Tools for Performance and/or Objective Based Structural Fire Design

ACI Convention
Kansas City, MO
April 2015

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Western Engineering

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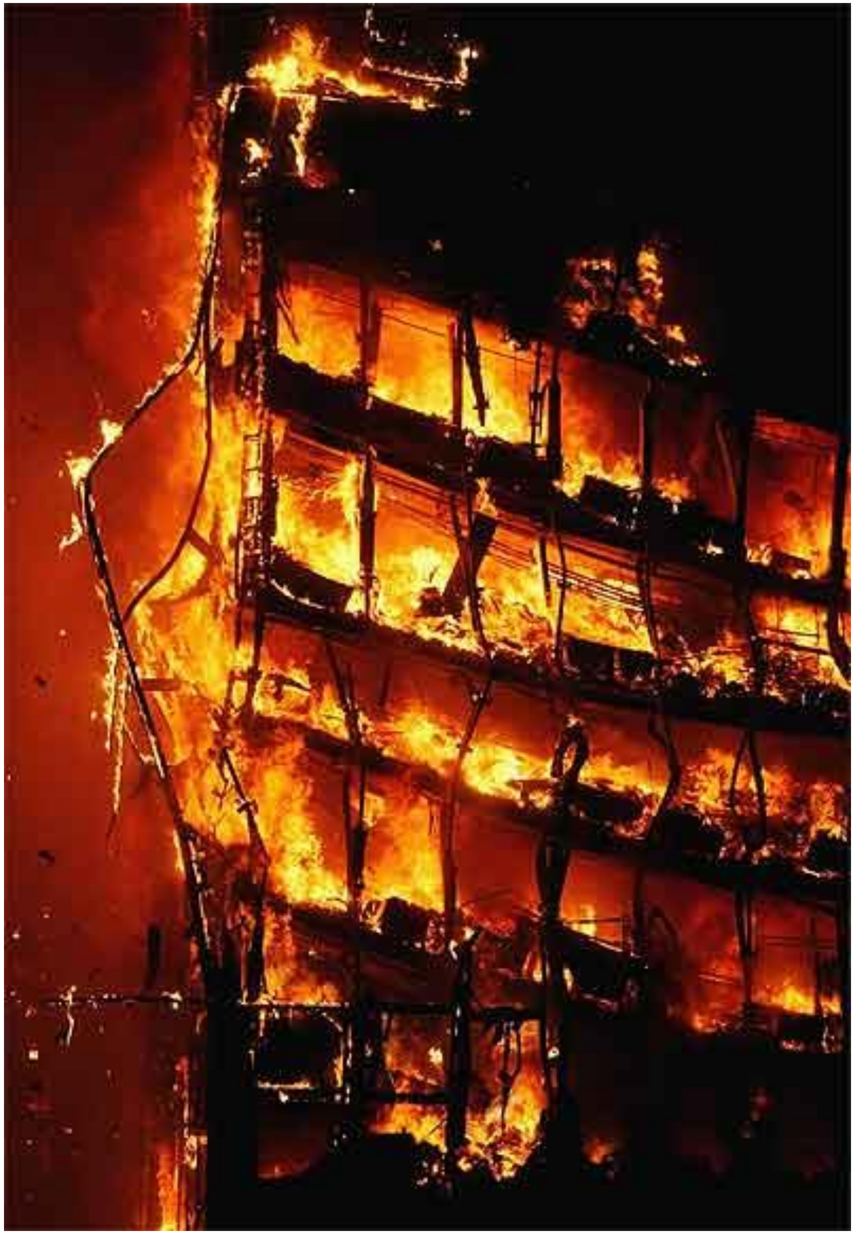


Design Codes and Structural Fire Engineering

- Architect and Structural Engineer
- *EuroCode 2:*
  - estimate the fire resistance of <u>structural elements</u>.
  - basis for advanced models at the structure level.
- *2005 NBCC:*
  - Objective-Based Design.
- *US:*
  - ASCE 7 / Performance-Based Design.

RESEARCH OBJECTIVES

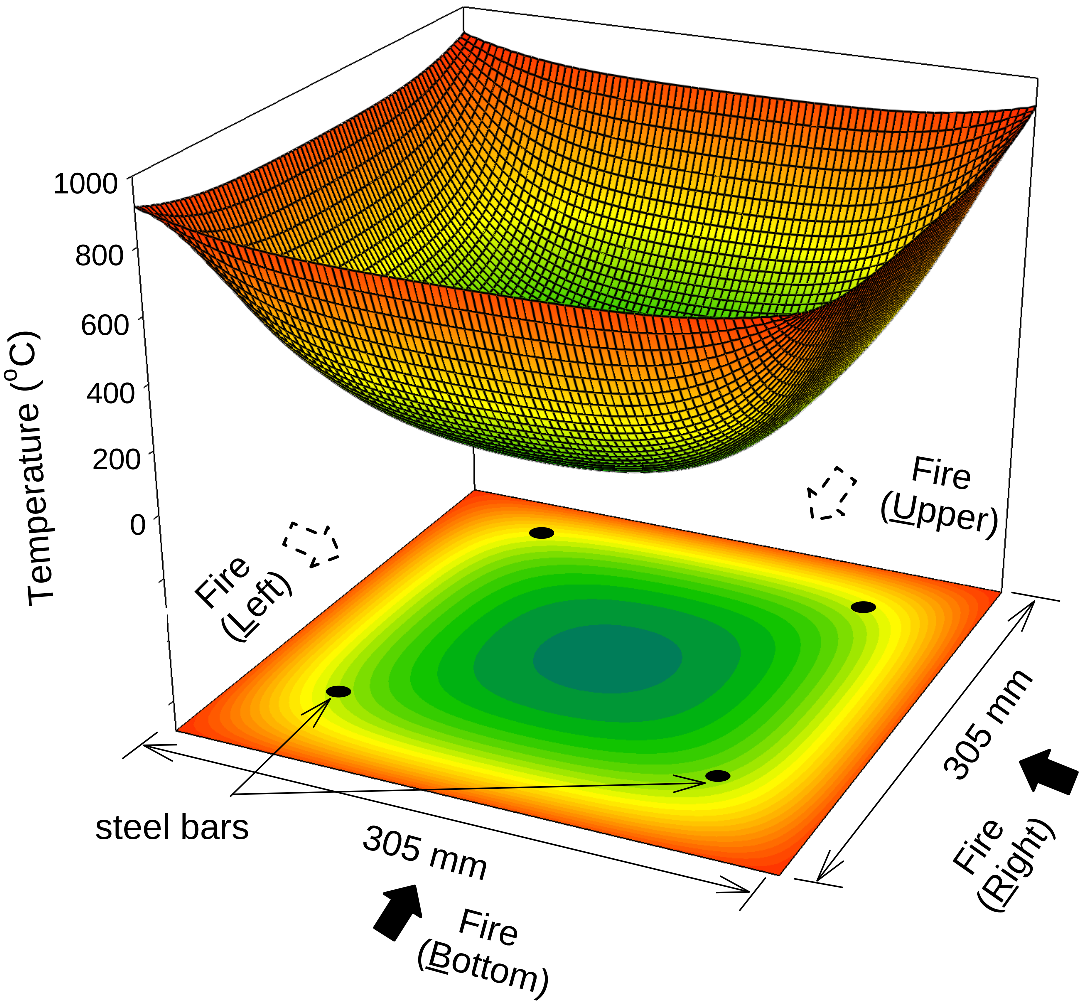
- Provide engineers with the ability to analyze structures exposed to fire
  - Simple Methods (develop engineering sense).
- Develop design tools for different RC elements.

This presentation will cover the major challenges and the overall vision

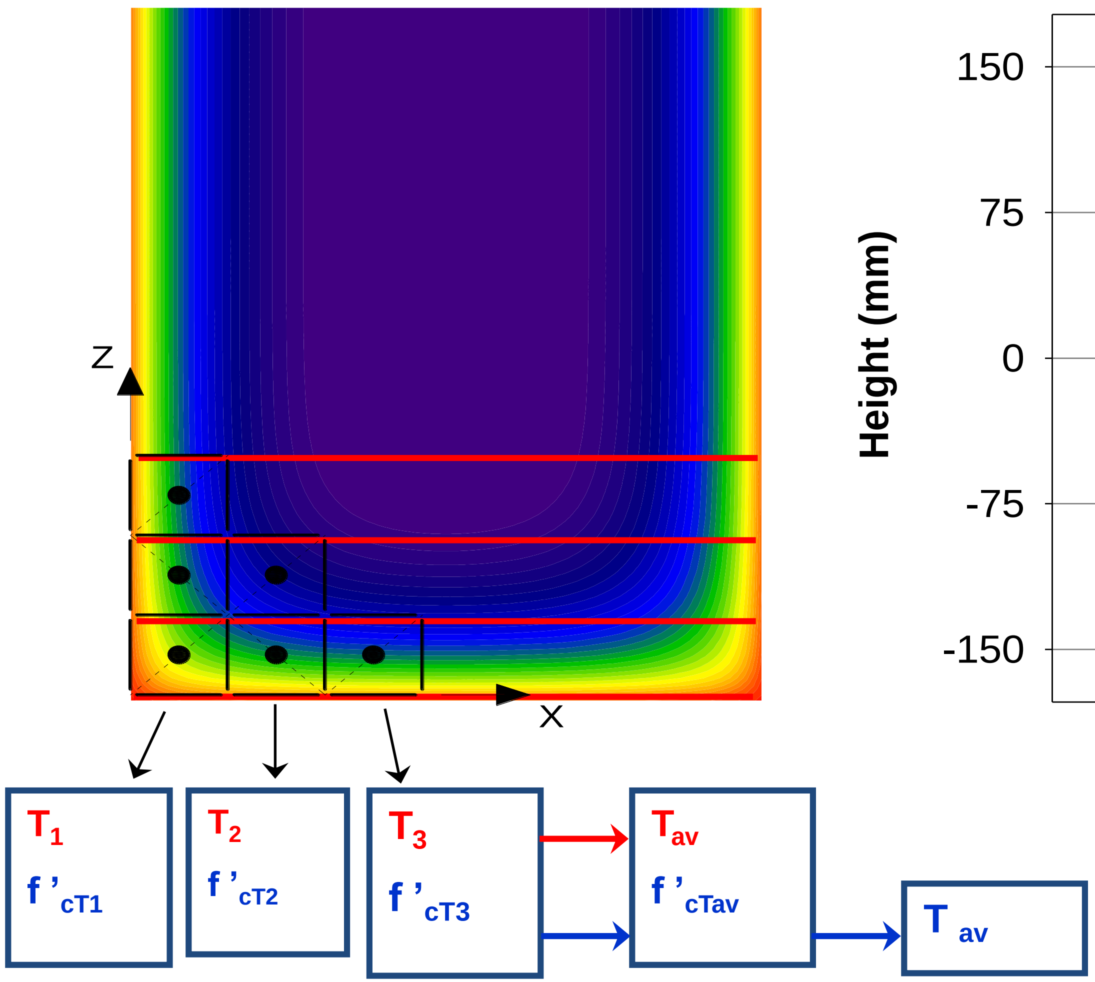
(1) Thermal Strains

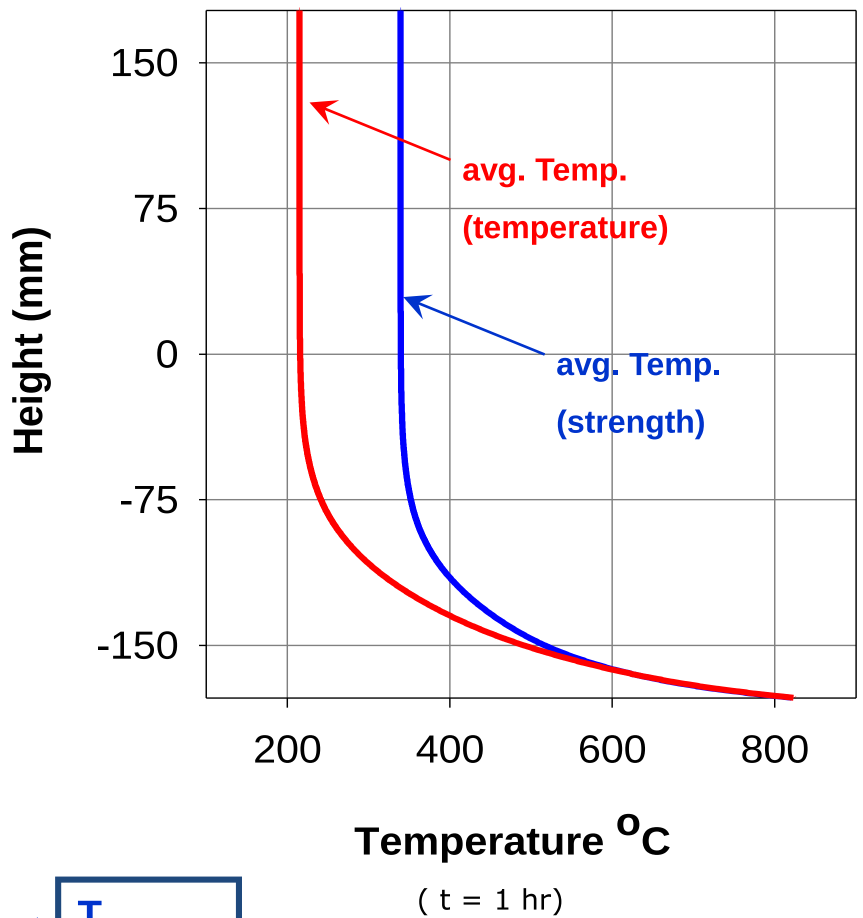
- Non-uniform distribution.
- Will the concrete section allow these strains to develop?

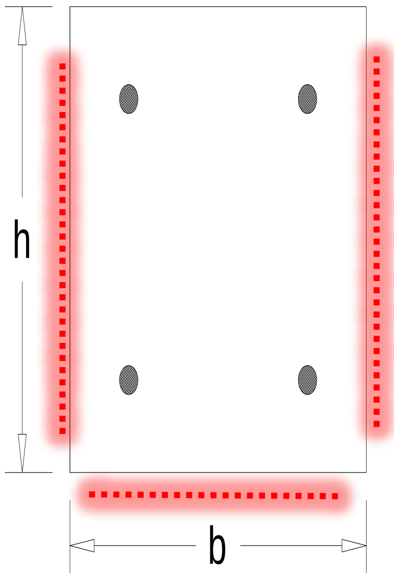
(Plane section!)

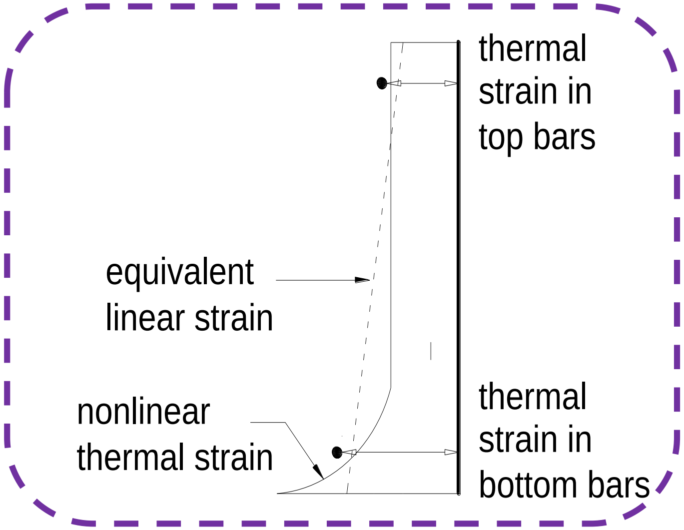


(2) Temperature Distribution





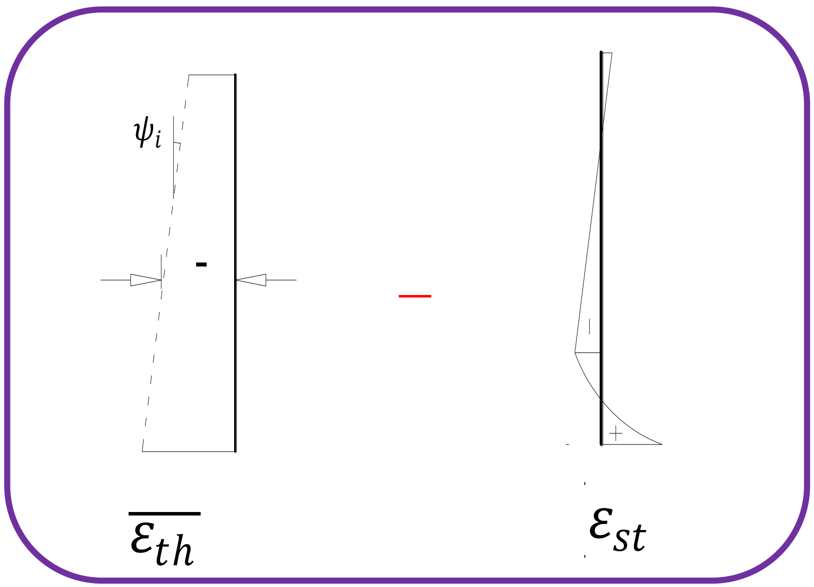




Thermal Strain

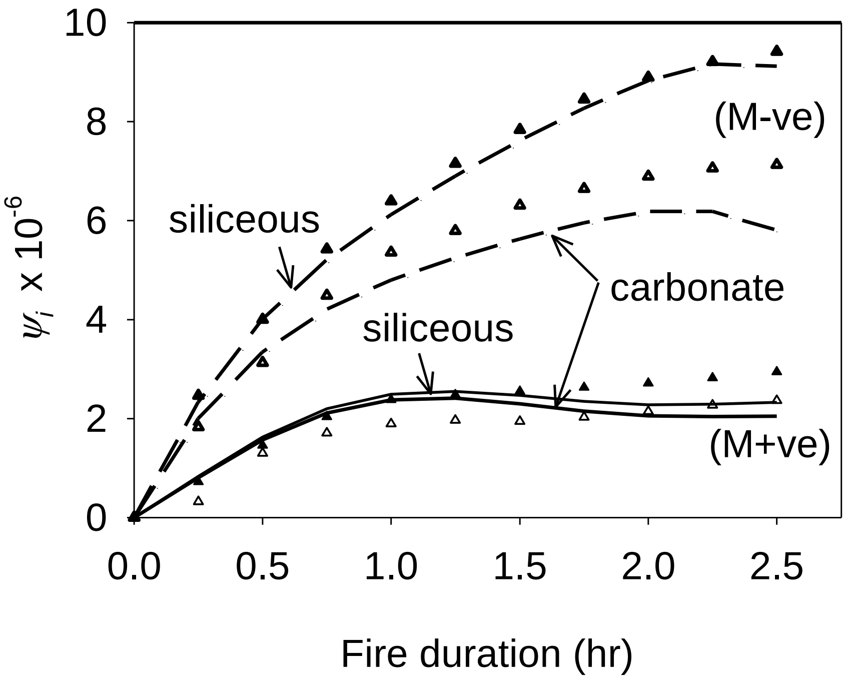
ε_{th}

Equivalent Thermal Strain



Self-induced Strain

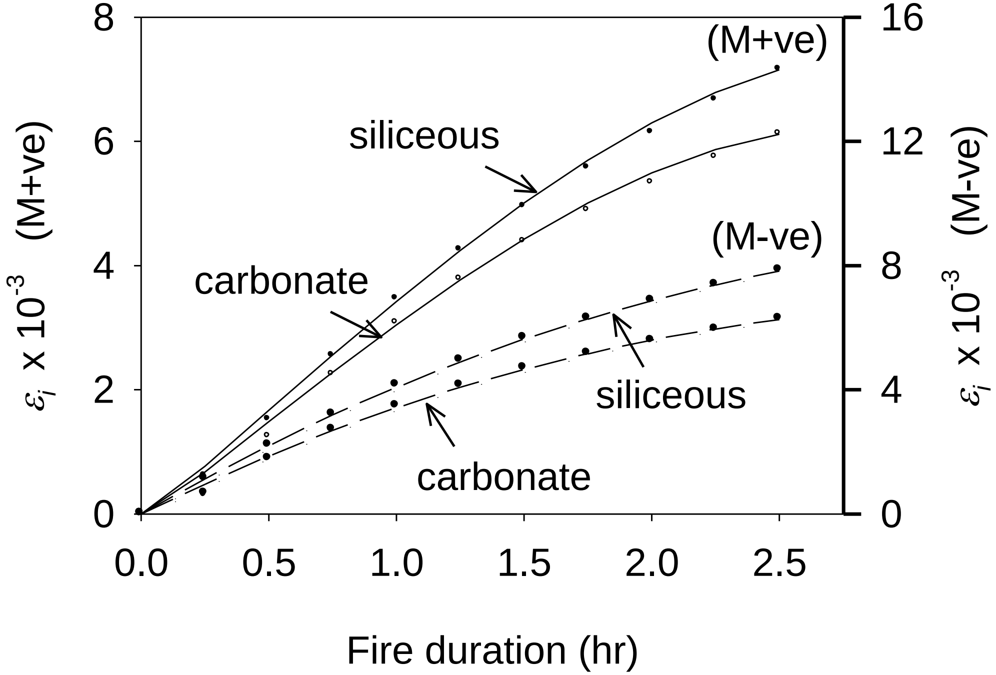
(3) Unrestrained Thermal Strains



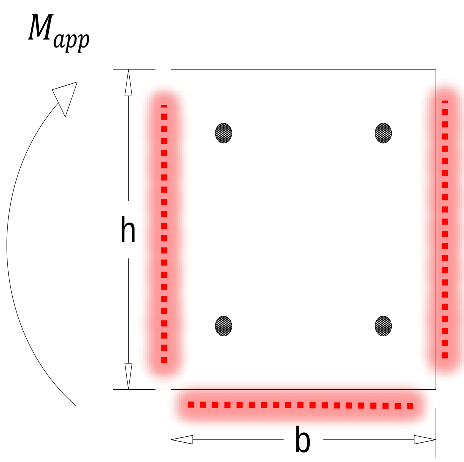
ψ_i = f (*ASTM-E119 Time, Width, Height, Area of Steel Bars in Tension and Compression, Number of Layers of Tension Steel Bars , Aggregate Size*)

M+ve: Lower tension steel properties,
need higher steel strain or lower curvature.
M-ve: Tension steel unaffected and
concrete in compression

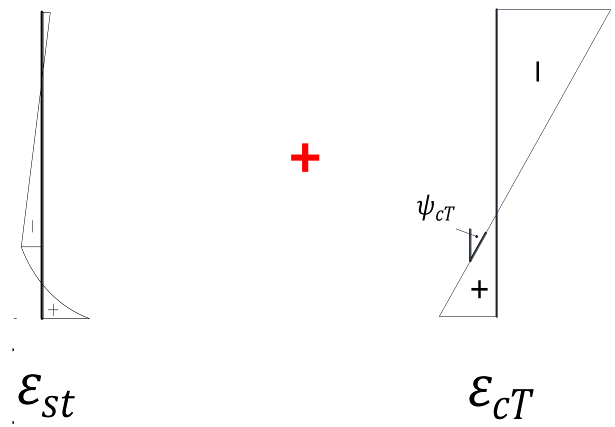
ε_i = f (*ASTM-E119 Time, Width, Area of Steel Bars in Tension and Compression, Number of Layers of Tension Steel Bars , Aggregate Size*)



(4) Sectional Analysis at Elevated Temperatures

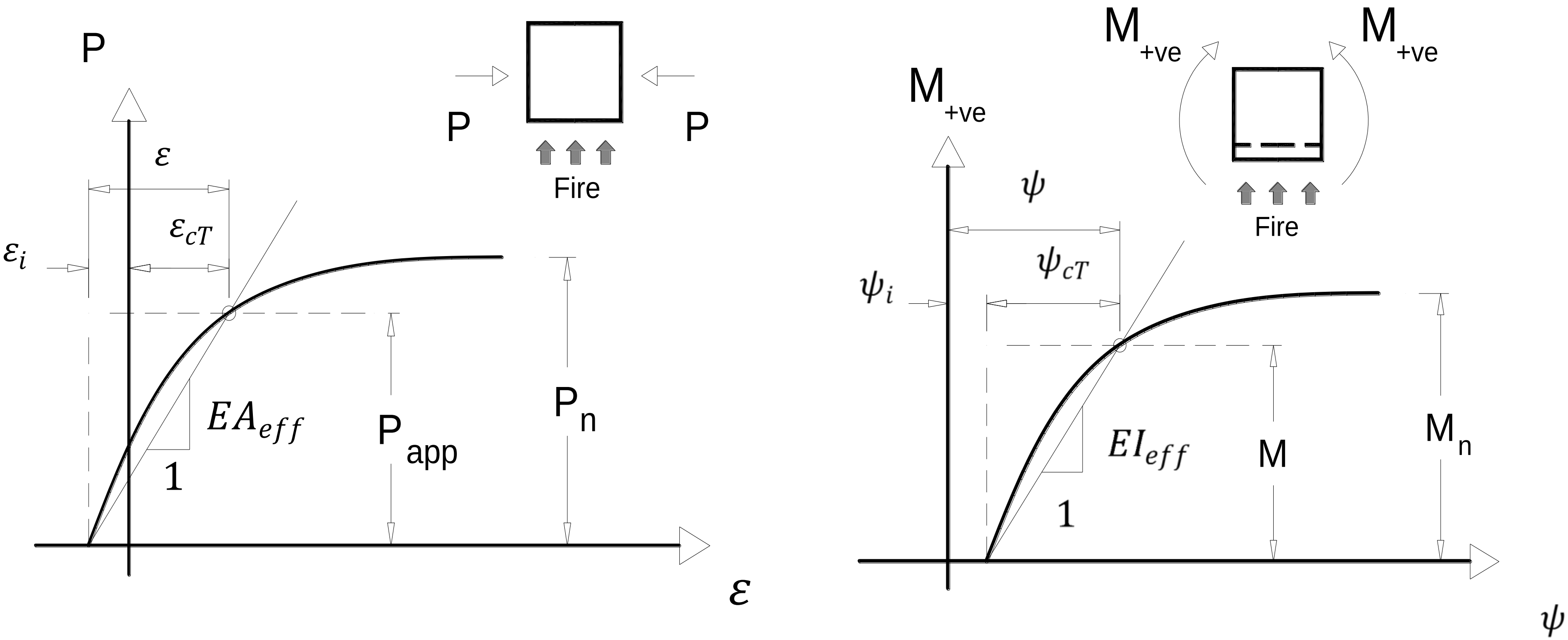


Self-induced Strain + **Mech. Strain**



Thermal Strains.
Transient Strains.
Temperature Distribution.
Temperature-dependent material properties.

(5)EA and EI for Fire-Exposed Elements



Simplified Approach to Calculate EA_{eff} and EI_{eff}

(6) Solution Procedure for a Structure

1) Calculate primary moments & axial forces in different members.

2) Identify elements exposed to fire and use their section properties and fire duration to evaluate ε_i , ψ_i , EA_{eff} *and* EI_{eff}.

3) Convert ε_i and ψ_i to elongations and rotations

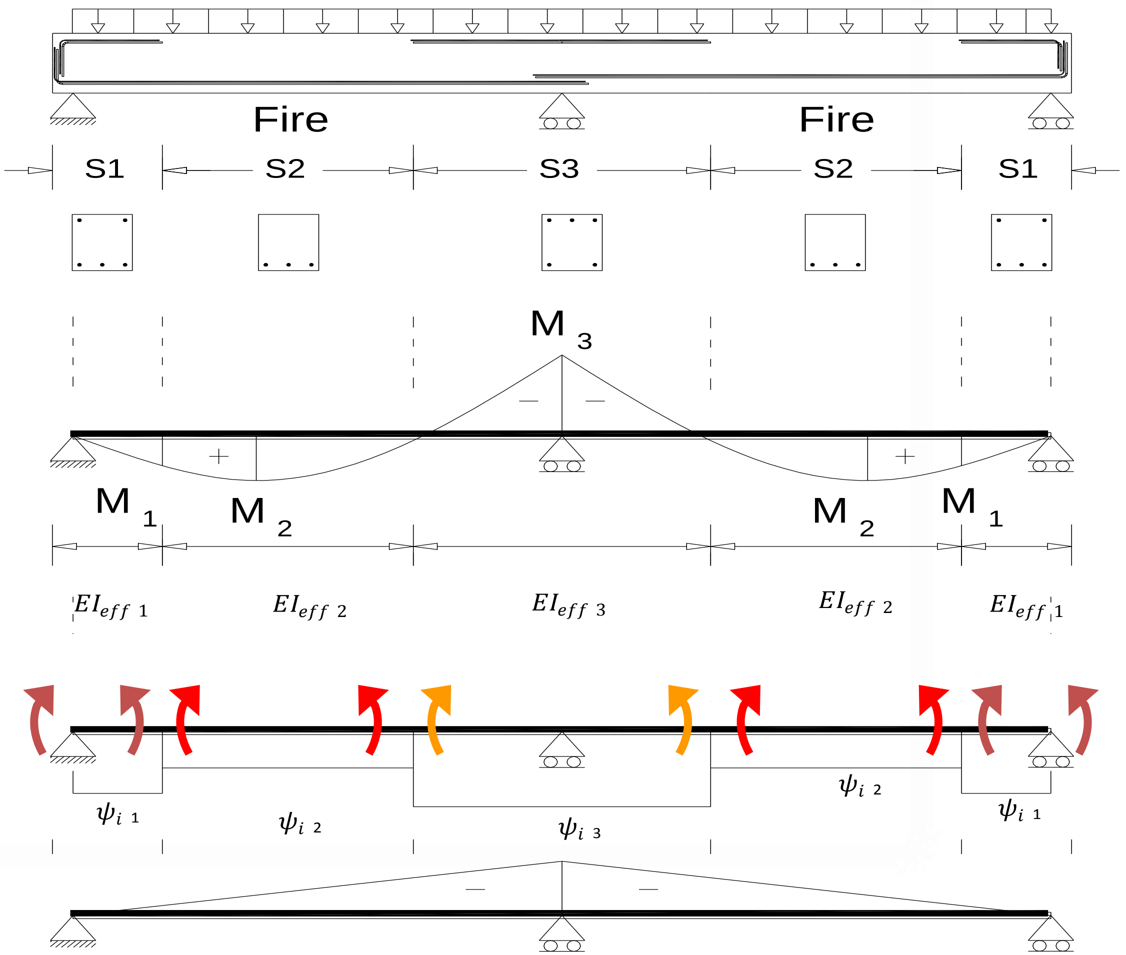
4) Apply the elongations and rotations for fire-exposed elements and calculate the secondary moments and associated axial forces.

5) Recalculate EA_{eff}, Ei_{eff}, *and the primary moments.*

6) Repeat steps 4 and 5 until convergence is achieved.

Application for a Continuous Beam

- The beam is divided into segments
- Ei_{eff} is calculated based on the primary BMD
- Thermal curvatures are simulated by concentrated rotations
- Secondary moments are generated

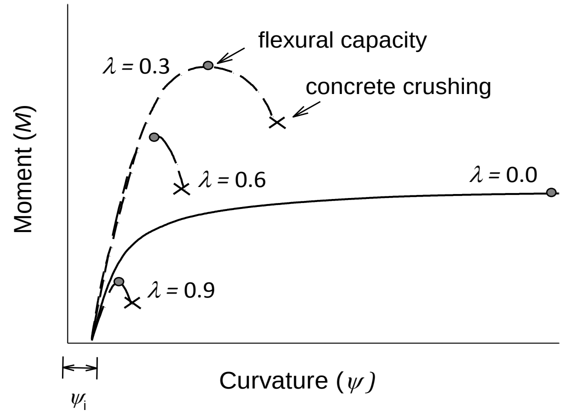


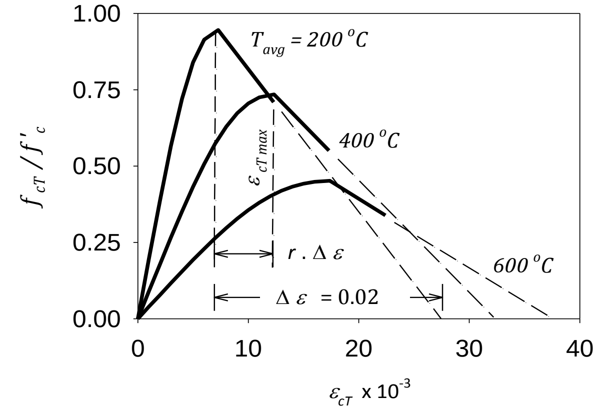
(7) Simplified Tools

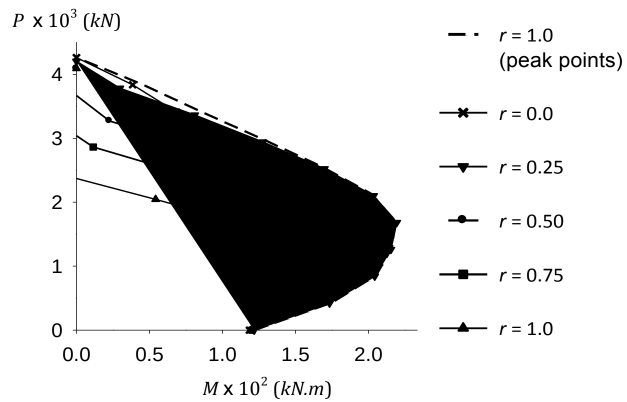
- Stress-Block Parameters of RC Beams Exposed to Fire.
- Interaction Diagrams of RC Columns Exposed to Fire.
- Shear Capacity of RC Beams Exposed to Fire.

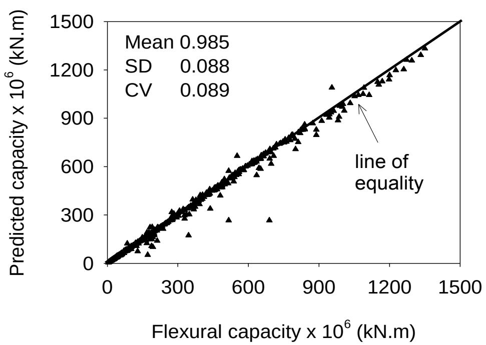
(8) Strain Defining Section Capacity

- $\varepsilon_{c\,max}$: concrete strain corresponds to Moment of Resistance M_r
- A parametric study is conducted to evaluate $\varepsilon_{c\,max}$ at elevated temperatures
- Reasonable predictions are obtained at $r = 0.25$



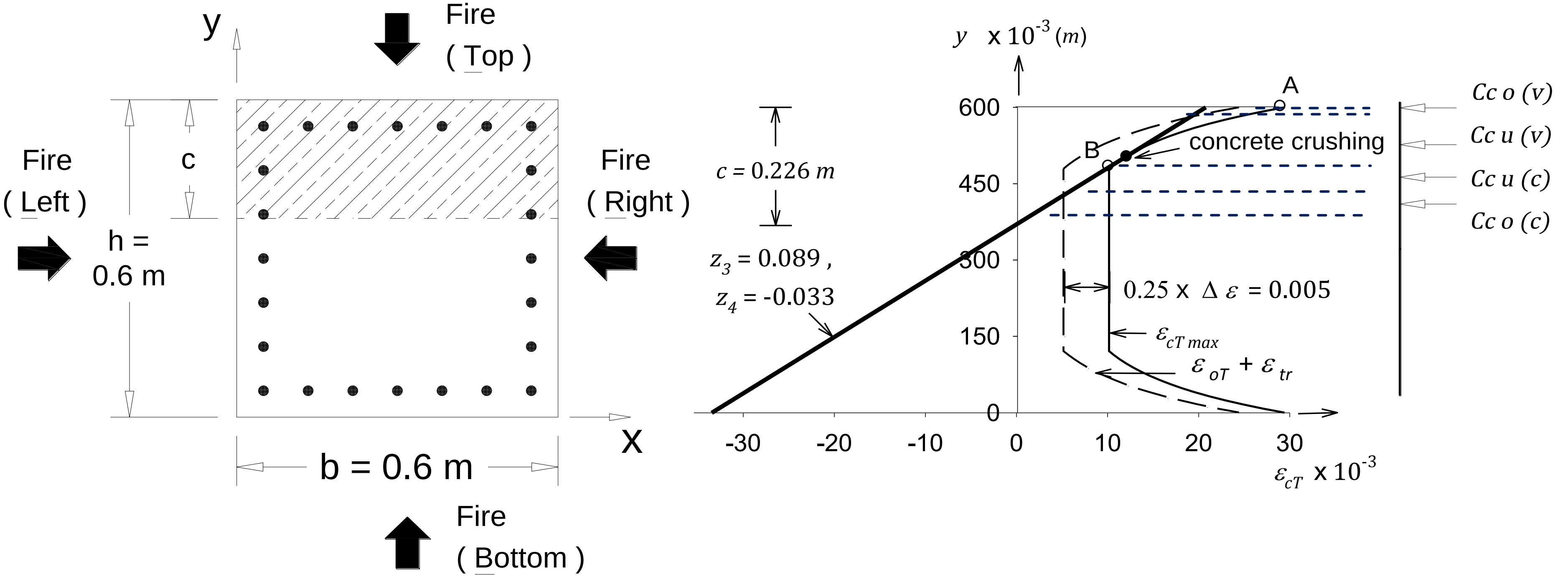






b)) $r = 0.25\,\Delta\varepsilon$

Location of Critical Strain

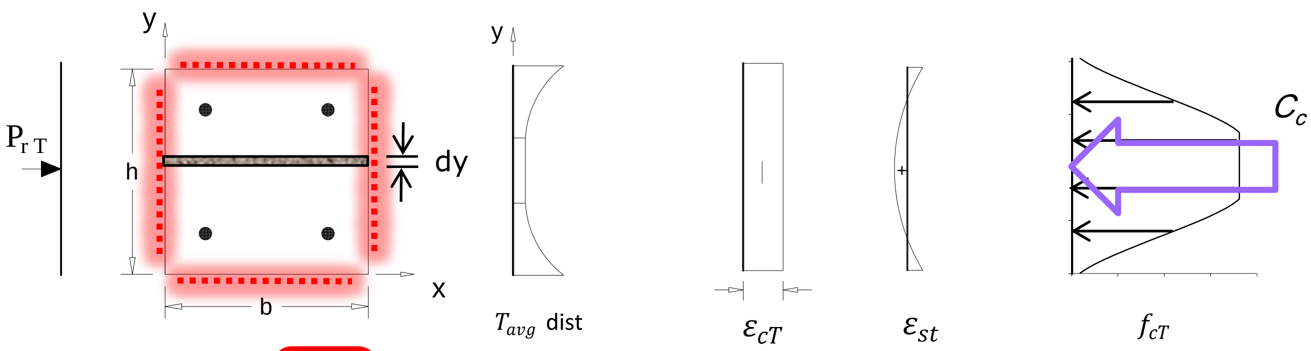


a) four-face heated RC section

b) ε_{cT} dist.

c) concrete forces

(9) Axial Capacity of Fire-Exposed RC Columns

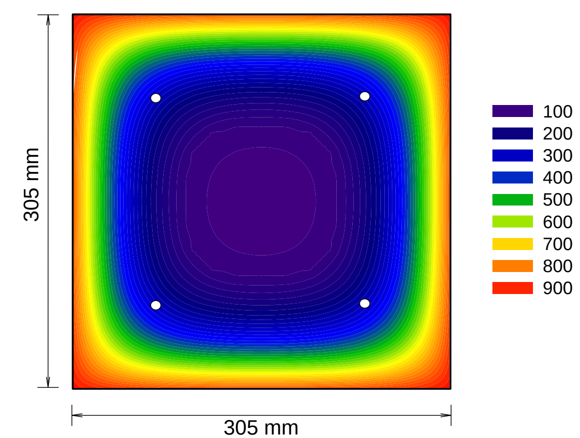


$$C_c = \int_{y\,=\,0.0}^{h} (f_{cT})\; b \;\; dy$$

$$f_{cT} = f'_{cT}\left[2\left(\frac{\varepsilon_{cT}}{\varepsilon_{oT}+\varepsilon_{tr}}\right)-\left(\frac{\varepsilon_{cT}}{\varepsilon_{oT}+\varepsilon_{tr}}\right)^2\right]$$

Temperature dependant

$f\,(T_{avg})$



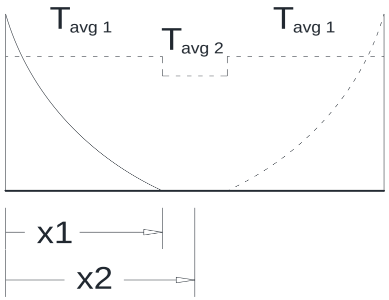
Closed Form Solution for Standard Fire Exposure

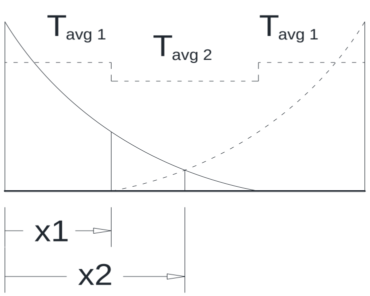
Temperature Distribution

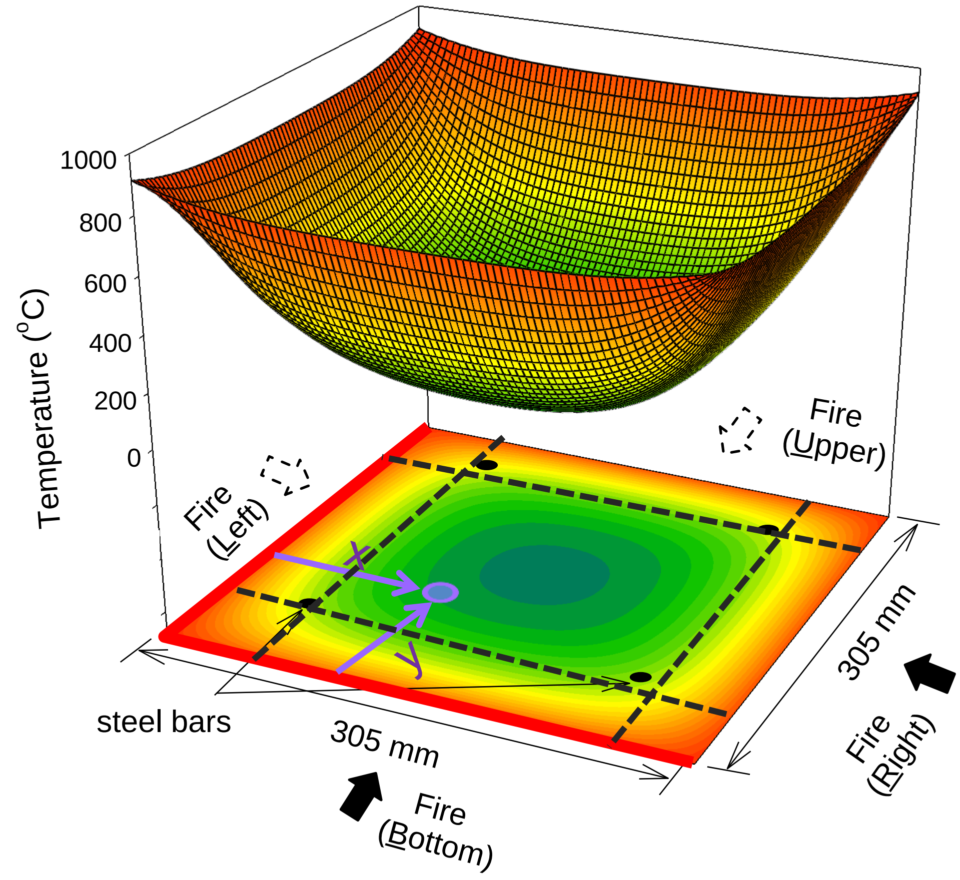
Wickstrom's Simple Method (1986)

$$T_{xy} = [n_w\,(n_x + n_y - 2n_x.n_y) + n_x.n_y]\,T_f$$

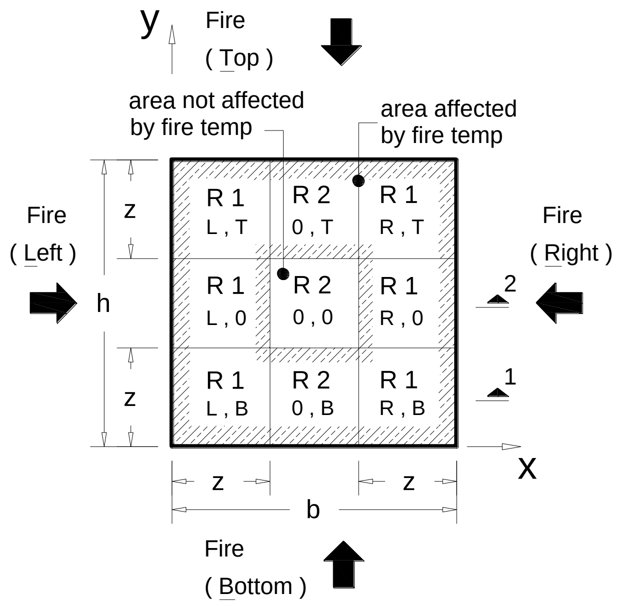
$$z = \sqrt{e^{-4.5}\;\;t}$$

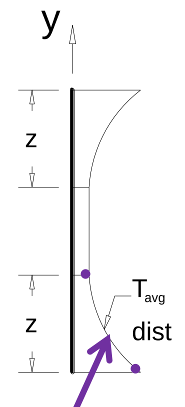






Average Temperature





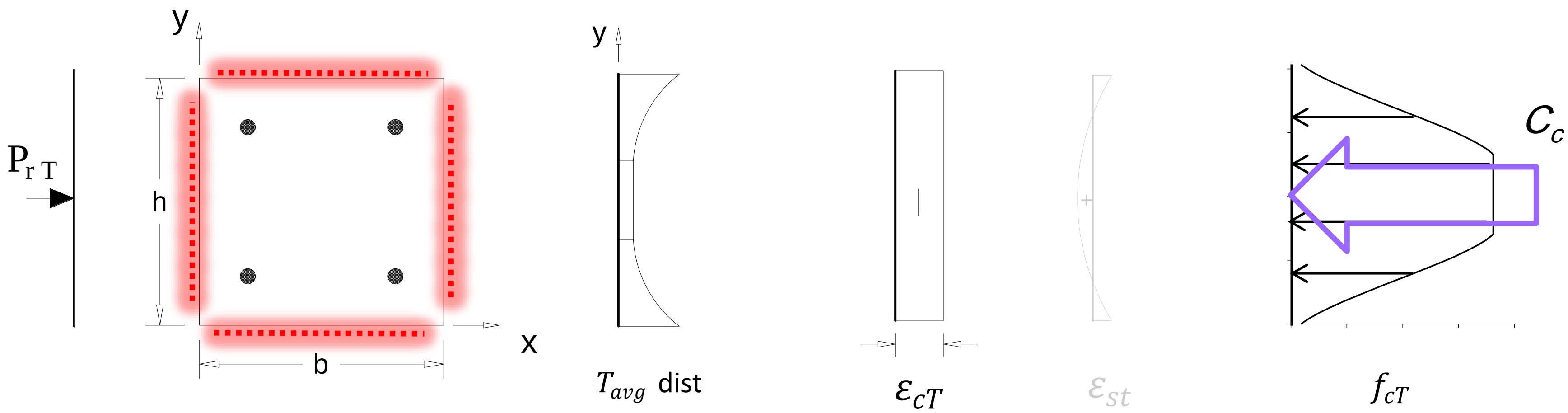
$$T_{avg} = z_1 \, . \, e^{(z_2 \, . \, y)}$$

$$T_{avg\ 1} = [0.18\, n_w - 0.36\, n_w . n_y + 0.18\, n_y] \left[x_2 \, ln\left(\frac{t}{{x_2}^2}\right) - x_1 \, ln\left(\frac{t}{{x_1}^2}\right) \right] \frac{T_f}{(x_2 - x_1)}$$

$$-0.45\, T_f . n_w + 1.9\, T_f . n_w . n_y - 0.45\, T_f . n_y \qquad x = x_1 \rightarrow x_2$$

$$T_{avg\ 2} = T_f . n_w . n_y$$

Integration



$$C_c = \int_{y=0.0}^{h} (f_{cT})\, b \;\, dy$$

closed form solution to evaluate f_{cT}

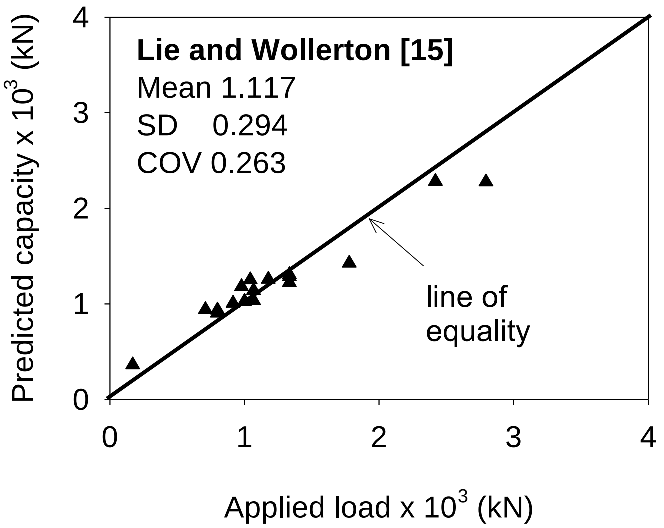
$$f_{cT} = f'_{cT}\left[2\left(\frac{\varepsilon_{cT}}{\varepsilon_{oT}+\varepsilon_{tr}}\right)-\left(\frac{\varepsilon_{cT}}{\varepsilon_{oT}+\varepsilon_{tr}}\right)^2\right]$$

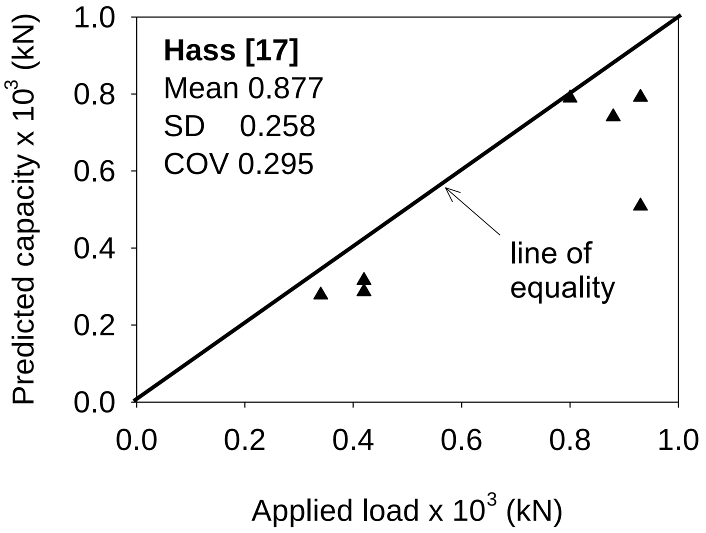
$$\varepsilon_{oT}+\varepsilon_{tr} = 2.52\times10^{-5}\,T_{avg}$$

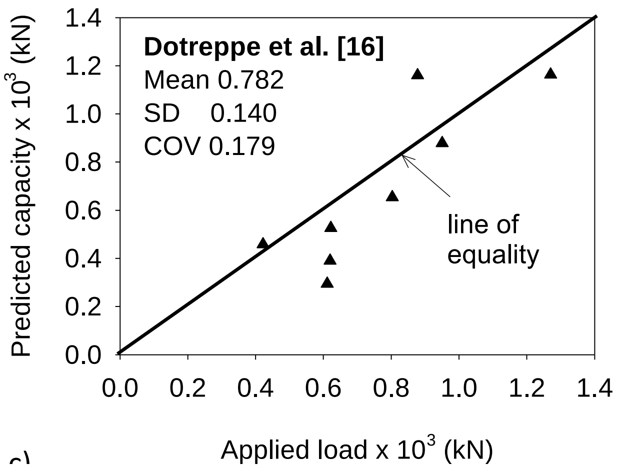
$$\frac{f'_{cT}}{f'_{c}} = 1.76\times10^{-9}\,T_{avg}^{\;3} - 3.00\times10^{-6}\,T_{avg}^{\;2} + 2.50\times10^{-4}\,T_{avg} + 1.00$$

$$T_{avg} = z_1 \,.\, e^{(z_2\,.\,y)}$$

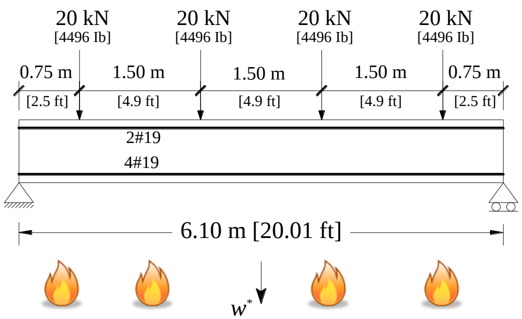
Validation (33 columns)

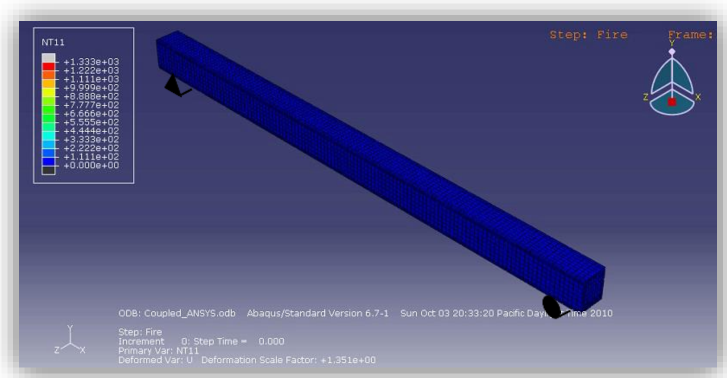


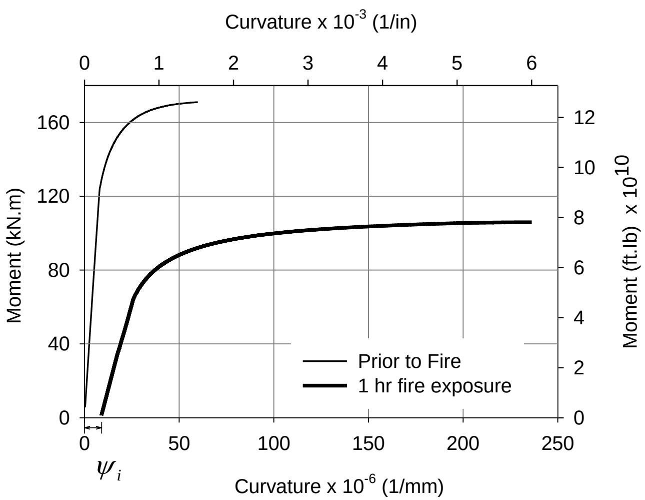


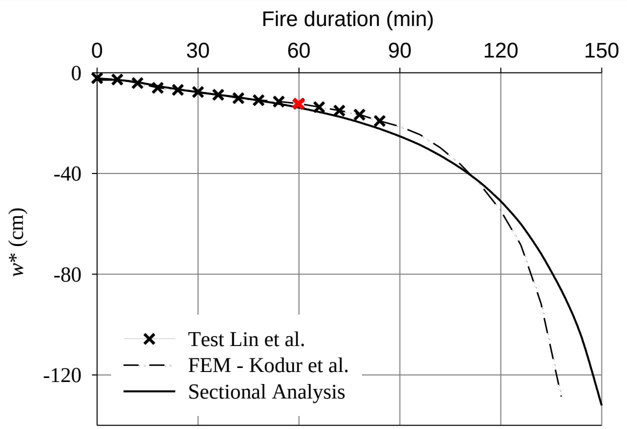


(10) Validation RC Beams

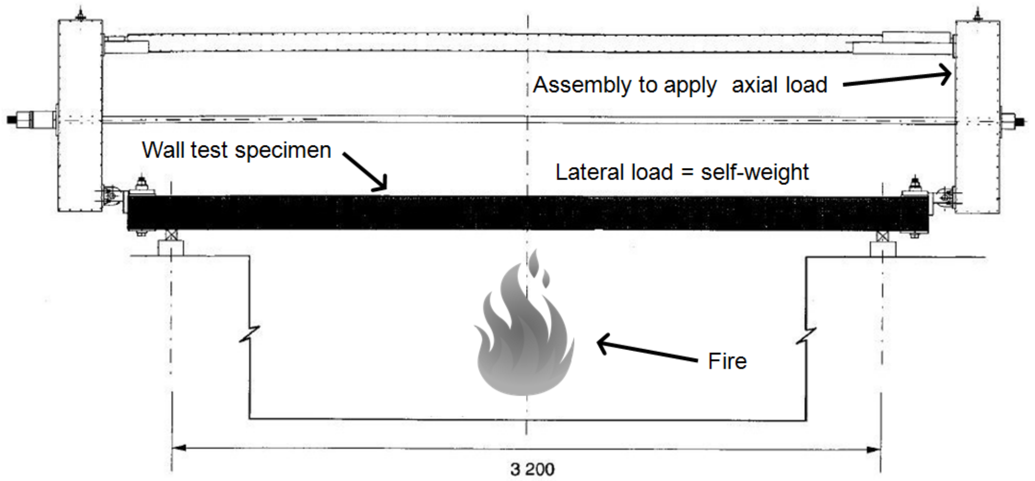


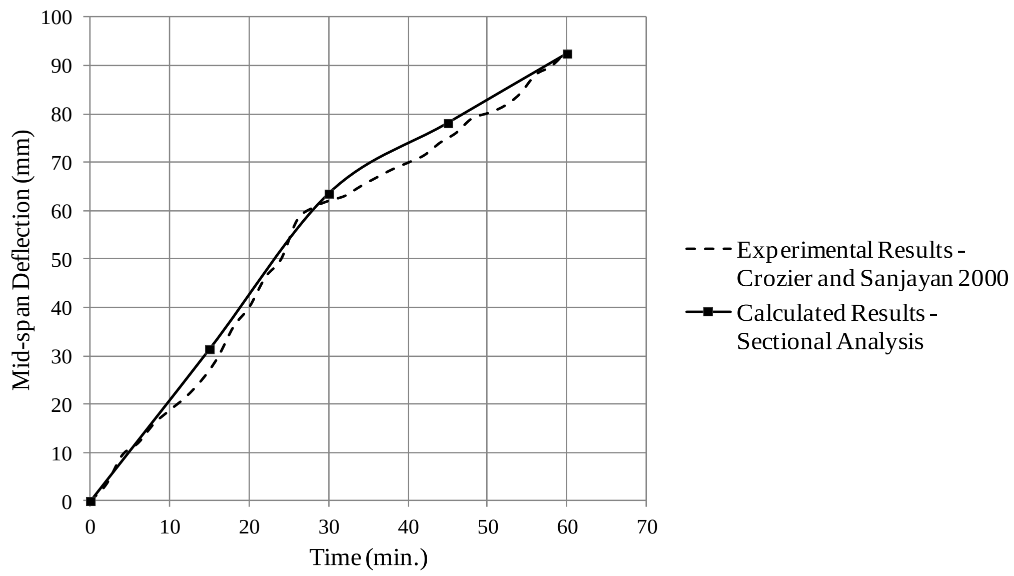




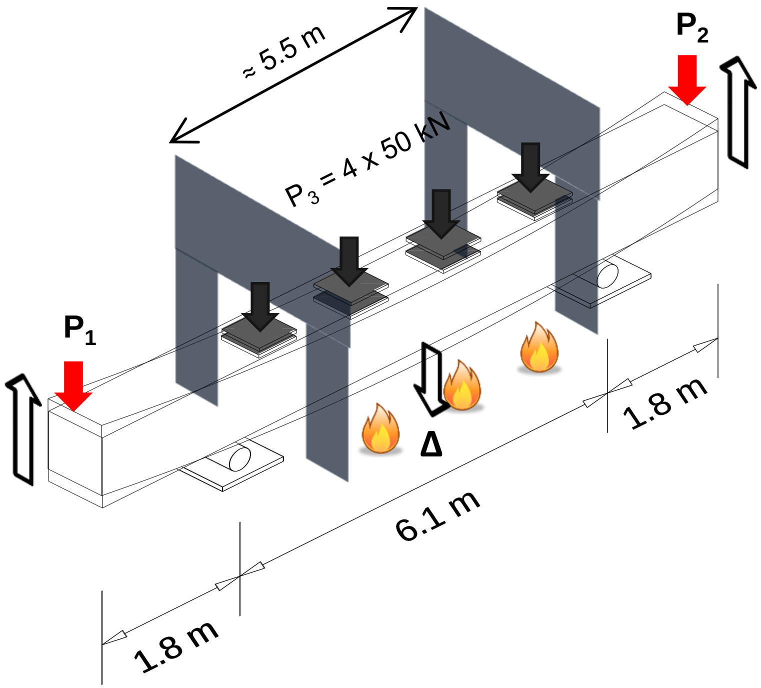


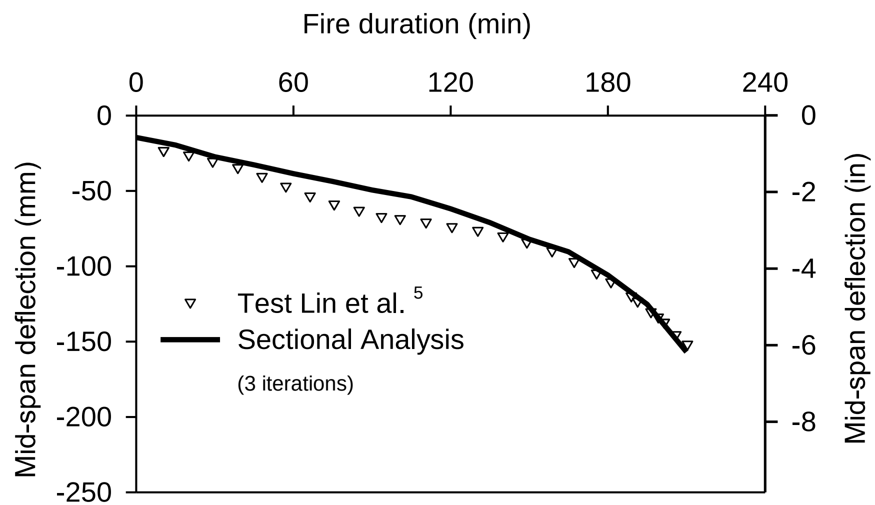
Validation for RC Walls



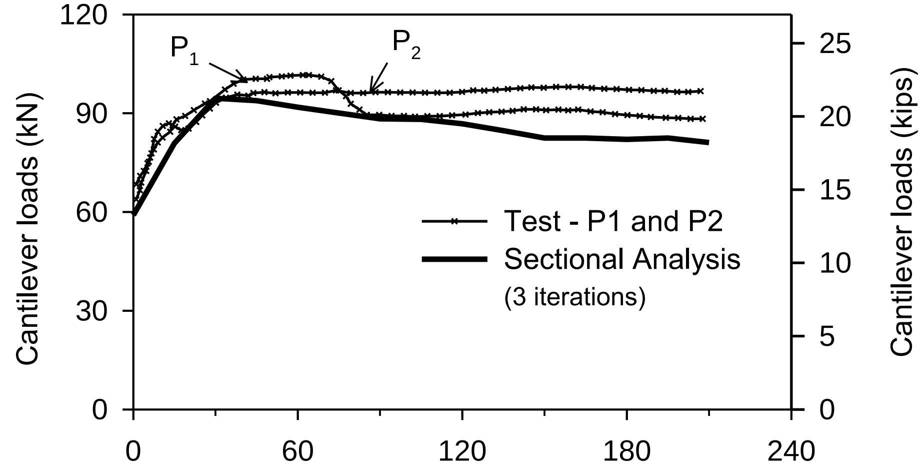


Validation Restrained Beam



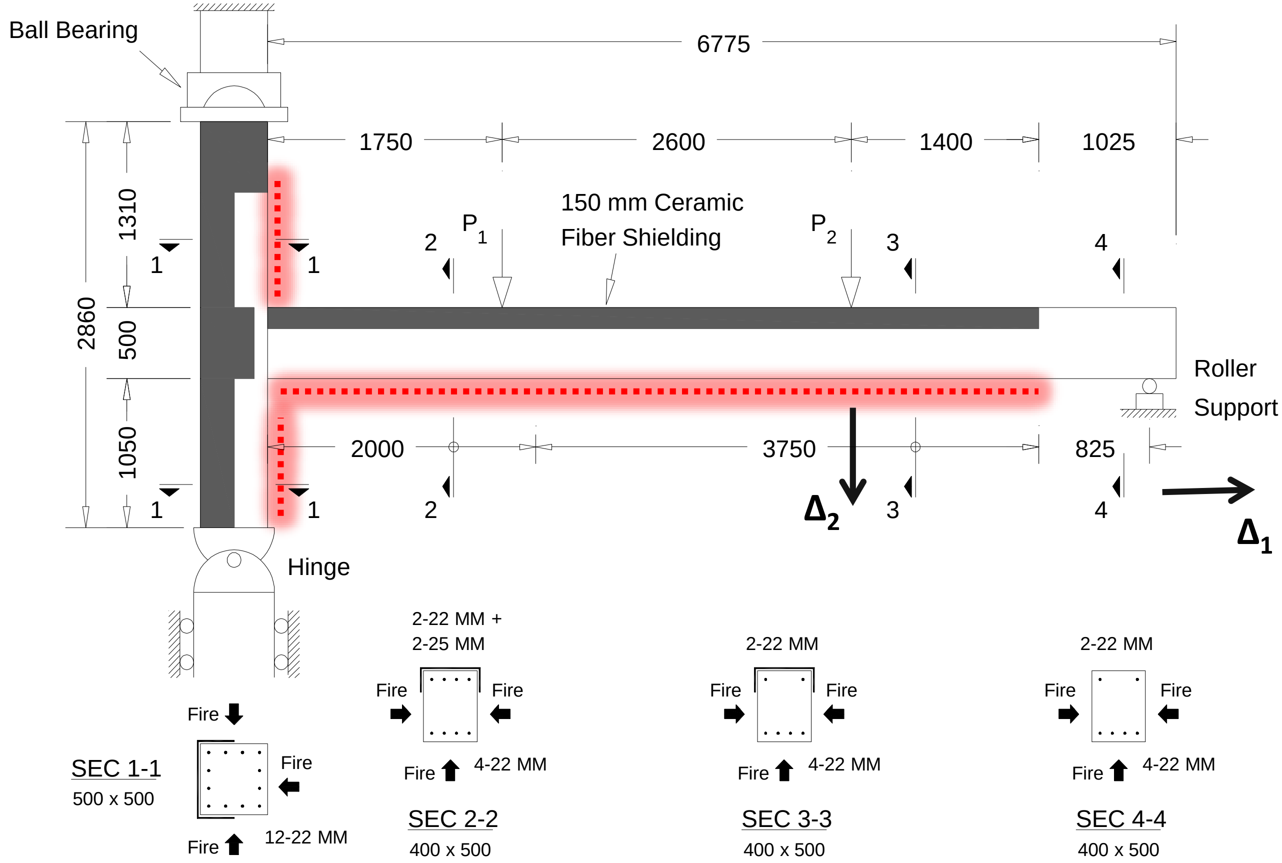


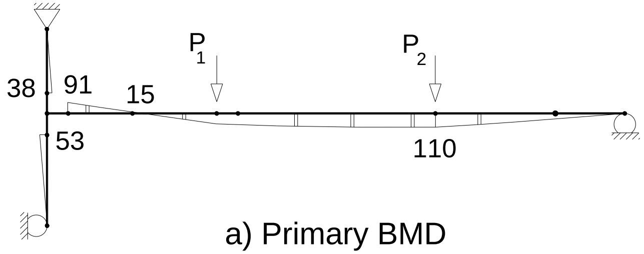
1. Loaded prior to Fire test
2. P1 and P2 were 59 kN prior to fire test.
3. During fire test, P1 and P2 varied such that the cantilever deflection stays constant.



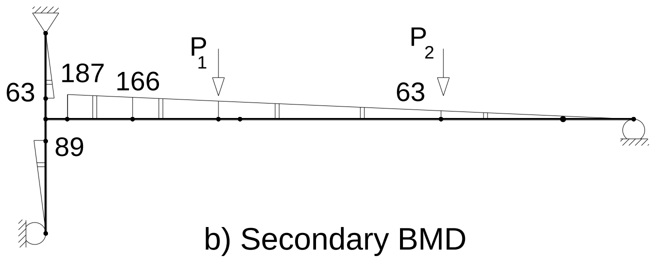
Validation for a Frame

- Axial load on column = 1727 kN
- P_1 & P_2= 78 & 49 kN
- Δ_1 and Δ_2 were monitored during the fire test

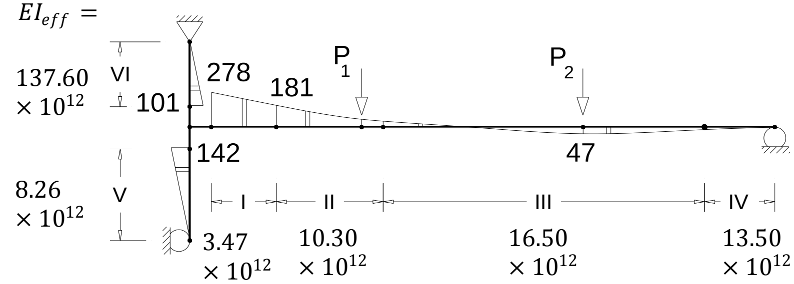




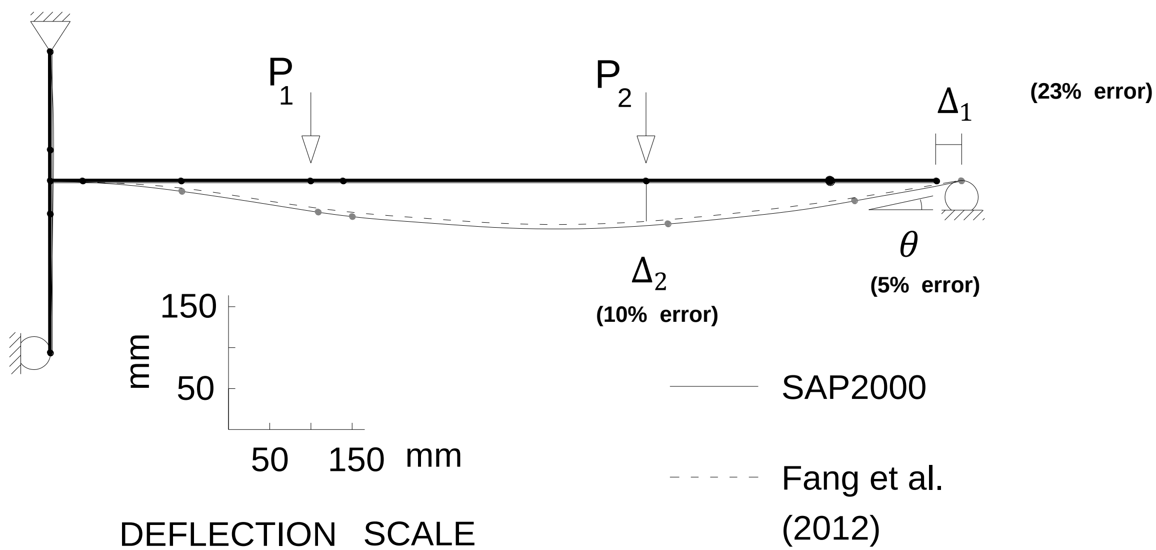
a) Primary BMD



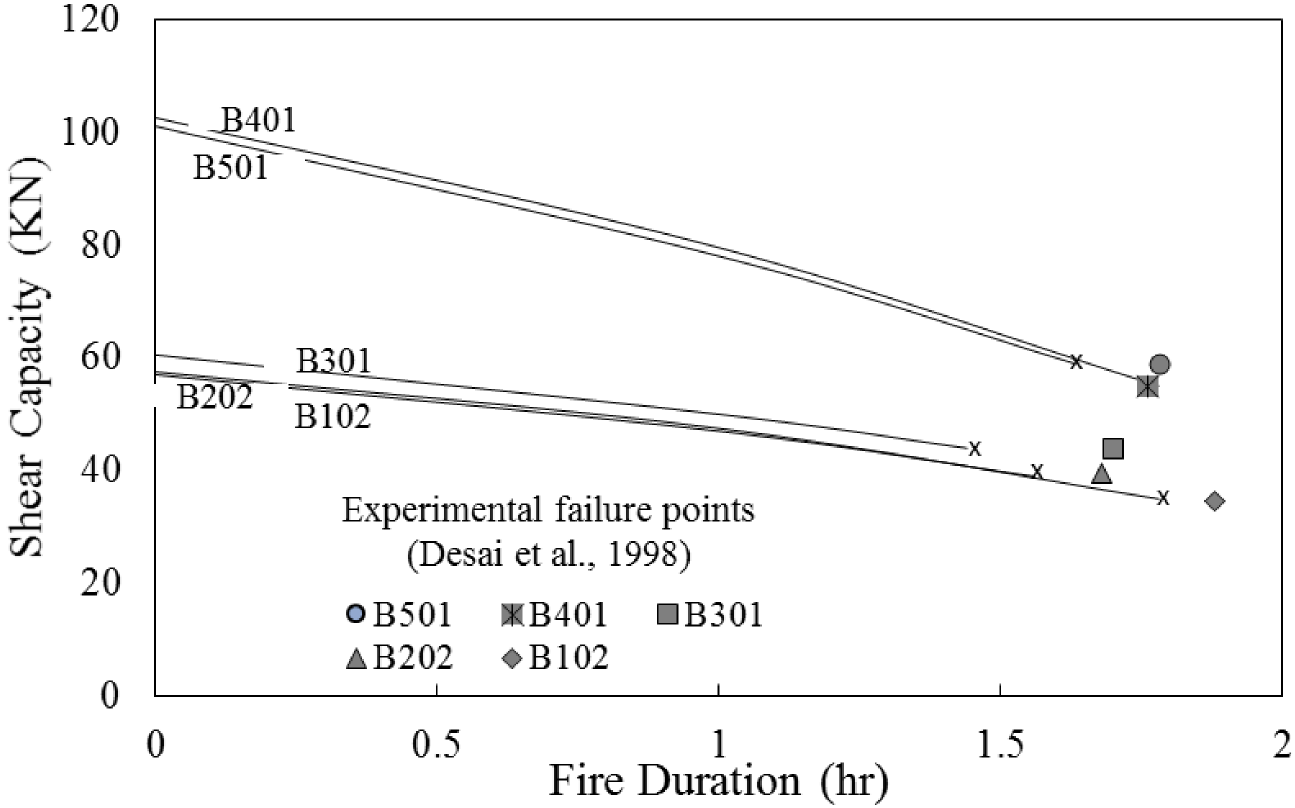
b) Secondary BMD



c) Total BMD (Stiffnesses in $N.mm^2$)



Shear Capacity Validation



For additional details, please refer to:

- **Youssef MA**, Diab M, EL-Fitiany SF, in-press, "Prediction of the Shear Capacity of Reinforced Concrete Beams at Elevated Temperatures", ***Magazine of Concrete Research***.
- El-Fitiany SF, **Youssef MA**, 2014, "Interaction Diagrams for Fire-Exposed Reinforced Concrete Sections", ***Engineering Structures***, 70: 246-259.
- El-Fitiany SF, **Youssef MA**, 2014, "Simplified Method to Analyze Continuous Reinforced Concrete Beams during Fire Exposure", ***ACI Structural Journal***, 111(1): 145-155.
- El-Fitiany SF, **Youssef MA**, 2011, "Stress-Block Parameters for Reinforced Concrete Beams during Fire Events", ***ACI SP-279: Innovations in Fire Design of Concrete Structures***, Paper No. 1, pp. 1-39.
- El-Fitiany SF, **Youssef MA**, 2009, "Assessing the Flexural and Axial Behaviour of Reinforced Concrete Members at Elevated Temperatures using Sectional Analysis", ***Fire Safety Journal***, 44(5): 691-703.
- **Youssef MA**, El-Fitiany SF, Elfeki M, 2008, "Flexural Behavior of Protected Concrete Slabs after Fire Exposure", ***ACI SP-255: Designing Concrete Structures for Fire Safety***, Paper No. 3, pp. 47-74.
- **Youssef MA** and Moftah M, 2007, "General Stress-Strain Relationship for Concrete at Elevated Temperatures", ***Engineering Structures***, 29 (10): 2618-2634.

Thank You !!