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Thermomechanical Performance of Protected Composite Cellular Beams at High Temperatures

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Structures in Fire Forum
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Background and Introduction

- Structural efficiency and
- Ability to accommodate services

Source: SCI P355 (Lawson et al., 2011)

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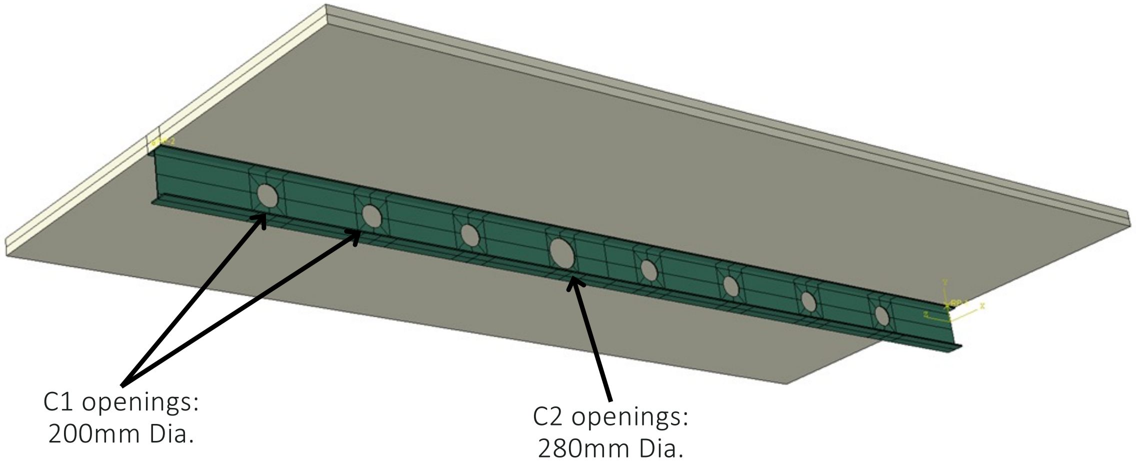
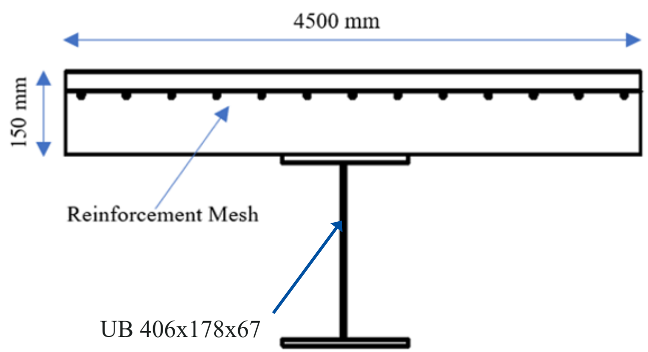
Research Problem:

- Based on a real-life project from the industry.
- Large opening near midspan needed for services.





Beam Height	409.4 mm
Beam Width	178.8 mm
Flange thickness	14.3 mm
Web thickness	8.8 mm
C1 openings	200 mm dia.
C2 opening	280 mm dia.
Slab depth	150 mm
Slab width	4.5 m

Study Objectives

- *Develop a finite element model to accurately represent the thermomechanical response at elevated temperatures*
- *Investigate critical parameters influencing structural capacity under fire conditions*
- *Compare numerical predictions with current design methods outlined in SCI 355 guidance*

Numerical Modelling

Sequentially Decoupled Thermal-Structural Analysis (Abaqus)

Heat Transfer Analysis → Mechanical Response Analysis

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Numerical Modelling

Input Parameters:

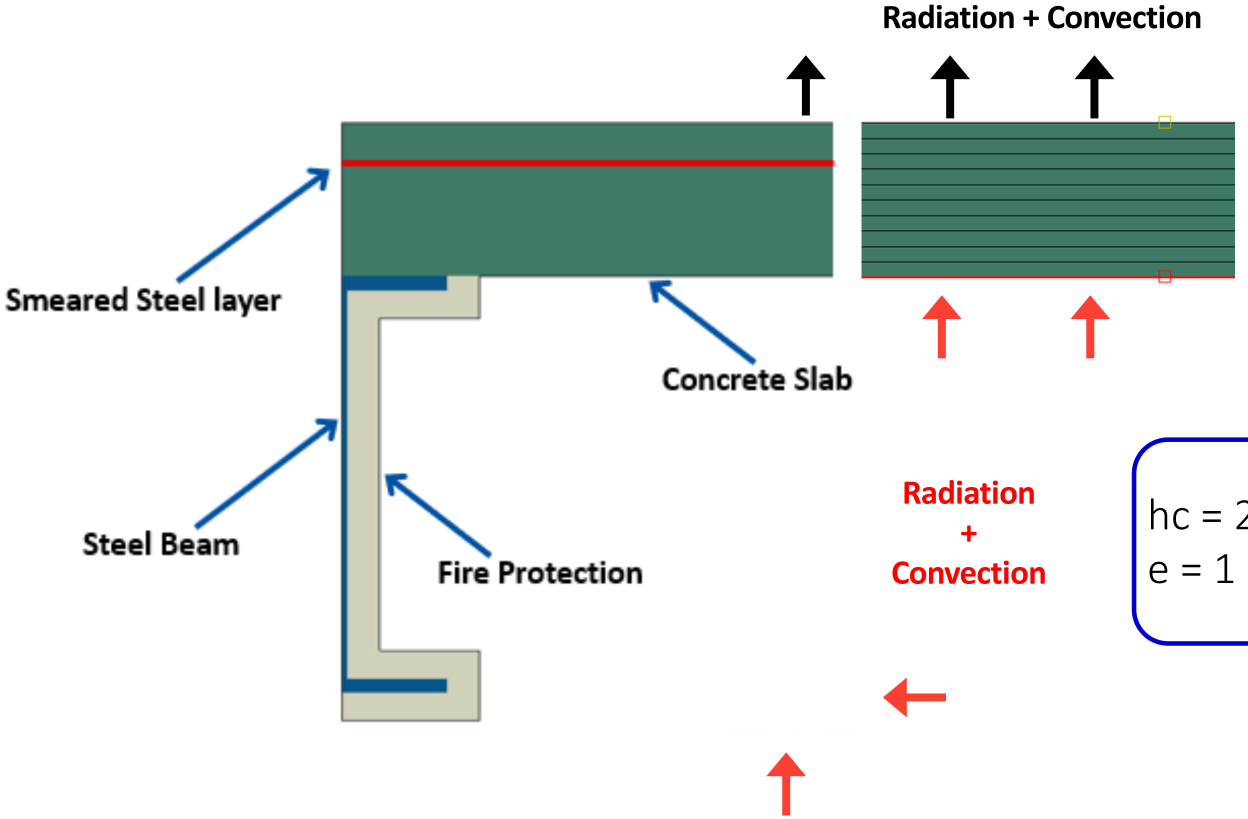
- Beam Geometry
- Material Properties
- Fire Scenarios
- Restraint Conditions
- Loading

Model Outputs:

- Temperature distributions (beam and slab)
- Deflections
- Axial forces and moments
- Stress distributions
- Failure modes and times

Numerical Modelling

Heat Transfer Analysis: Model Development



hc = 25 W/m².k
e = 1

Numerical Modelling

Heat Transfer Analysis: Temperature-dependent thermal properties

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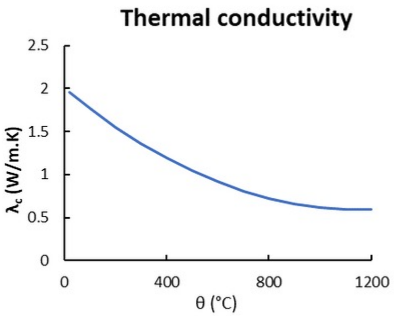

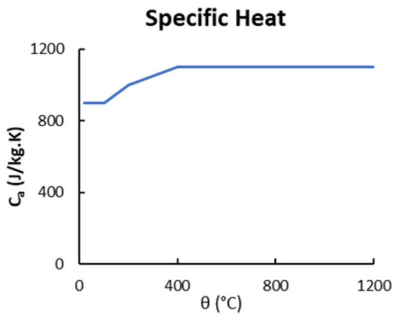

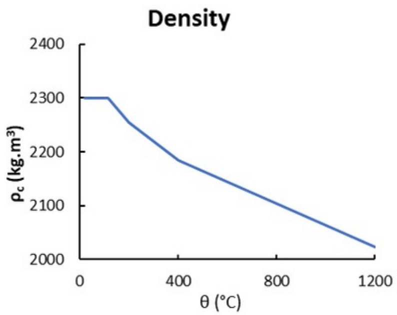

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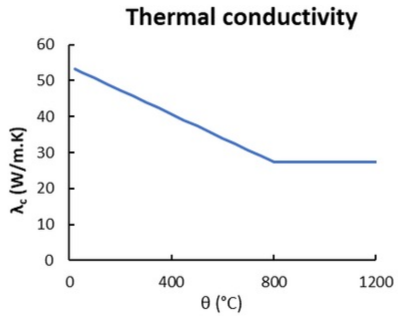
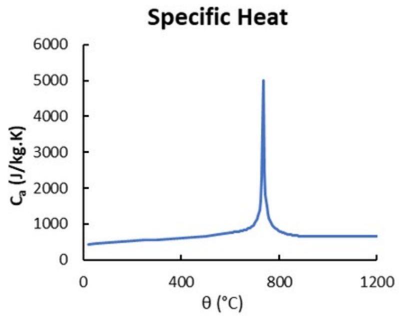




Density = 7850 kg/m^3

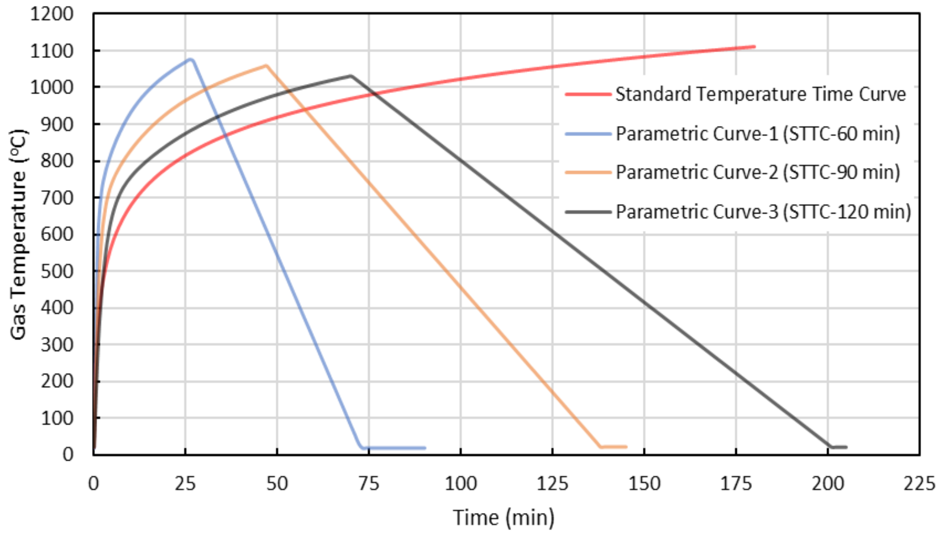
(EN 1992-1-2:2004, EN 1993-1-2:2005)

Numerical Modelling

Heat Transfer Analysis: Fire Scenarios

- Standard ISO 834 temperature-time curve
- Three parametric fire curves:
  - Curve 1: Equivalent to 60 minutes standard fire
  - Curve 2: Equivalent to 90 minutes standard fire
  - Curve 3: Equivalent to 120 minutes standard fire

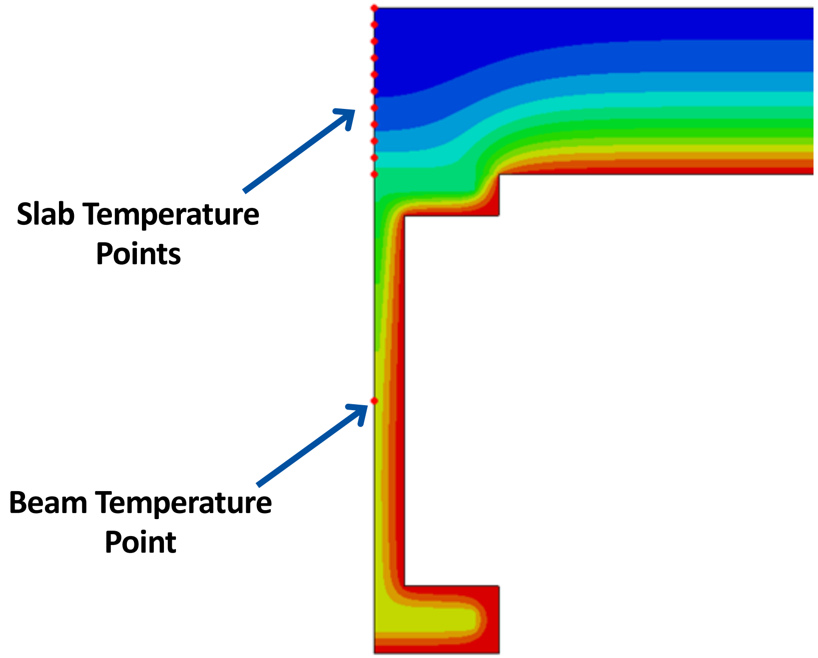
- Parametric curves include both heating and cooling phases
- Applied to both protected and unprotected beam configurations



Numerical Modelling

Heat Transfer Analysis: Temperature Extraction Points

- Steel beam: Single point at mid-web height
- Concrete slab: 12 points evenly distributed across thickness
- Captures thermal gradient through slab depth
- Data used as input for subsequent mechanical analysis

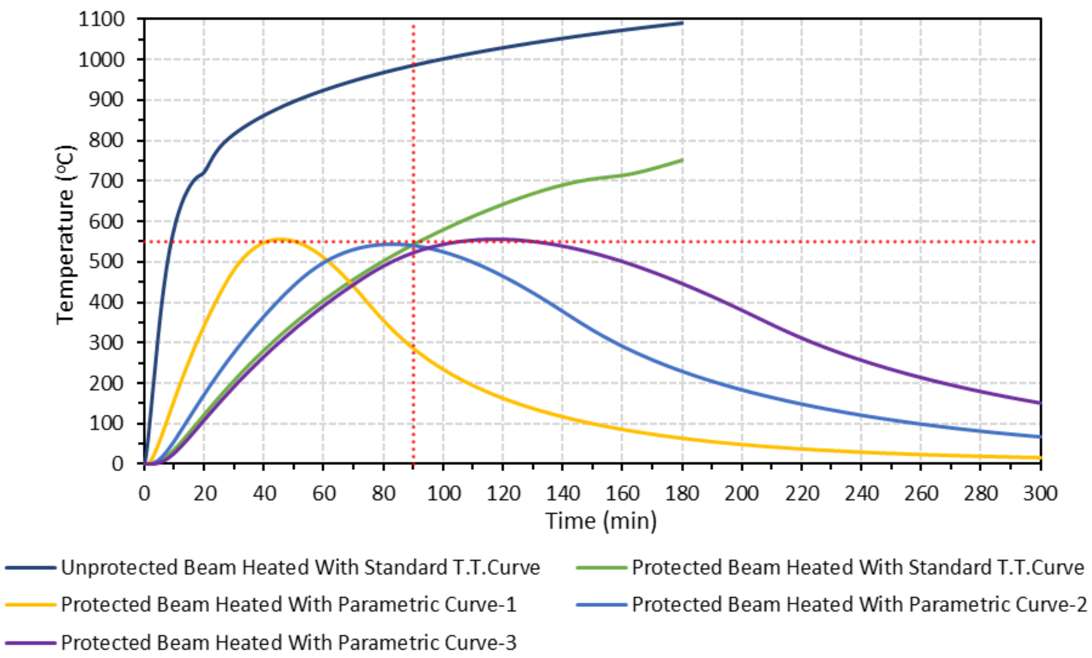


Numerical Modelling

Heat Transfer Analysis: Results - Beam Temperature Development

Limit the steel temperature to 550°C at 90 minutes:

- Curve 1 required 15 mm of protection.
- Curve 2 needed 23 mm of protection.
- Curve 3 required 27.5 mm of protection.
- standard curve's protection requirement 24.5 mm.



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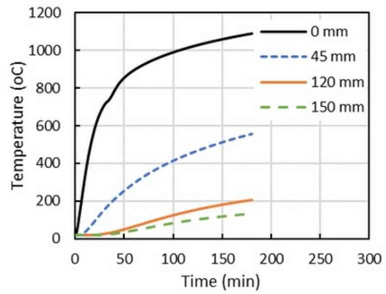
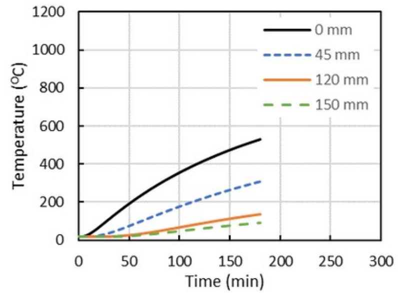
Numerical Modelling

Heat Transfer Analysis: Results - Slab Temperature Development

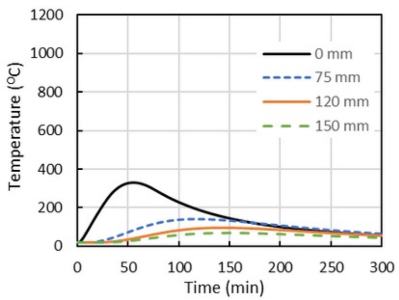
Standard Curve-Unprotected beam



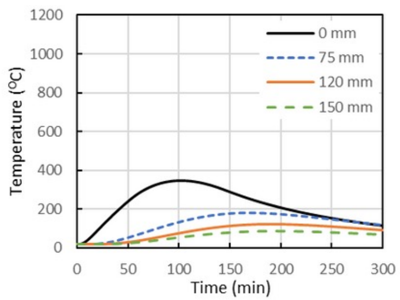
Standard Curve-Protected beam



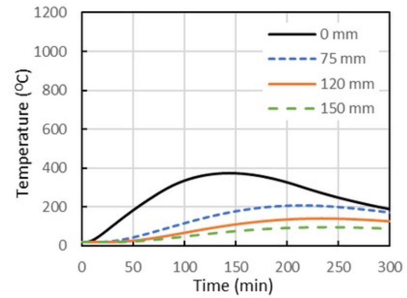
Parametric curve 1-Protected beam



Parametric curve 2-Protected beam



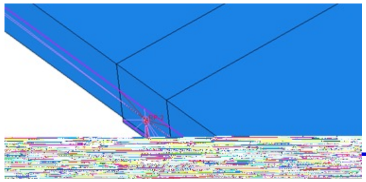
Parametric curve 3-Protected beam

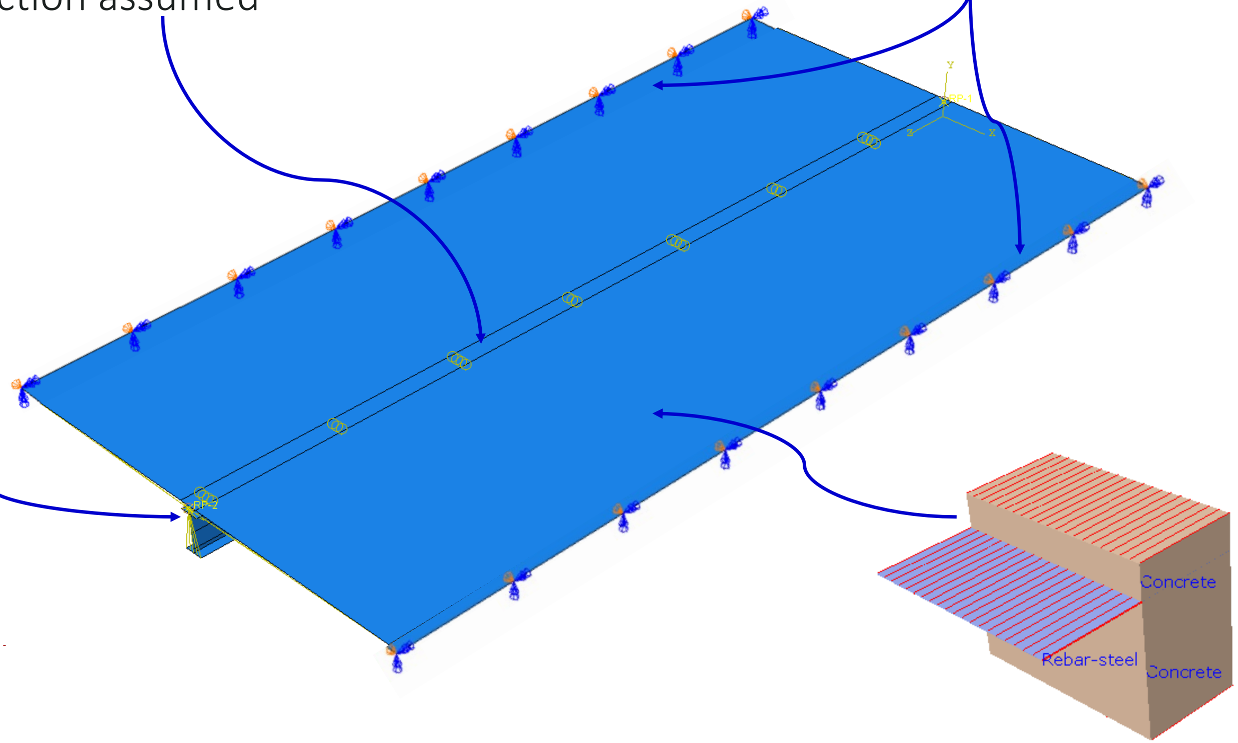


Numerical Modelling

Mechanical Analysis: Model Development

- Symmetry conditions along longitudinal edges
- Composite action: Full shear interaction assumed
- Whole sides kinematically coupled to the neutral axis/supports





Numerical Modelling

Mechanical Analysis: Material Properties and Non-linear Considerations

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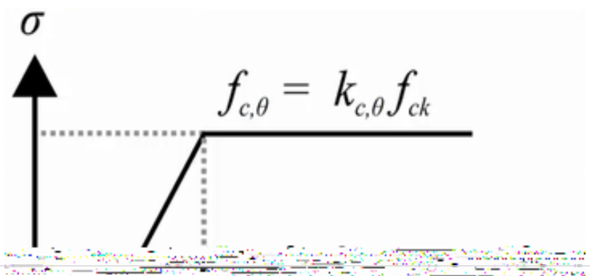

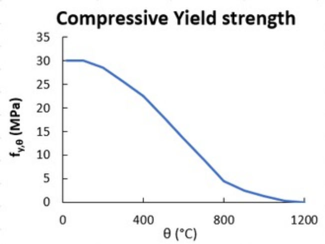

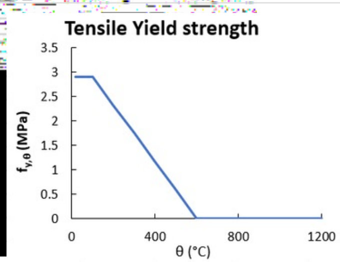

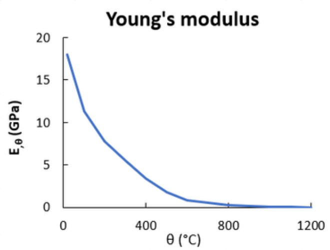

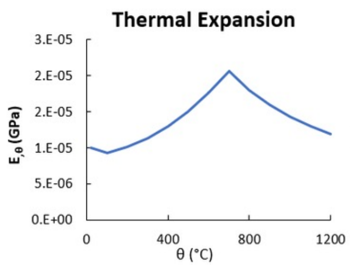

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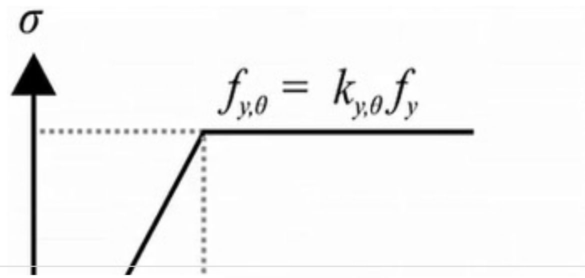
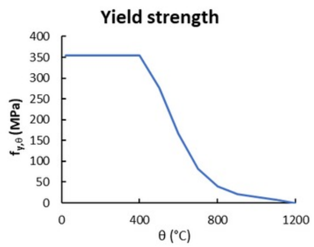
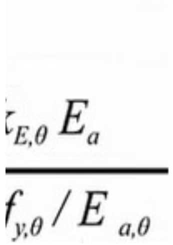
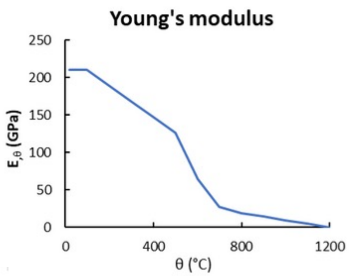
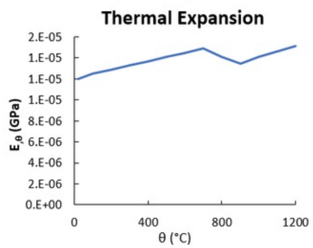








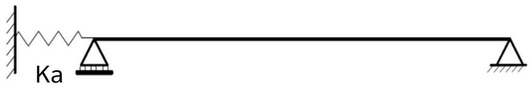


Numerical Modelling

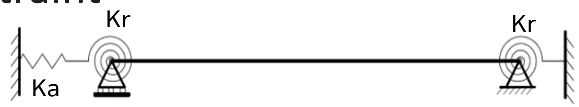
Mechanical Analysis: End Restraint Conditions

Partial axial restraint

Full axial restraint



Partial axial and rotational restraint

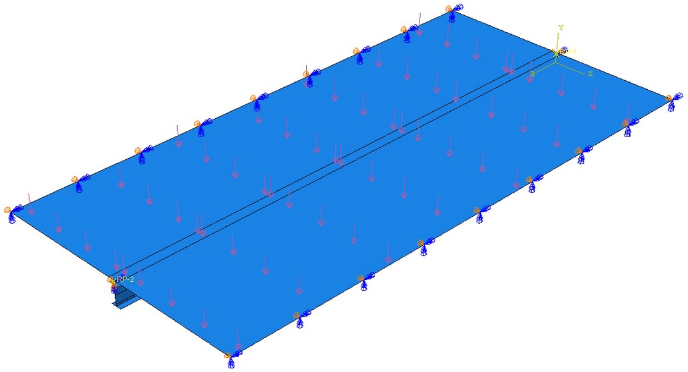


- Axial stiffness $k_a = \frac{EA}{L}$
- Rotational stiffness $k_r = \frac{EI}{L}$

Numerical Modelling

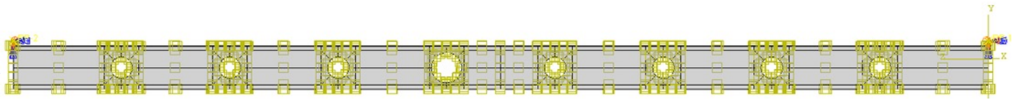
Mechanical Analysis: Loading and Analysis Procedure

Static Loads
$(\gamma_G = 1, \gamma_Q = 0.5)$

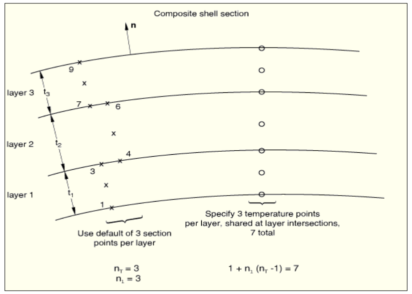


Thermal loads

Beam: Uniform temperature field



Slab: Non-linear gradient temperature field



Abaqus 2024 Documentation, Figure 23.6.5–1

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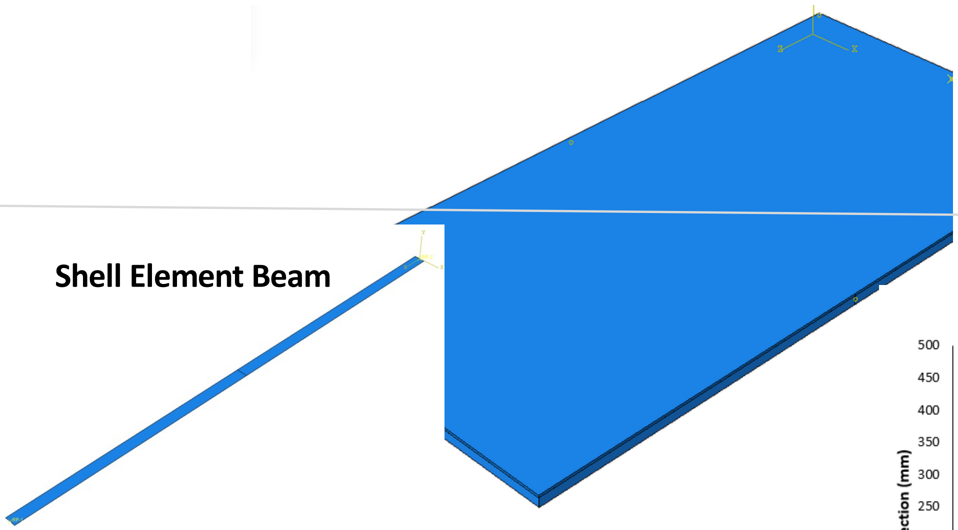
Numerical Modelling

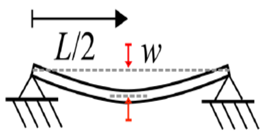
Mechanical Analysis: Model Validation

Solid Slab Model

Shell Element Beam

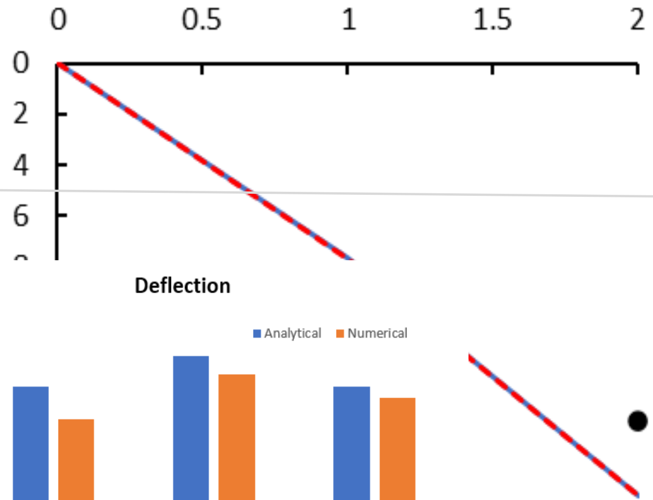


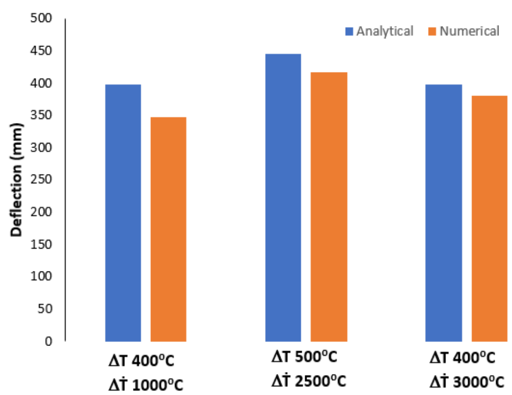
$$w \approx \frac{2L}{\pi}\sqrt{\varepsilon_{tot} + \frac{1}{2}\varepsilon_{tot}^{2}}$$



Usmani et al. (2001)

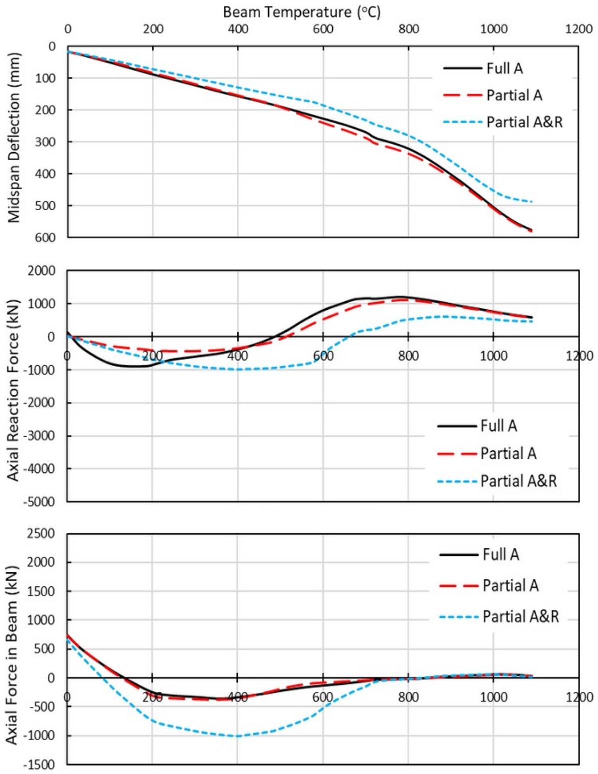
Static Loads Deflection



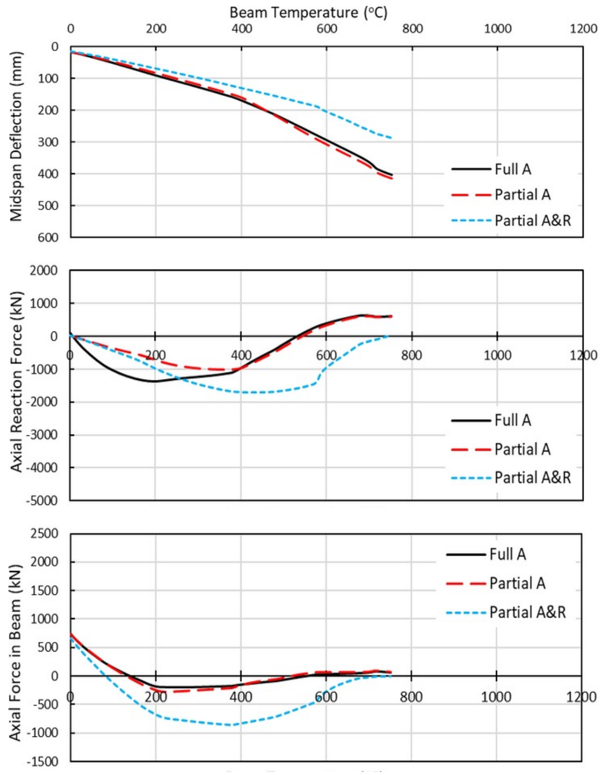


Results Overview

Standard Curve- Unprotected beam



Standard Curve- Protected beam



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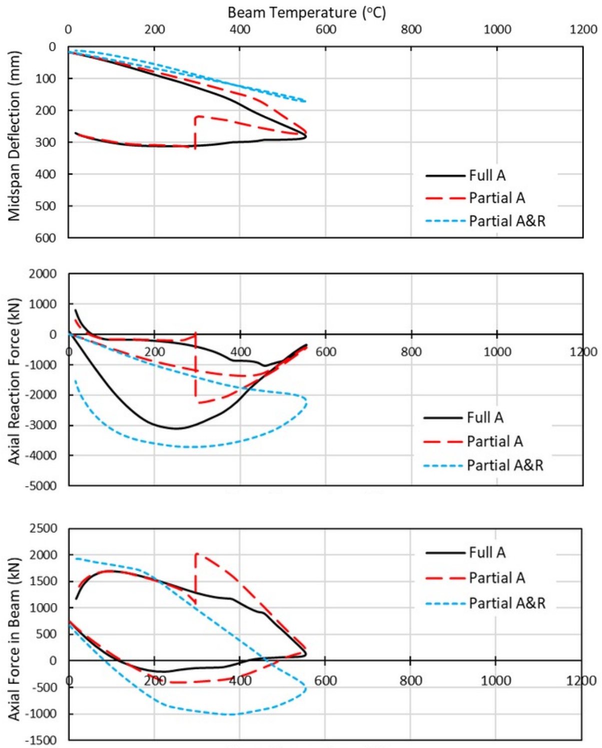
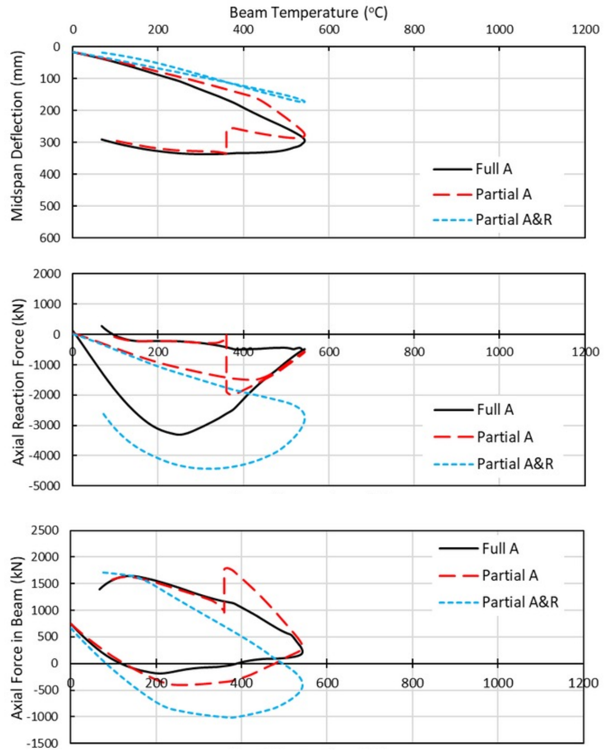
Results Overview

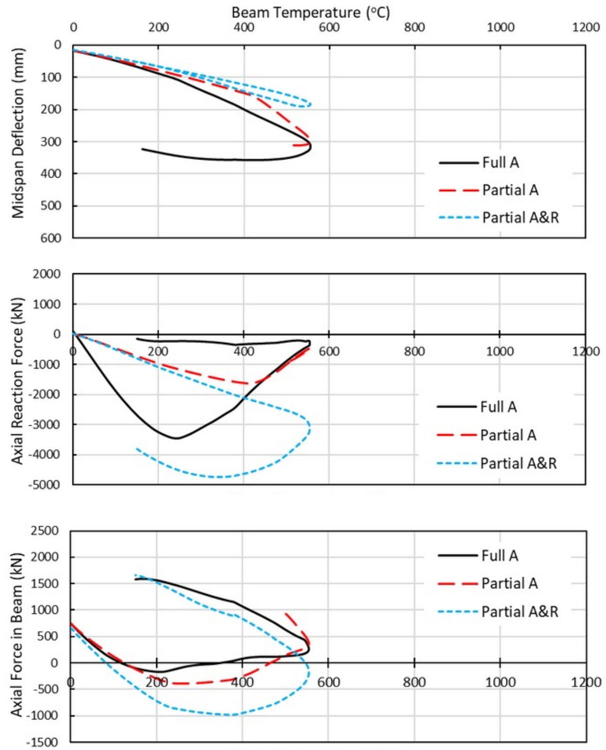
Parametric Curve 1



Parametric Curve 2



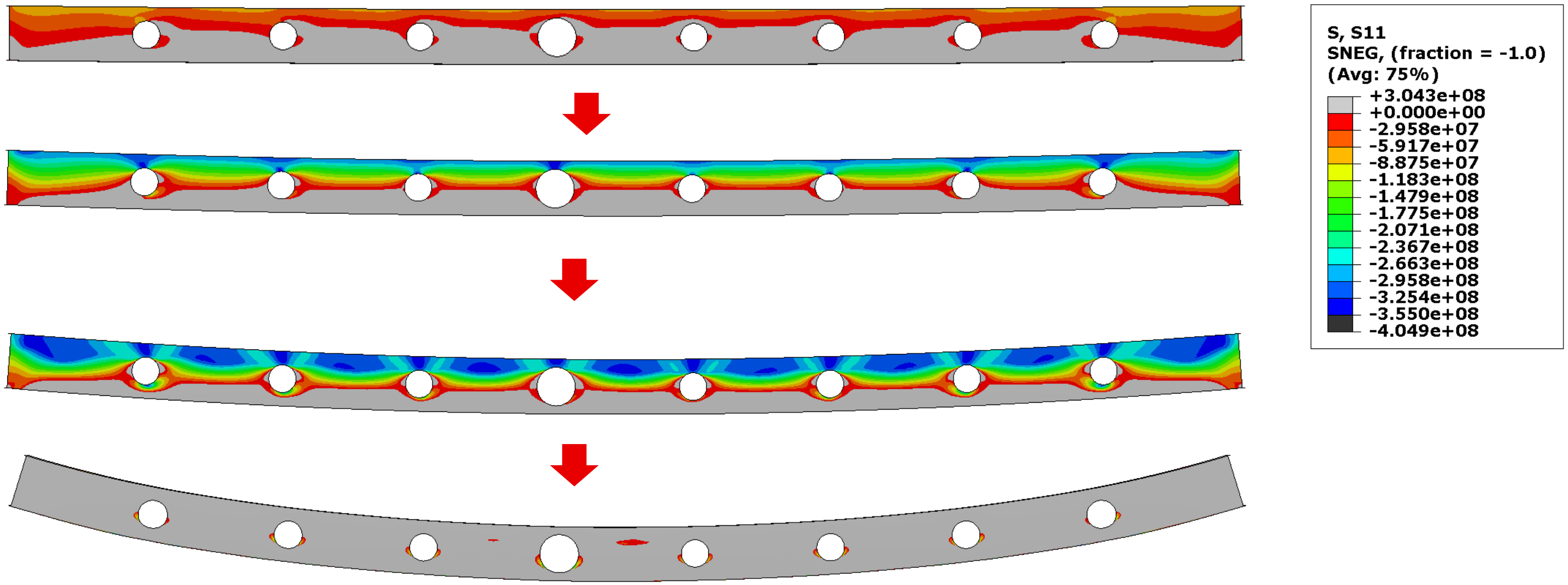
Parametric Curve 3



Results Overview

General Behaviour: Unprotected beam - Standard temperature-time curve

- 1 min
- 3 min
- 8 min
- 130 min

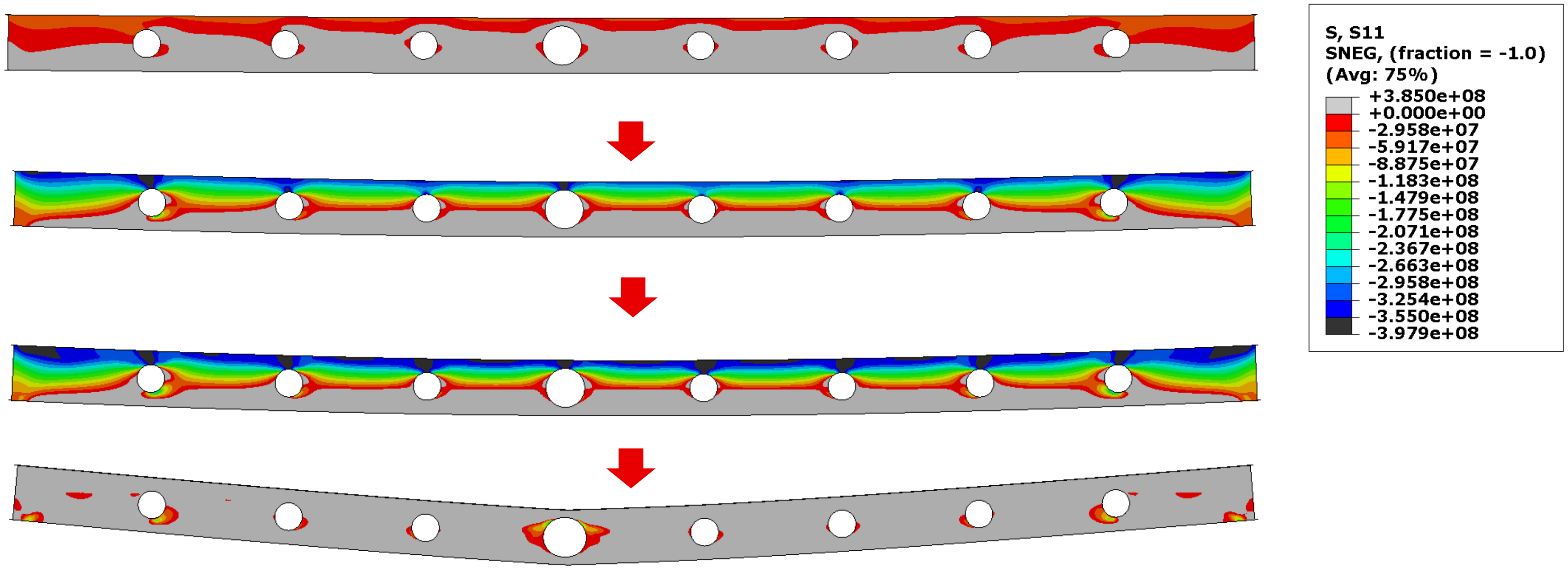


Axial Stresses (S11) - Tensile stresses in grey

Results Overview

General Behaviour: Protected beam - Parametric curve 1

- 1 min
- 11.5 min
- 15.5 min
- 104 min

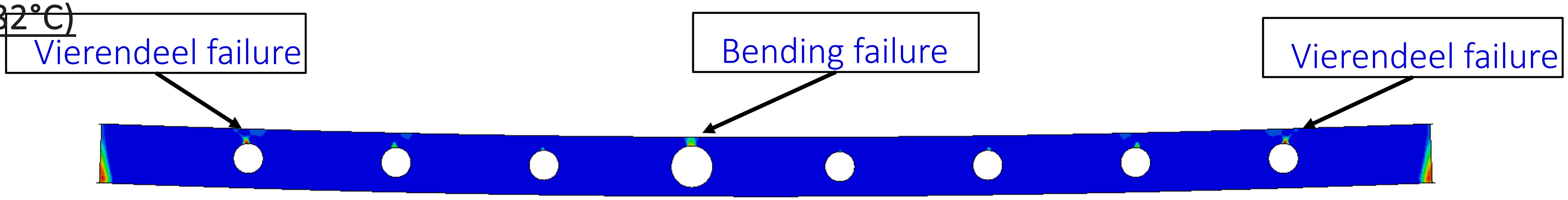


Axial Stresses (S11) - Tensile stresses in grey

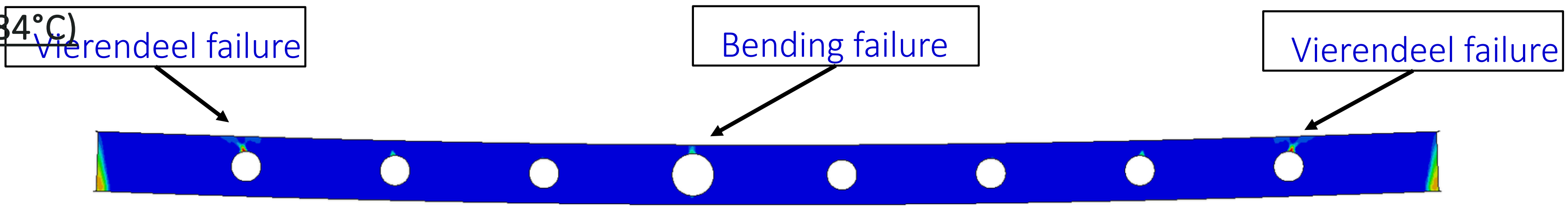
Results Overview

Failure Modes and Local Effects:

- Standard Curve - Unprotected Beam: Failure at 3 minutes (182°C)



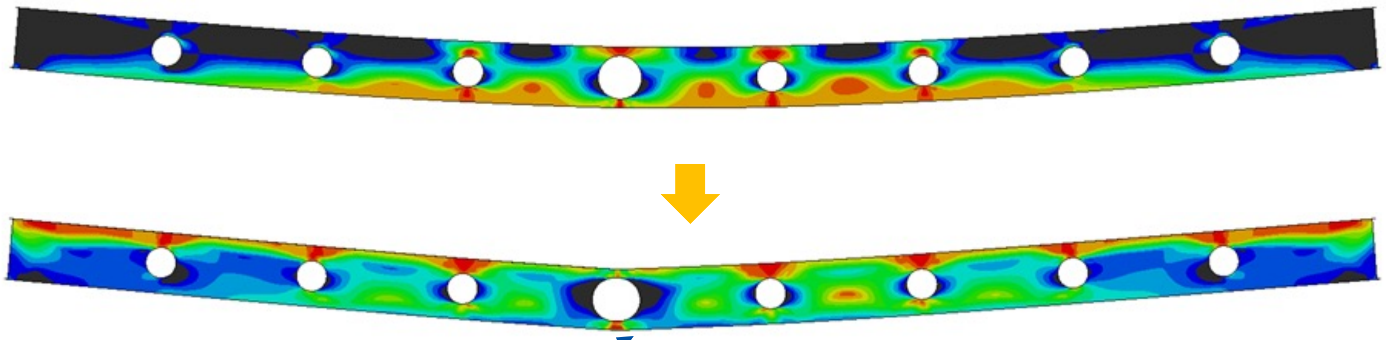
- Standard Curve - Protected Beam: Parametric Curve 1-Failure at 11.5 minutes (184°C)

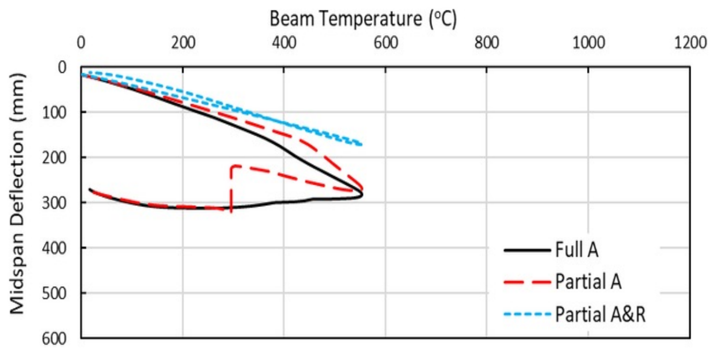


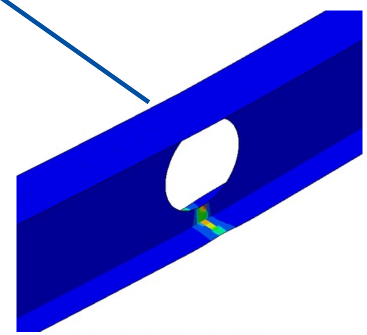
Equivalent Plastic Strain

Results Overview

Parametric Curves: Cooling Phase

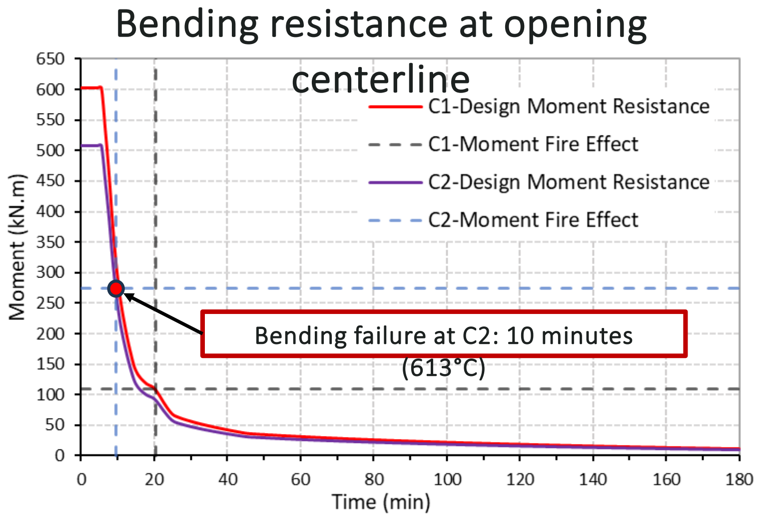


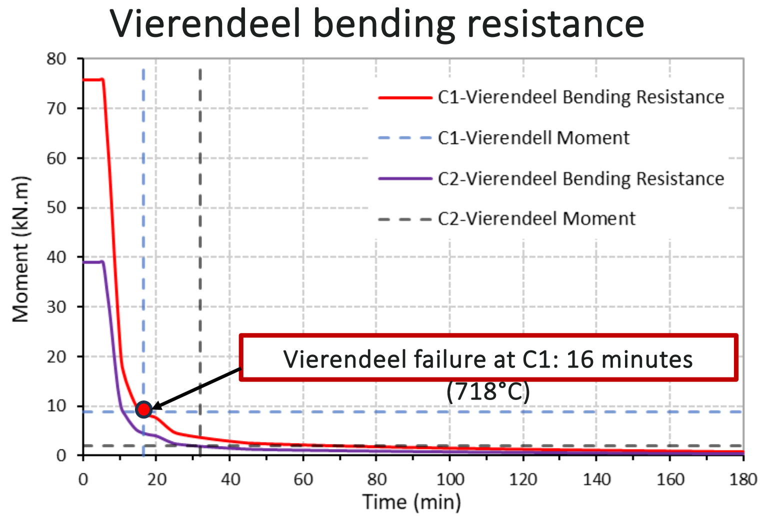




Comparison with Analytical Methods

Standard Curve - Unprotected beam





- Numerical model shows failure at 3 minutes (182°C)

Current design guidelines do not fully account for:

- Interactions between failure modes
- Complex stress distributions and concentrations around openings
- Thermal gradient effects

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Conclusions and Implications

- Web openings significantly impact fire performance, with the large central opening playing a critical role in failure initiation.

- Current simplified design methods may not adequately capture the complex behaviour of these beams under fire conditions.

- Restraint conditions crucially influence the beam's response to fire.

- The cooling phase in fire scenarios introduces additional complexities often overlooked in current design guidance.

Future Work

- Experimental validation of these numerical findings to confirm the observed behaviours.

- Investigation of different opening configurations and sizes to optimise cellular beam design for fire performance.

- Development of more refined analytical methods that can capture the complex behaviours observed in the numerical study.

- Investigation of more realistic material models that account for irreversible changes and residual effects after exposure to high temperatures

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Thank you

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