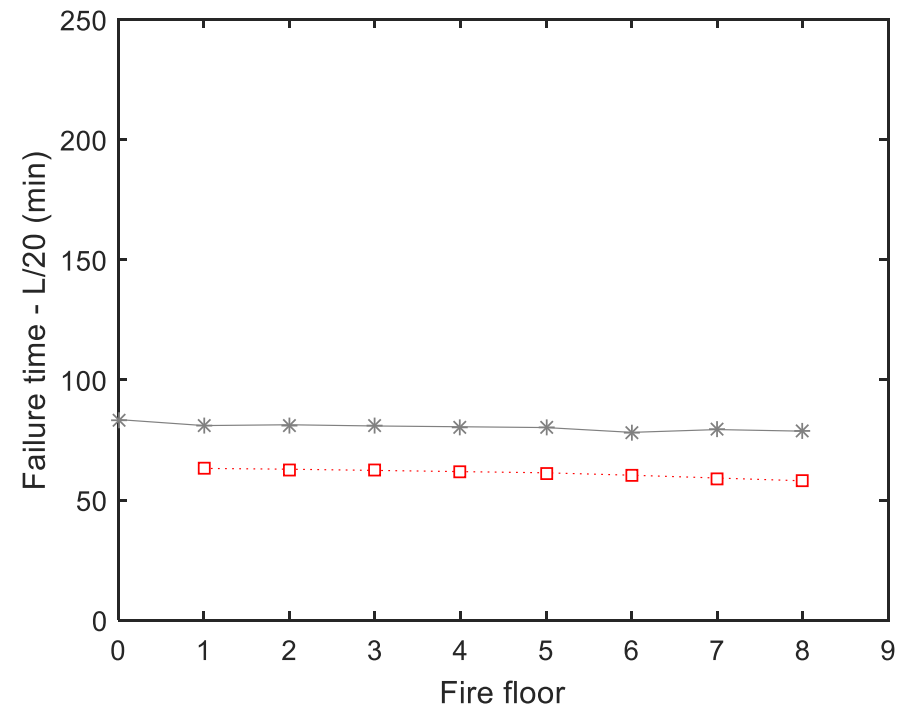
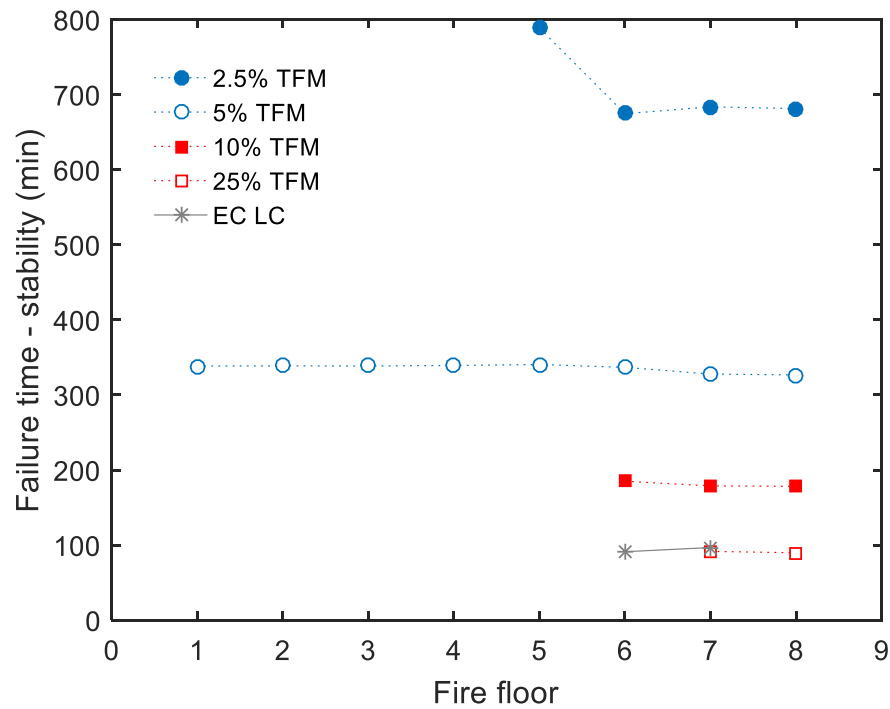
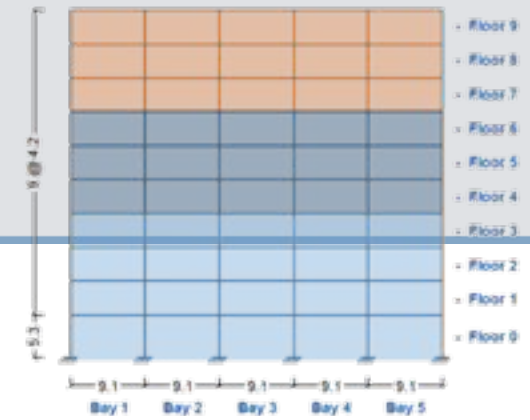
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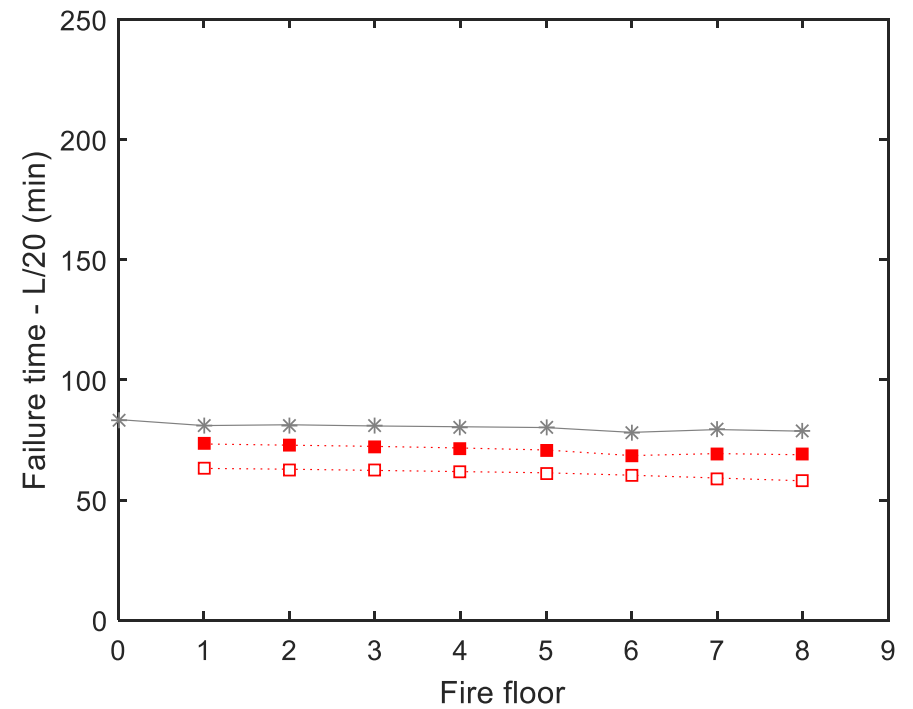
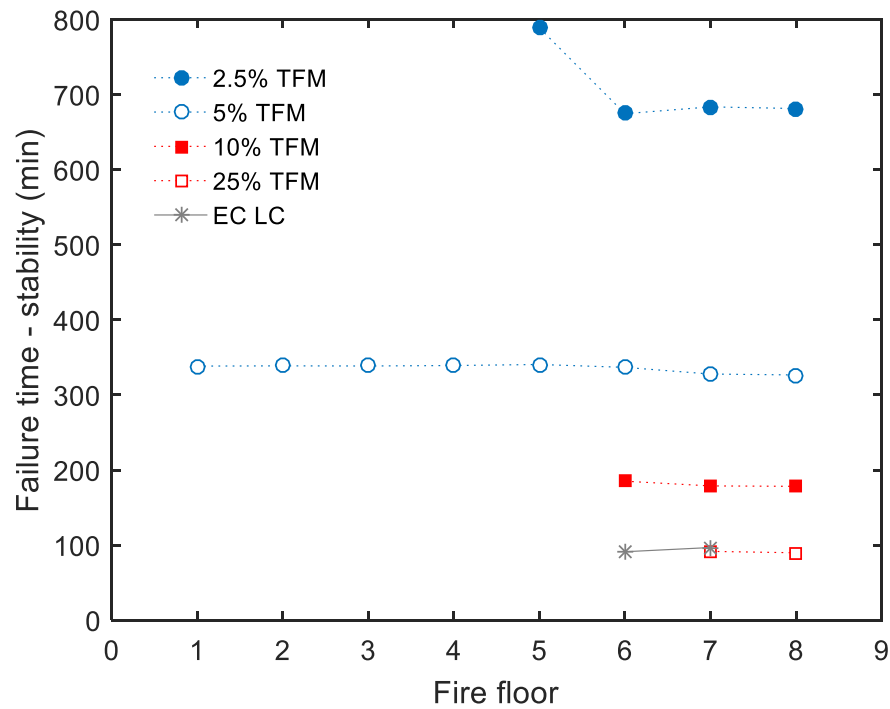
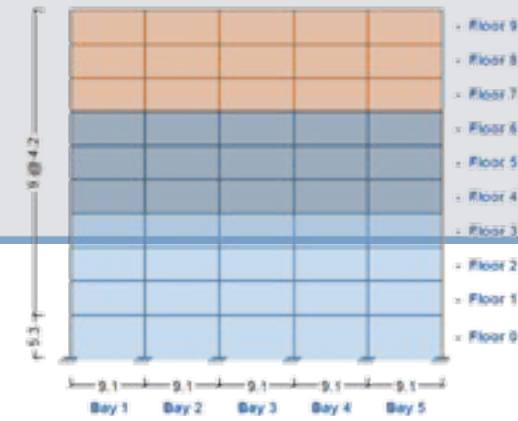
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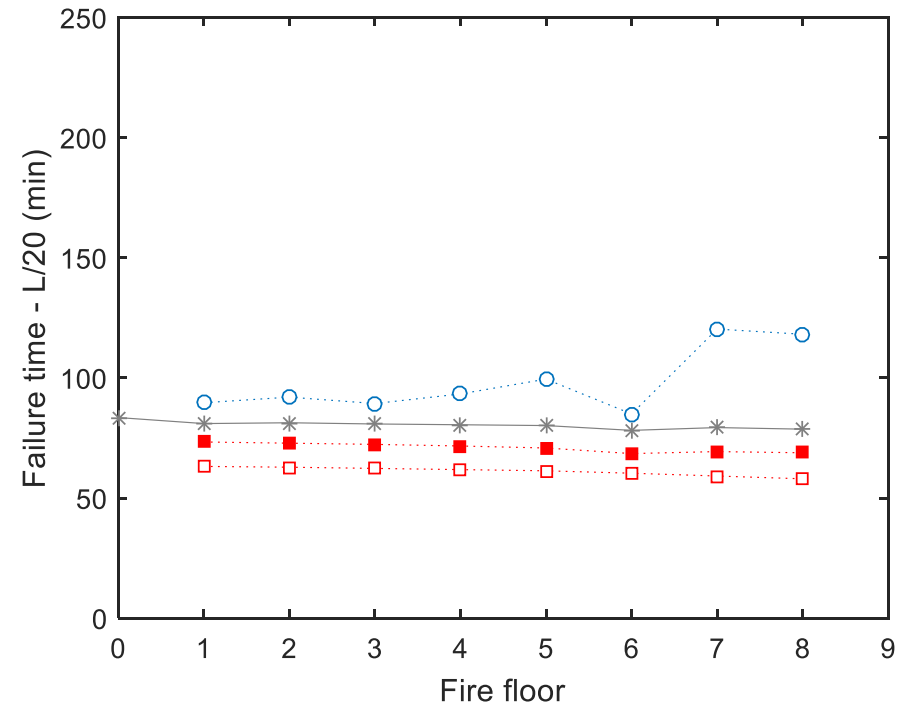
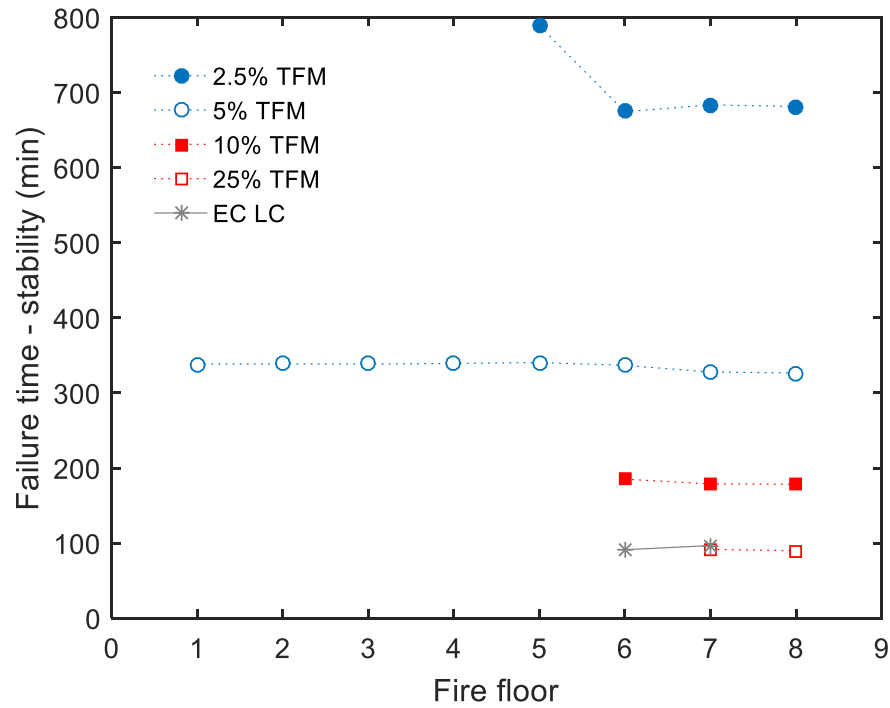
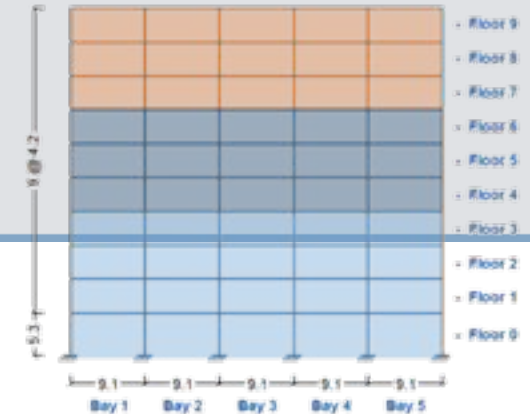
STRUCTURAL FAILURE



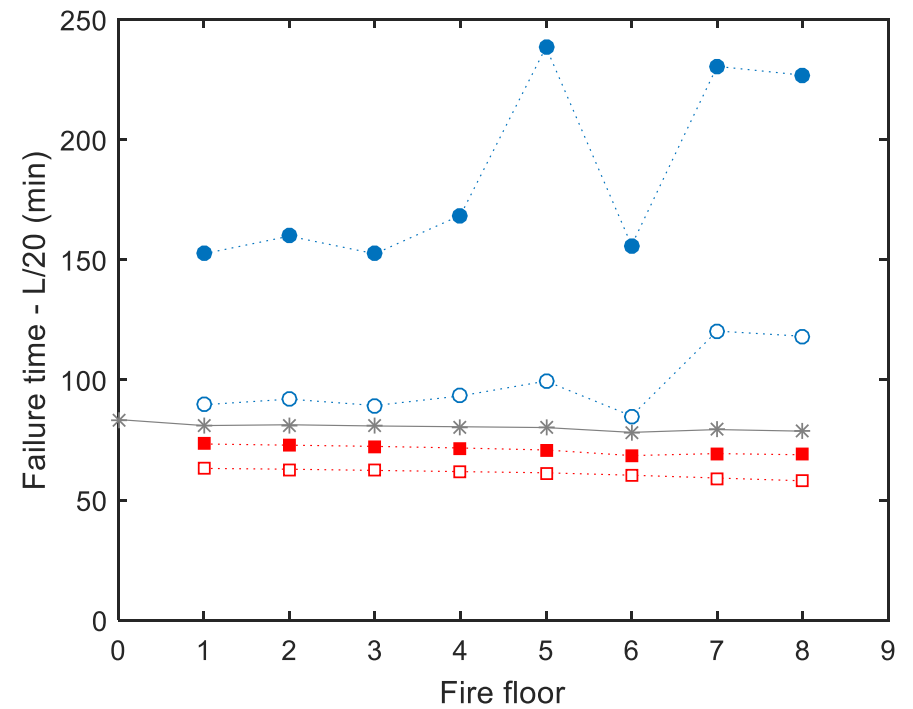
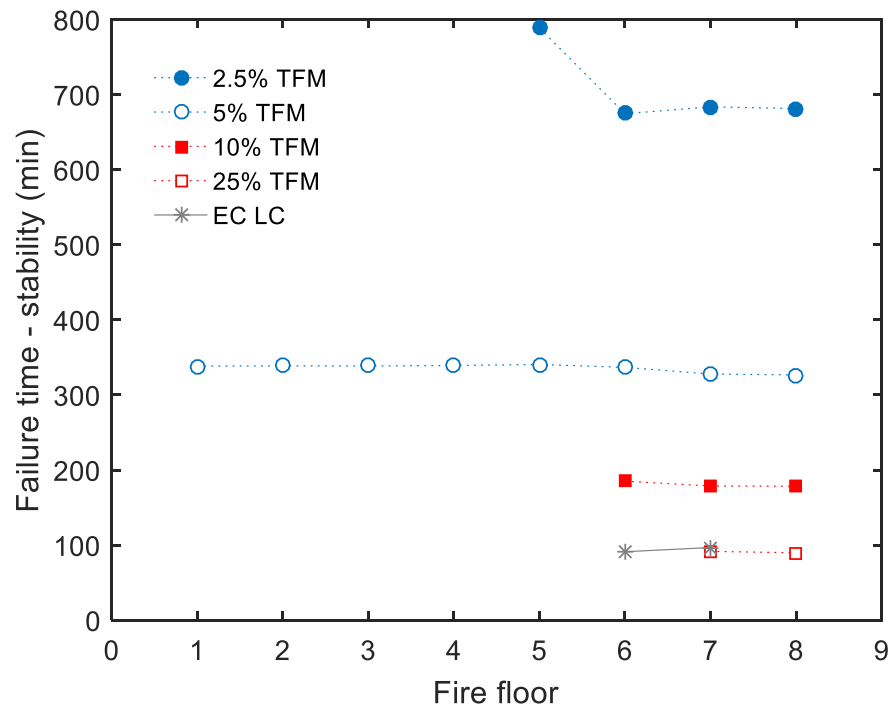
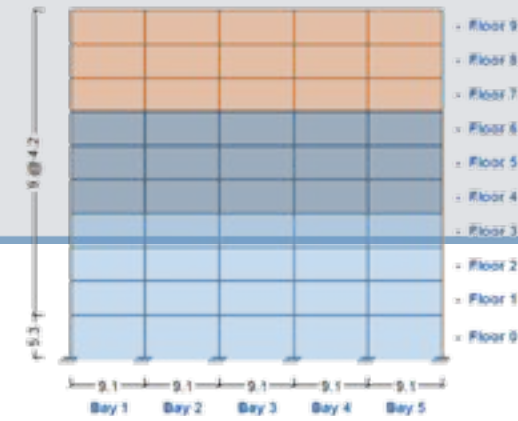
STRUCTURAL FAILURE



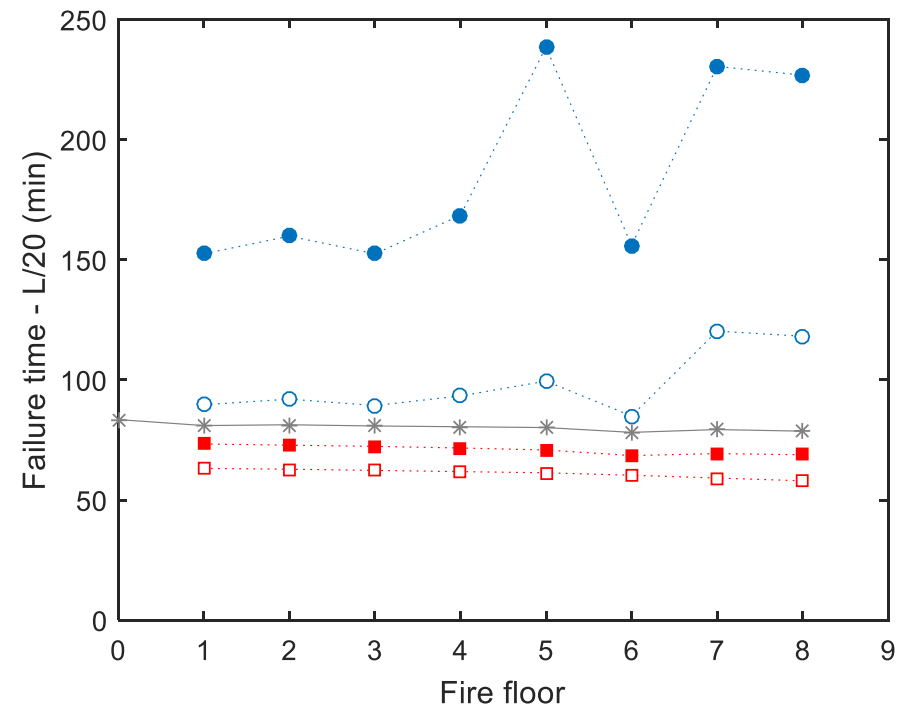
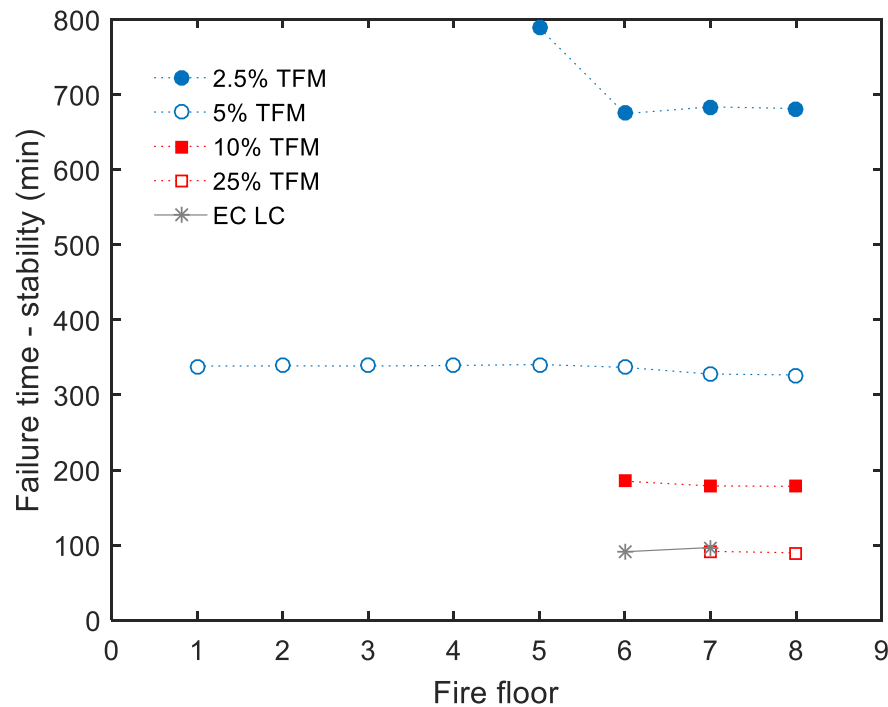
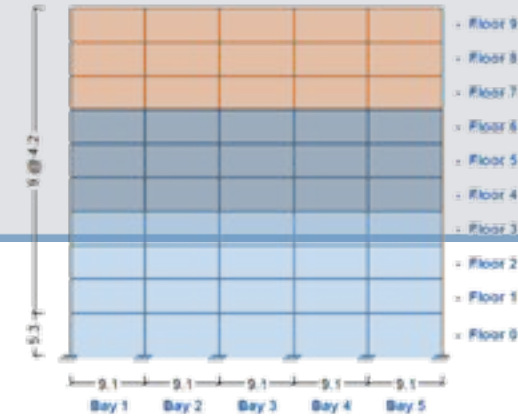
STRUCTURAL FAILURE



STRUCTURAL FAILURE

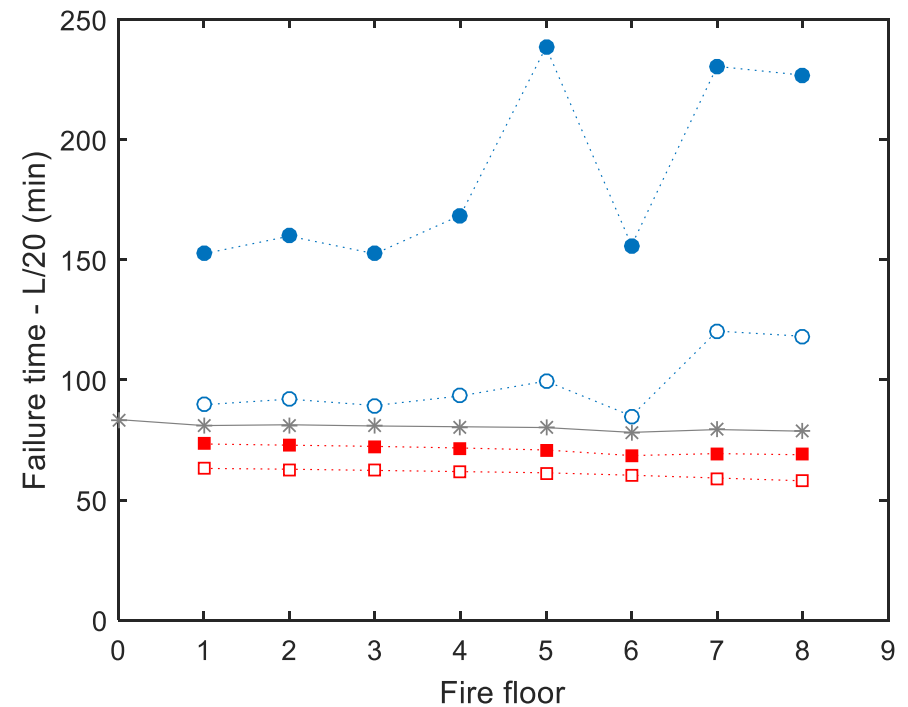
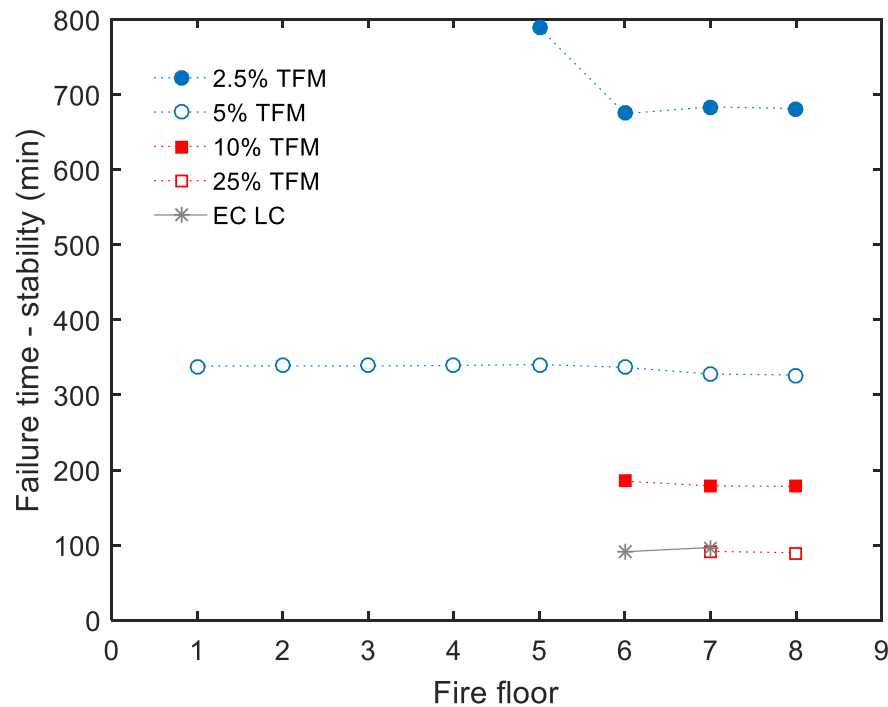
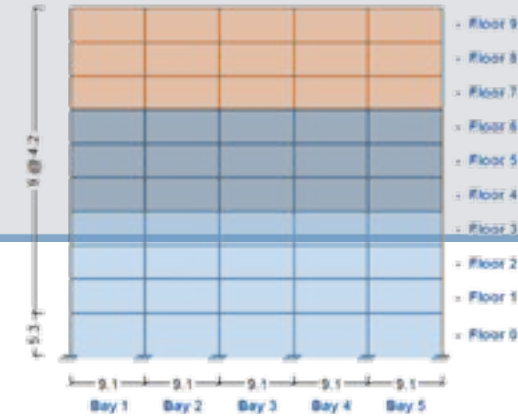


STRUCTURAL FAILURE



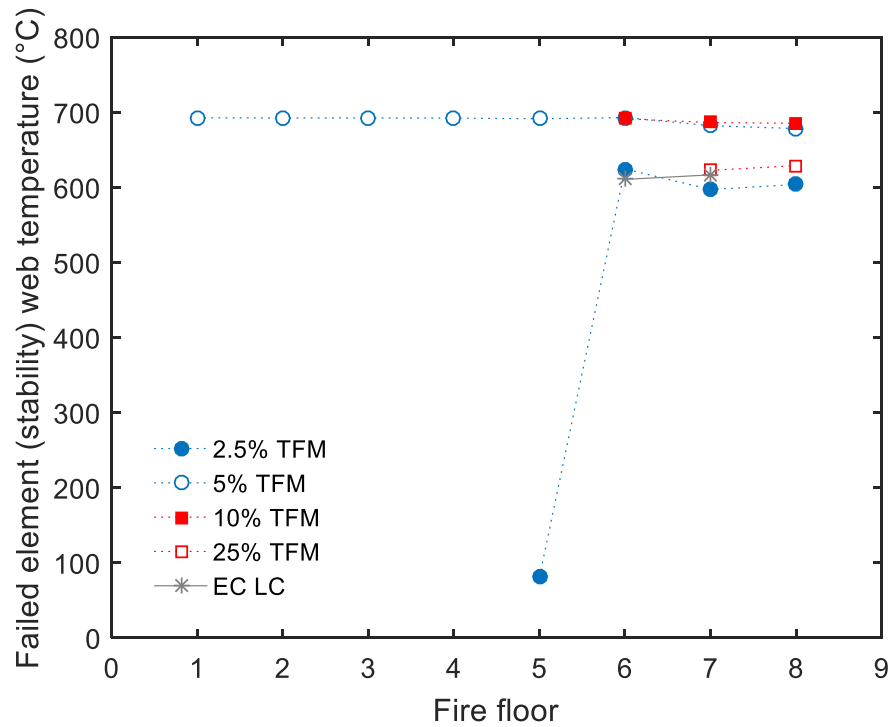
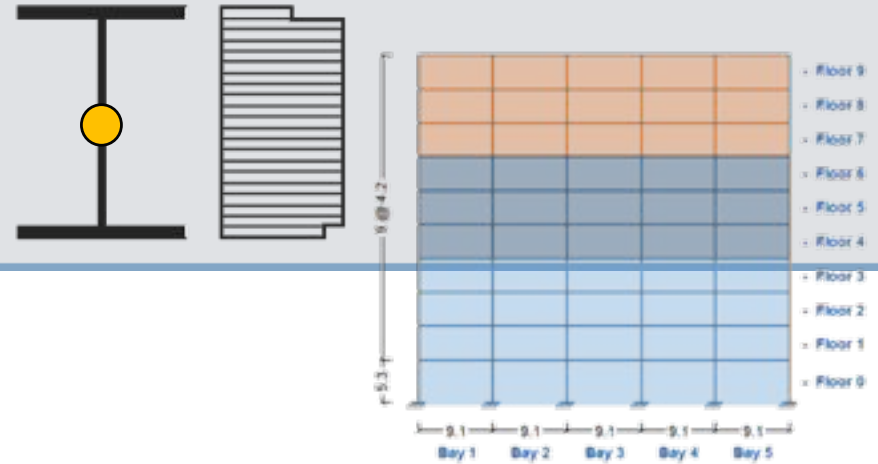
- There is no single fire scenario which would represent the worst case

STRUCTURAL FAILURE



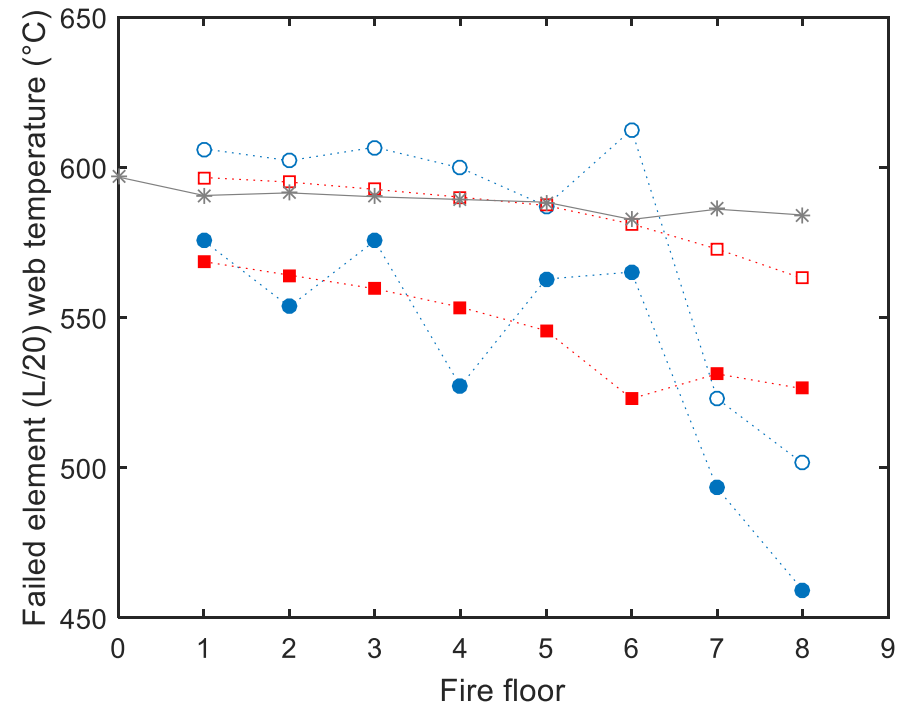
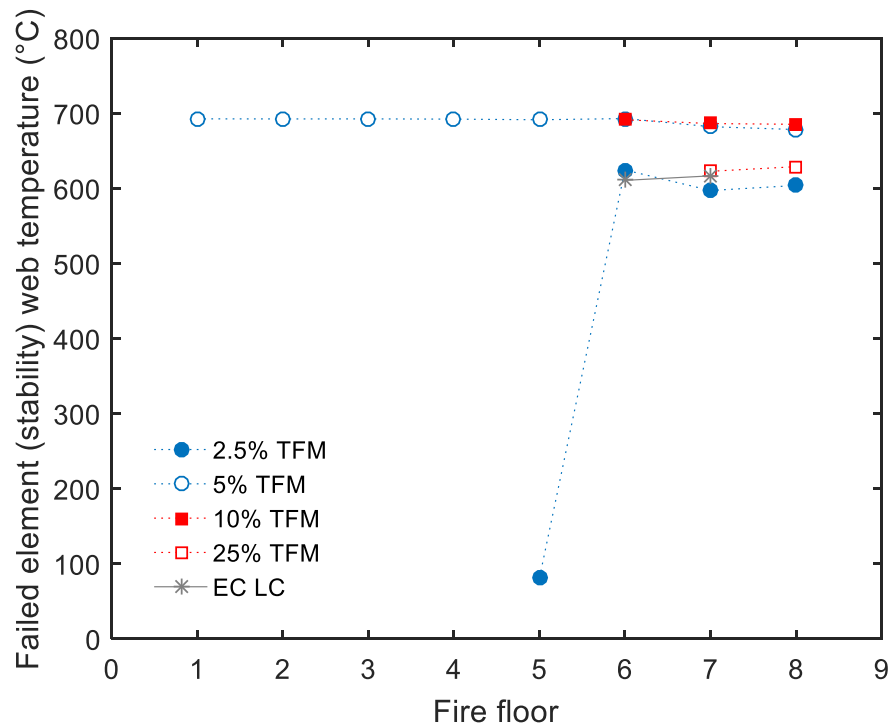
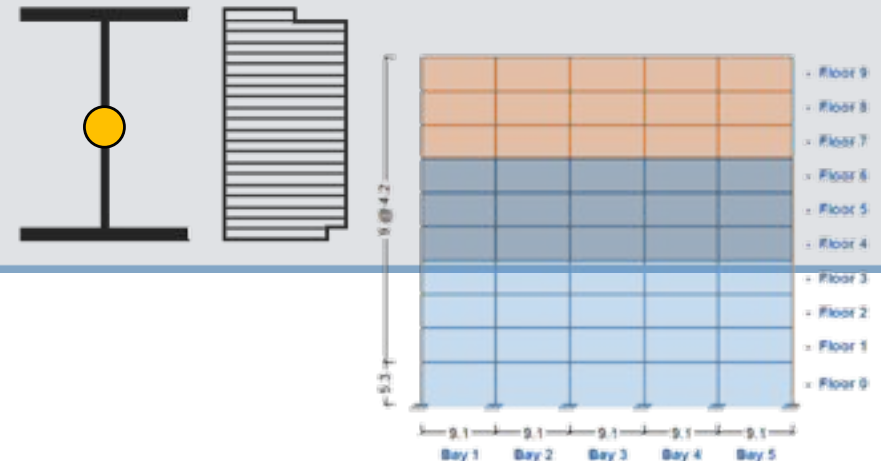
- There is no single fire scenario which would represent the worst case
- For different fire exposure failure occurs on different floors

WEB TEMPERATURE AT FAILURE



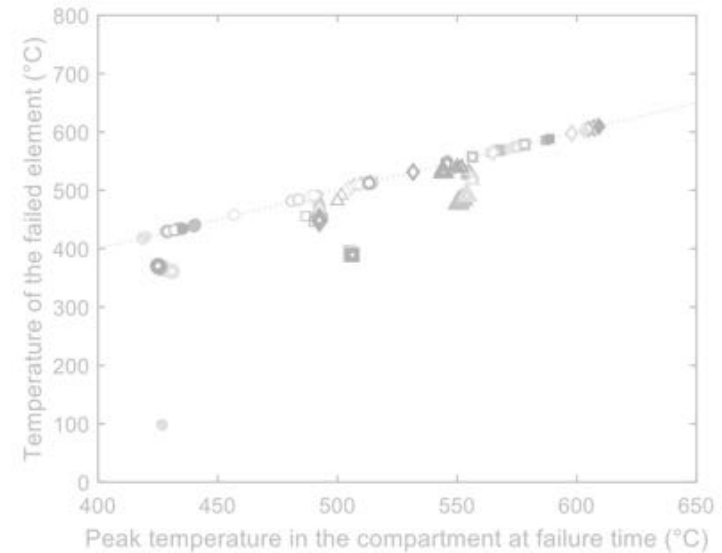
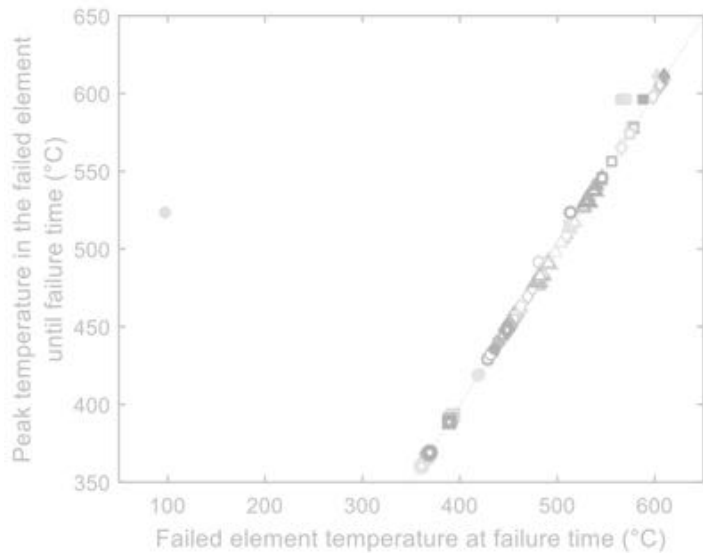
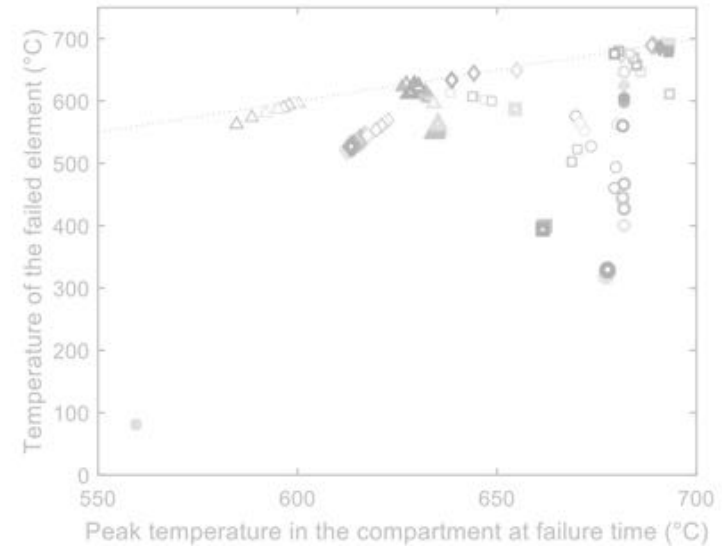
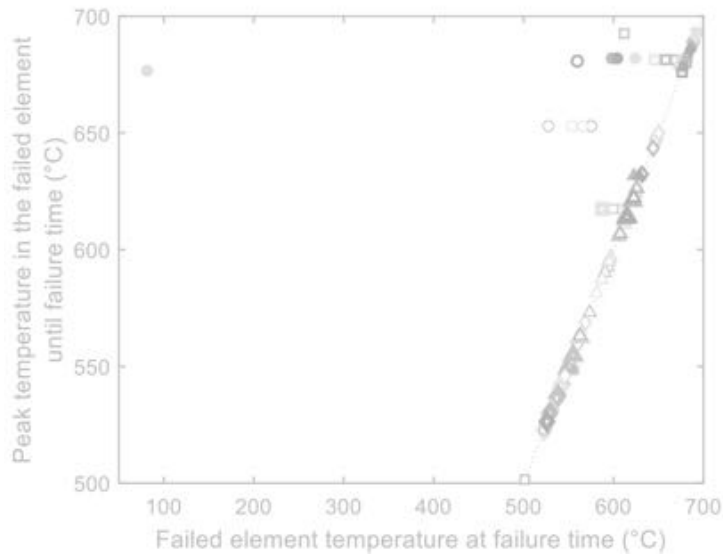
- Stability criterion - 600–740°C

WEB TEMPERATURE AT FAILURE



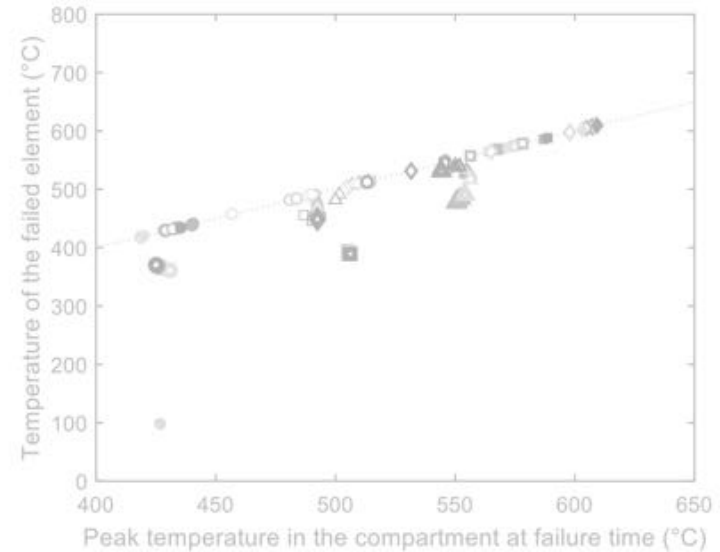
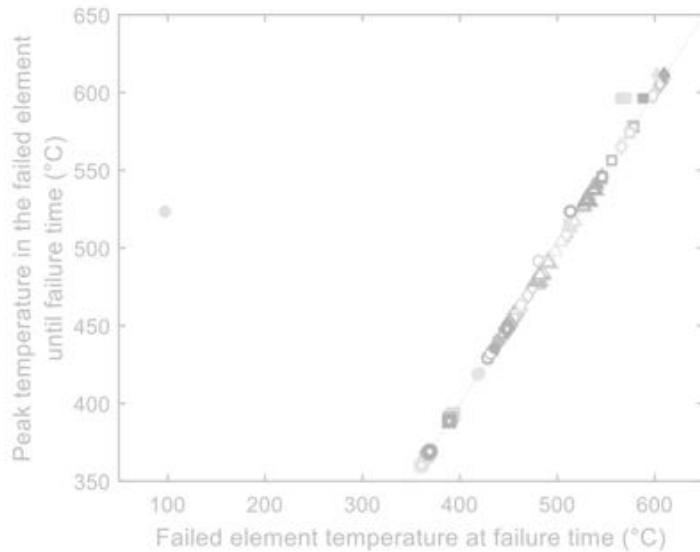
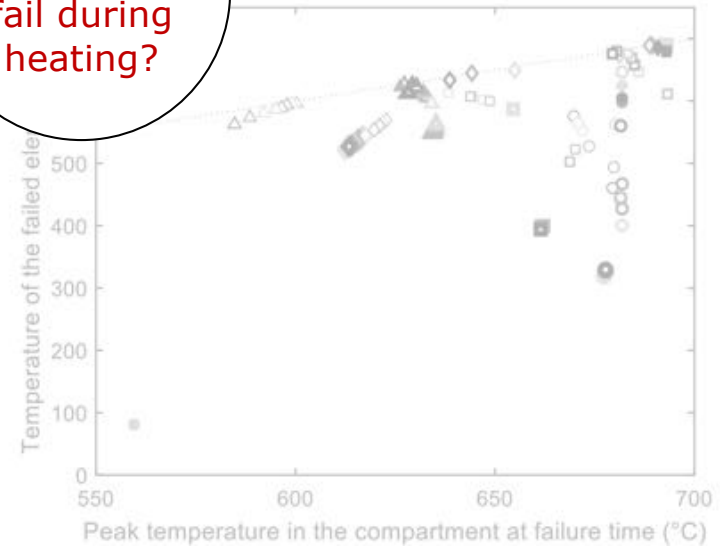
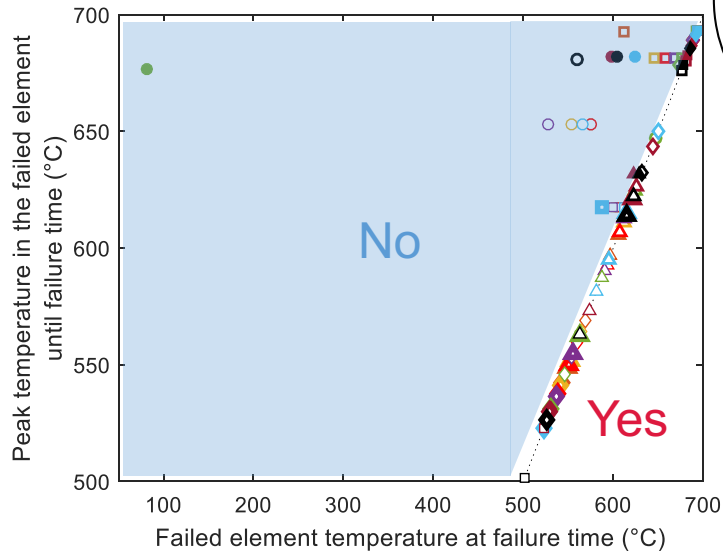
- Stability criterion - 600–740°C
- Deflection criterion - 450–620°C

FAILURE TEMPERATURE



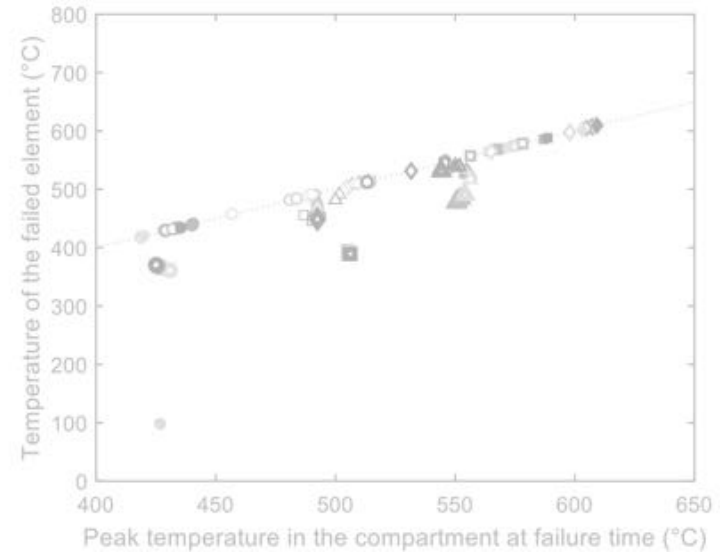
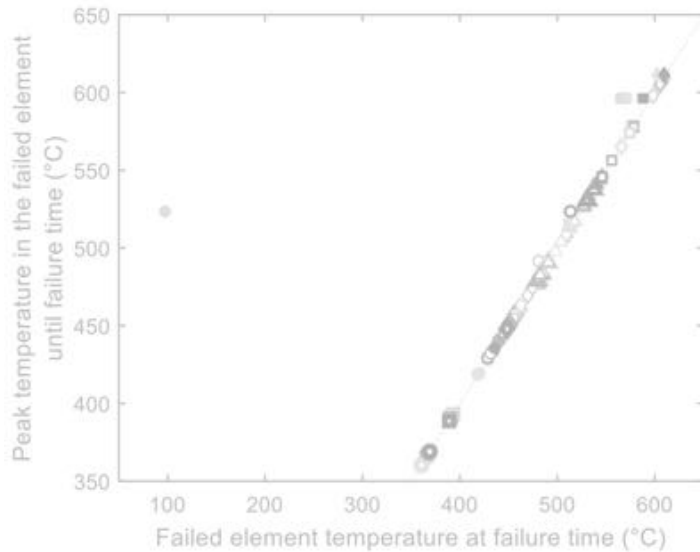
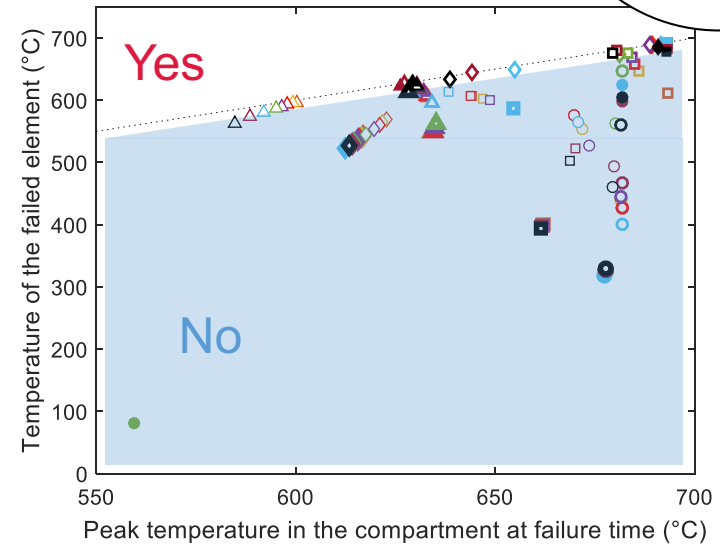
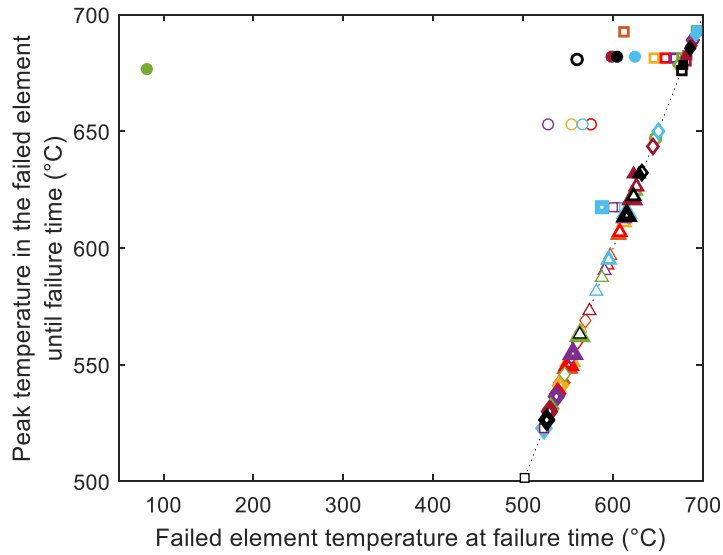
FAILURE TEMPERATURE

Does the element fail during heating?



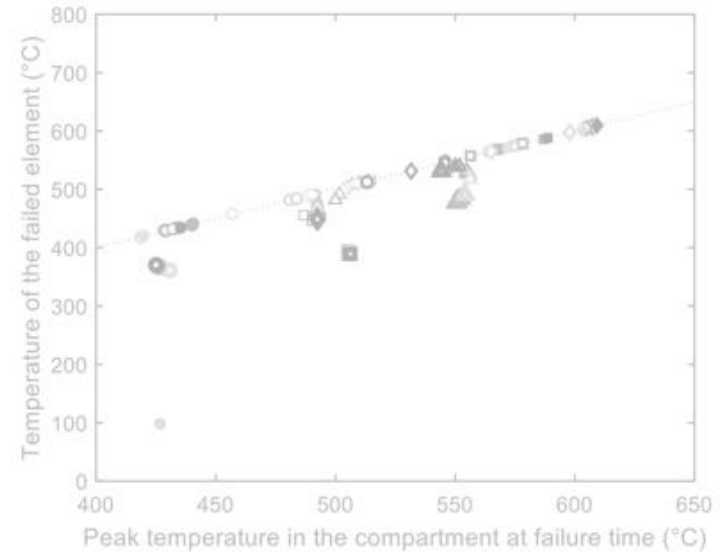
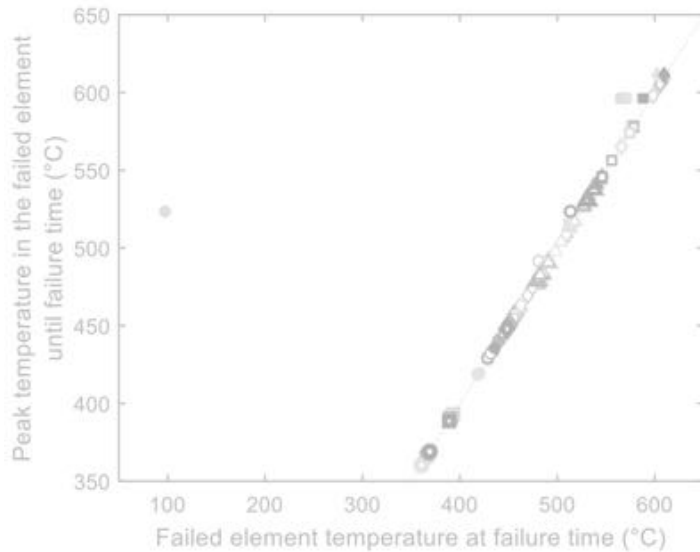
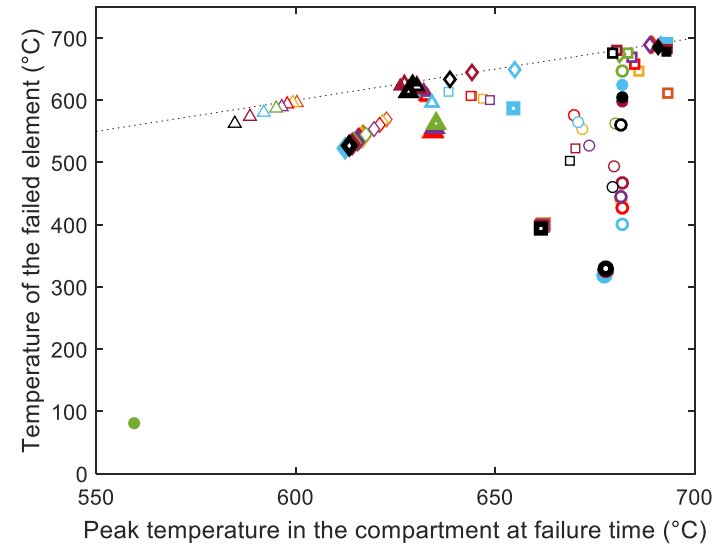
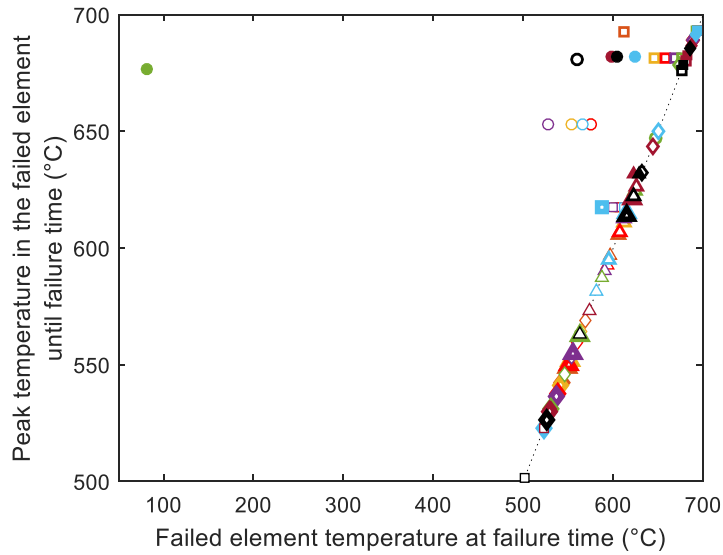
FAILURE TEMPERATURE

Is element at
the location
of peak
temperature?



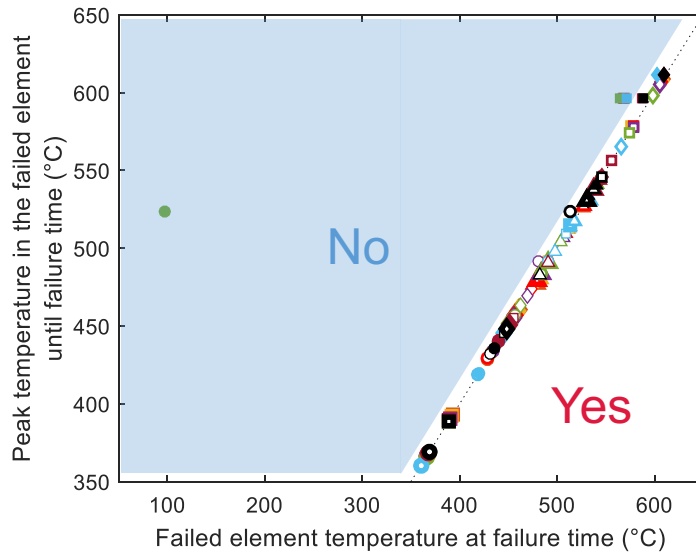
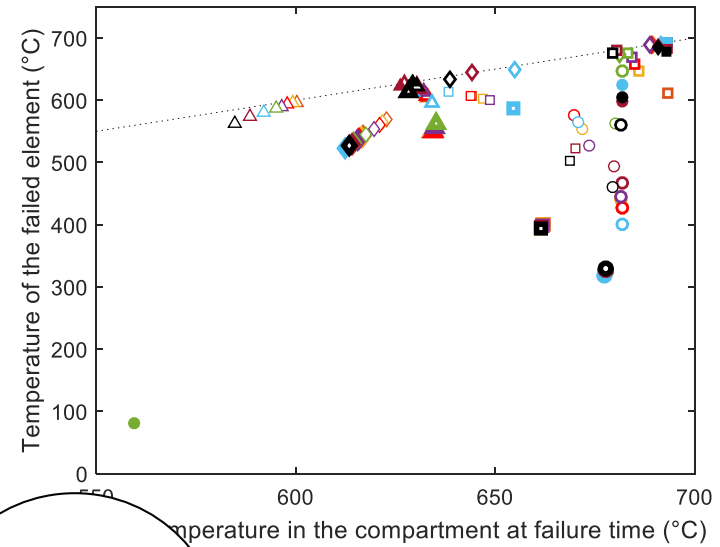
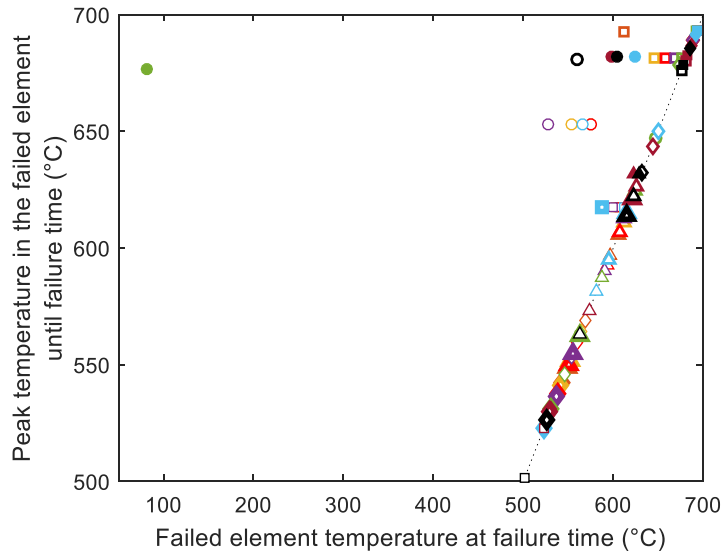
FAILURE TEMPERATURE

Average Bay temperatures

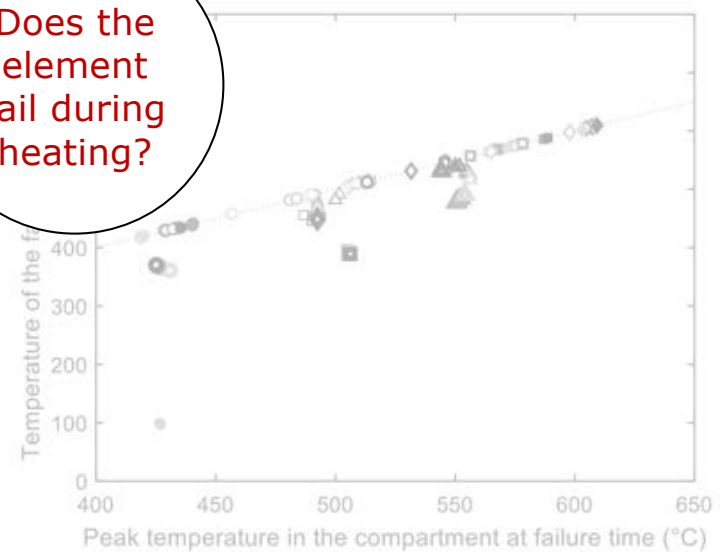


FAILURE TEMPERATURE

Average Bay temperatures

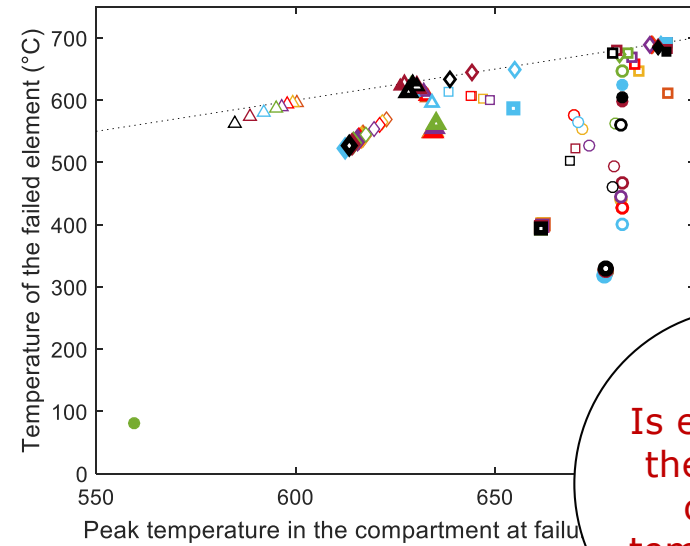
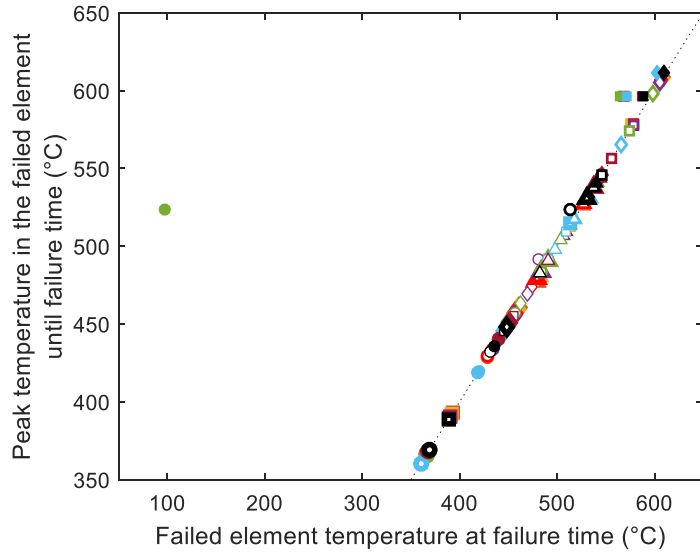
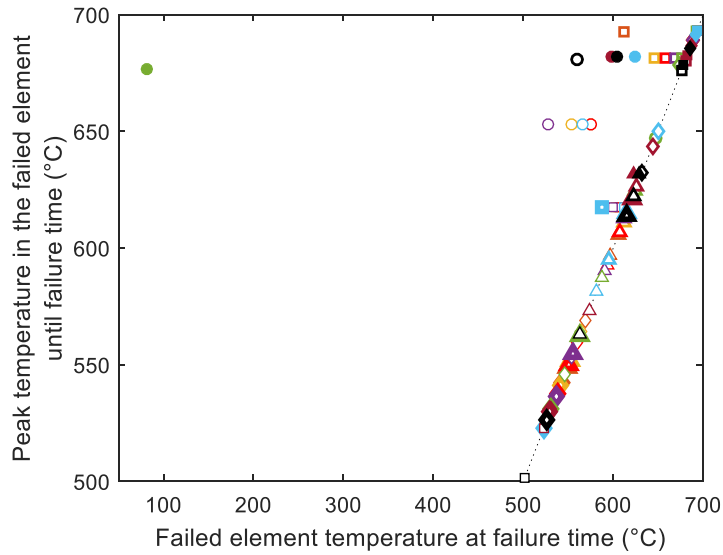


Does the element fail during heating?

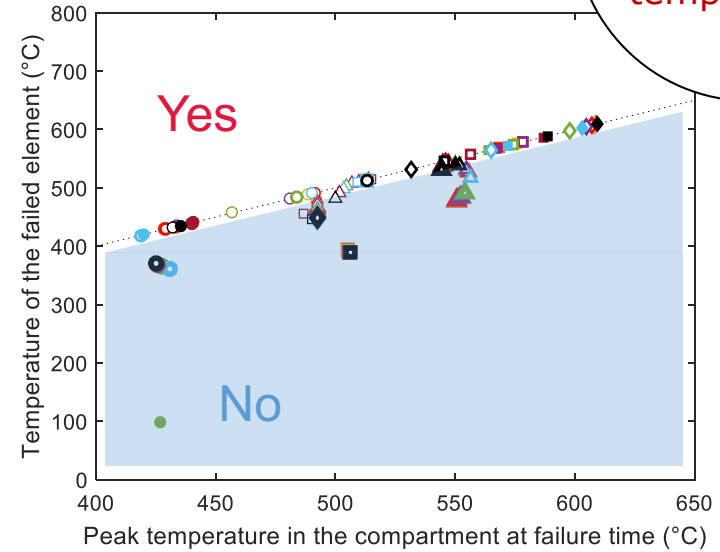


FAILURE TEMPERATURE

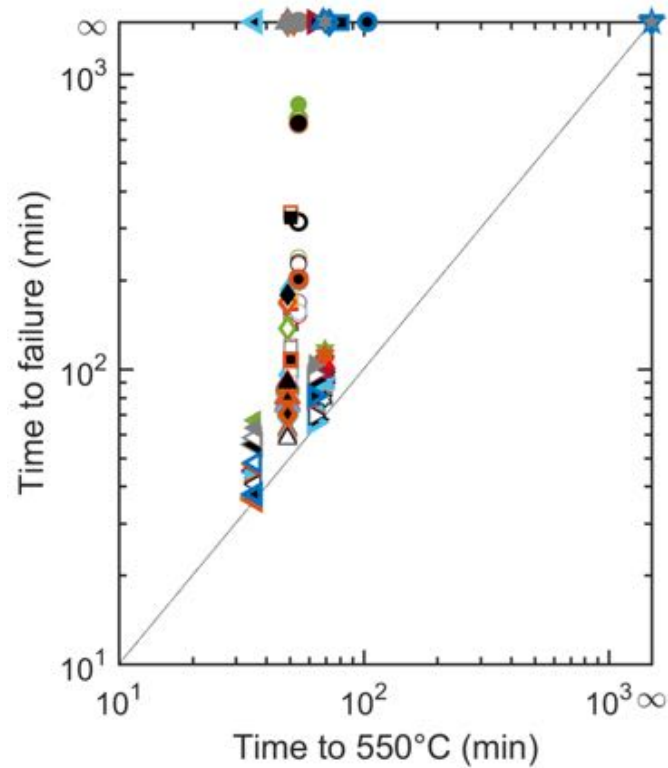
Average Bay temperatures



Is element at the location of peak temperature?

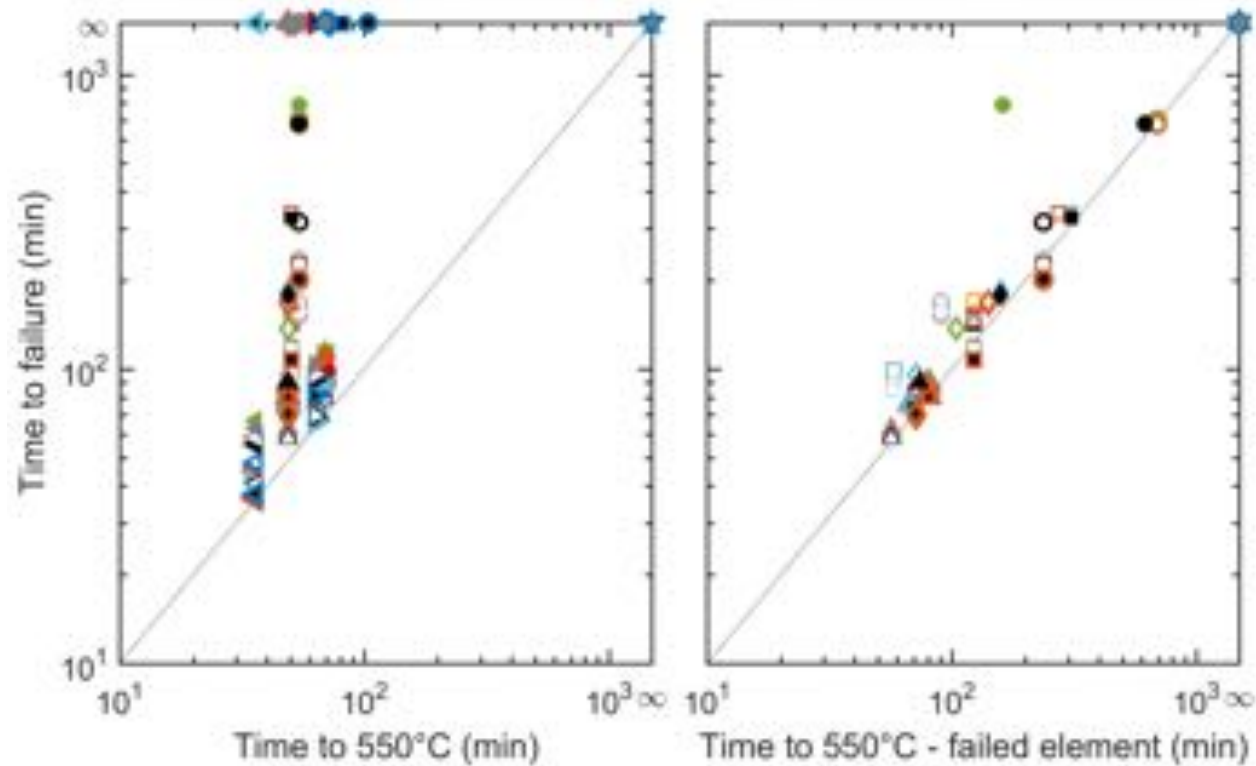


TIME TO FAILURE



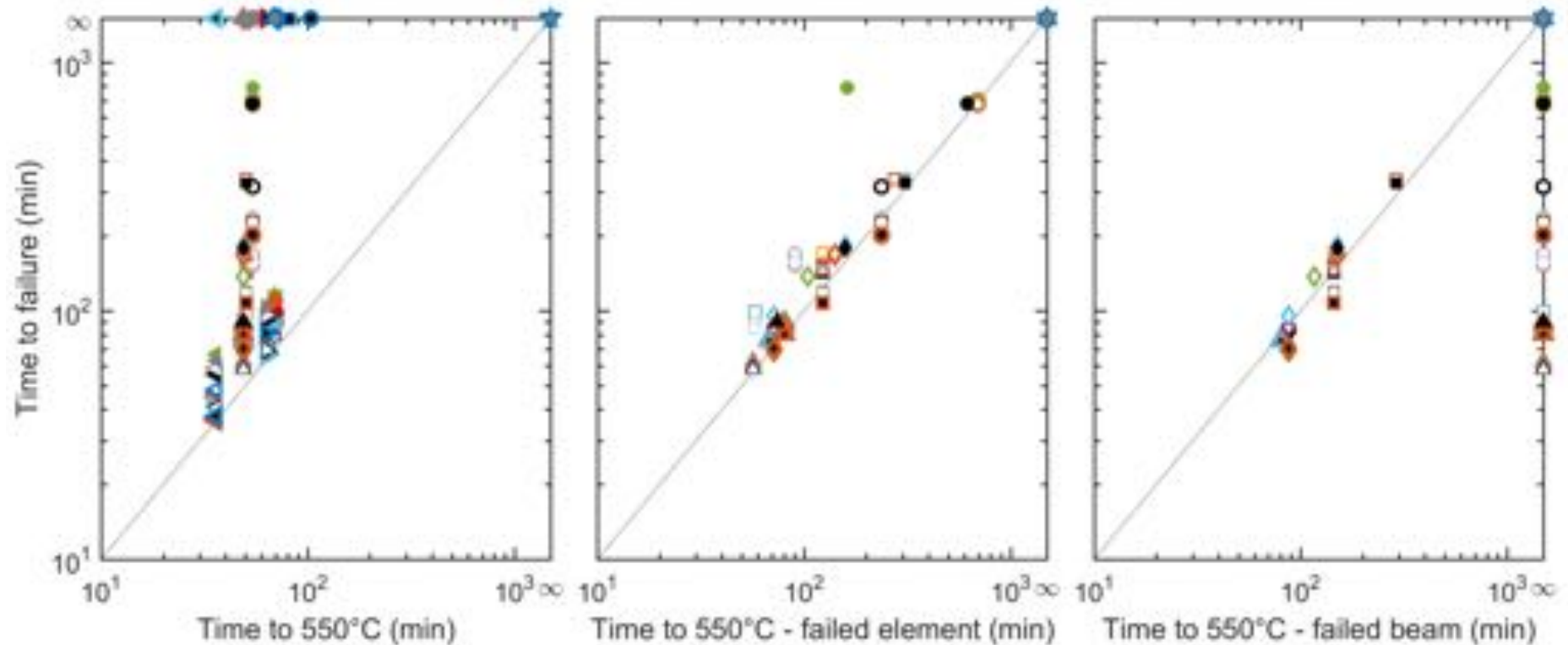
- No relationship between the time to reach the critical temperature in the compartment and the failure time.

TIME TO FAILURE



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

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.

Imperial College
London

THANK YOU!



**39 iconic
buildings
in UK**

**IMPERIAL
HAZELAB**

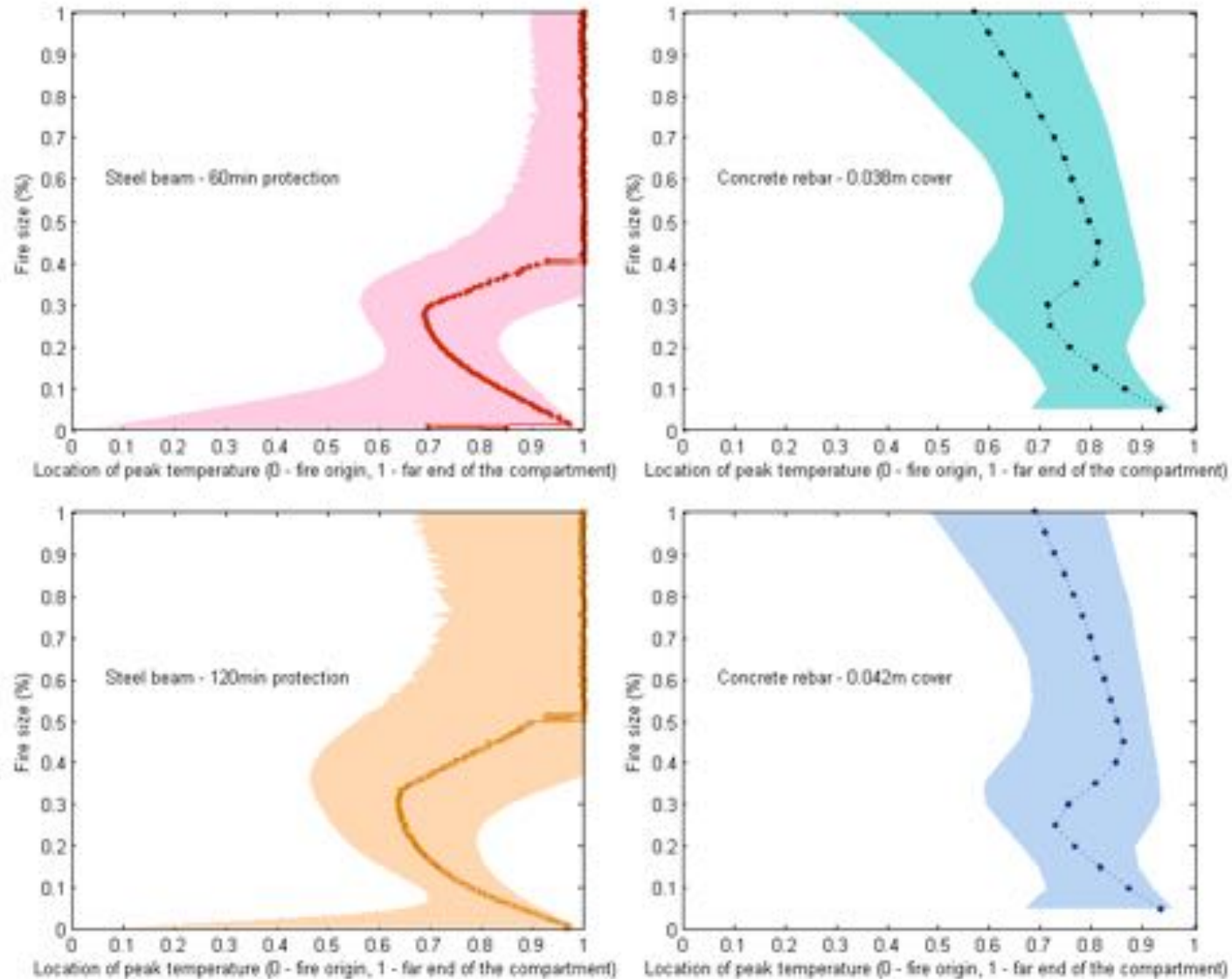
SFPE
Engineering A Fire Safe World

CERiB

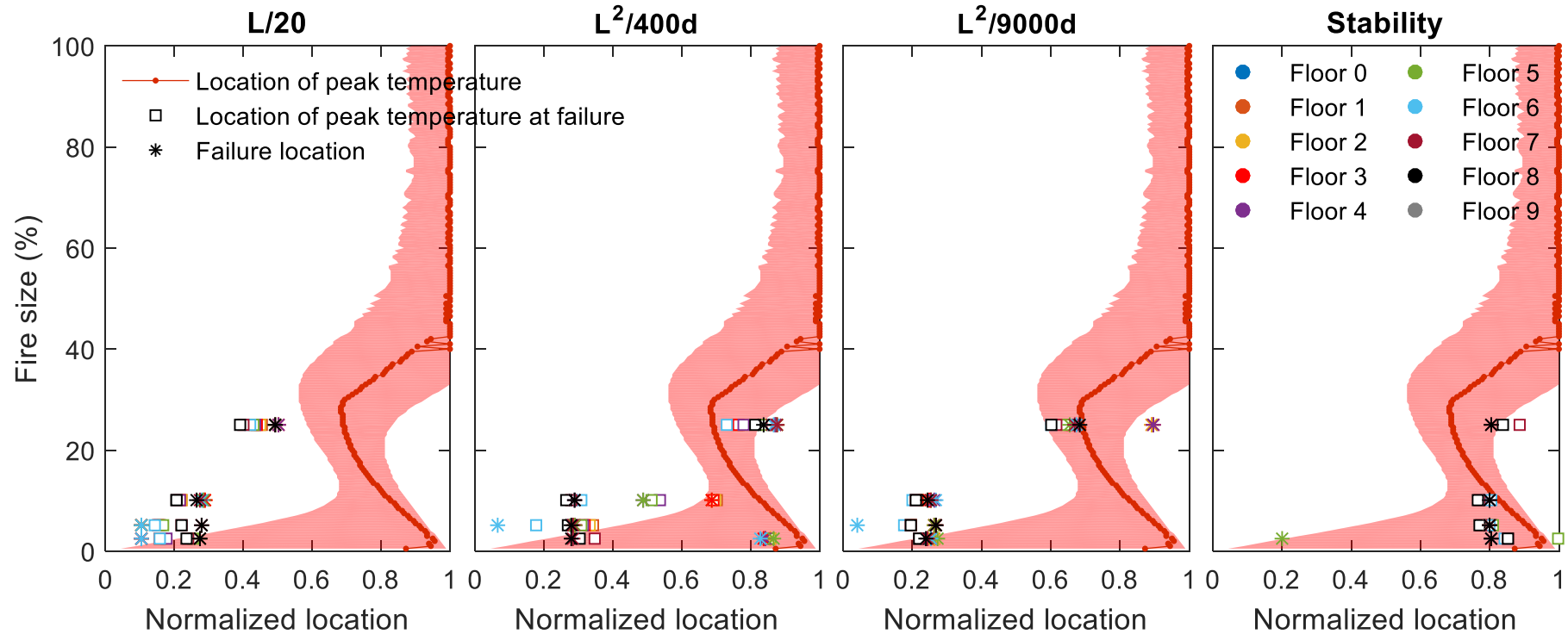
ARUP

EPSRC
Engineering and Physical Sciences
Research Council

LOCATION OF PEAK TEMPERATURE

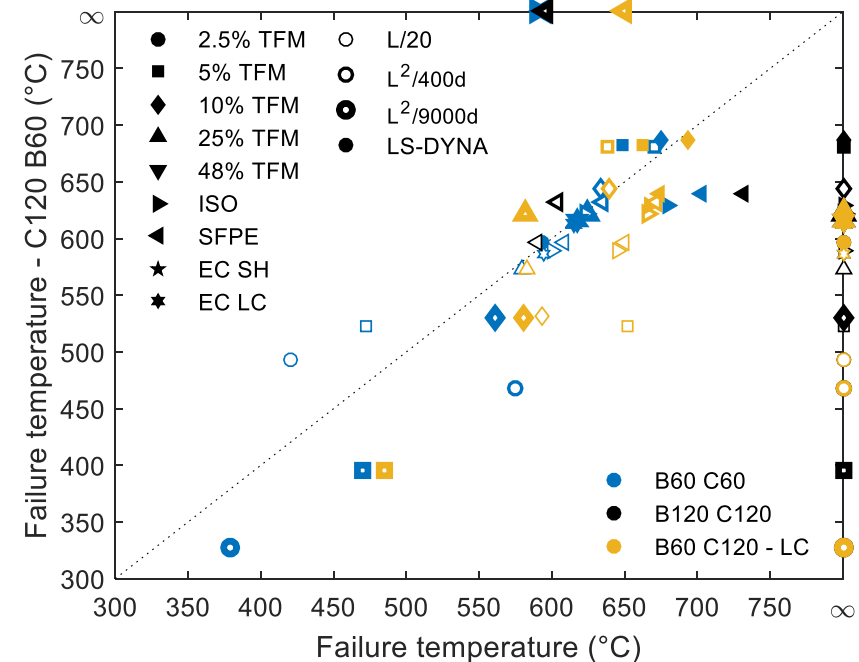
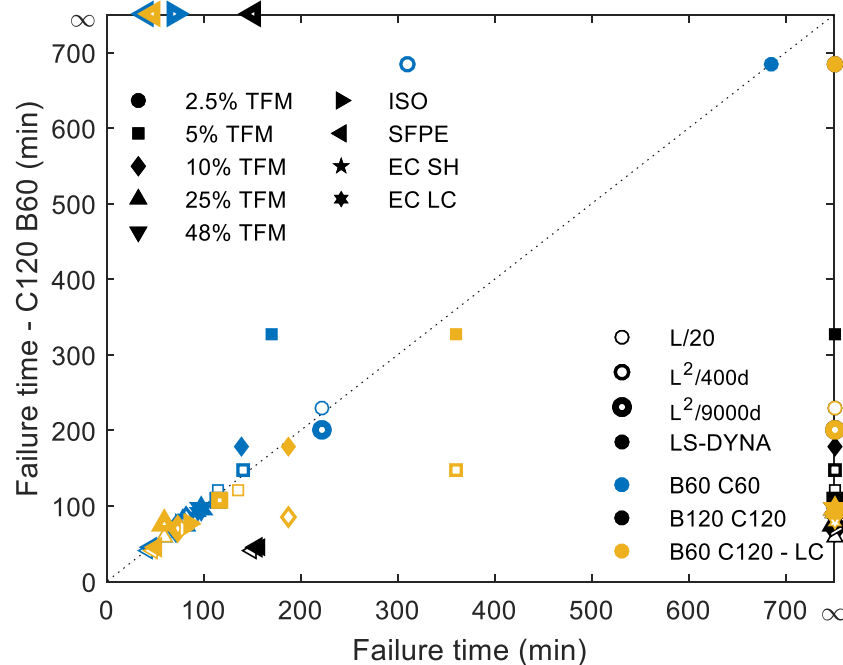


LOCATION OF PEAK TEMPERATURE



- 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.

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

EFFECT OF FIRE PROTECTION AND BEAM SECTION SIZE

