Fire Resistance of Reinforced Concrete Structures

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Western UNIVERSITY · CANADA

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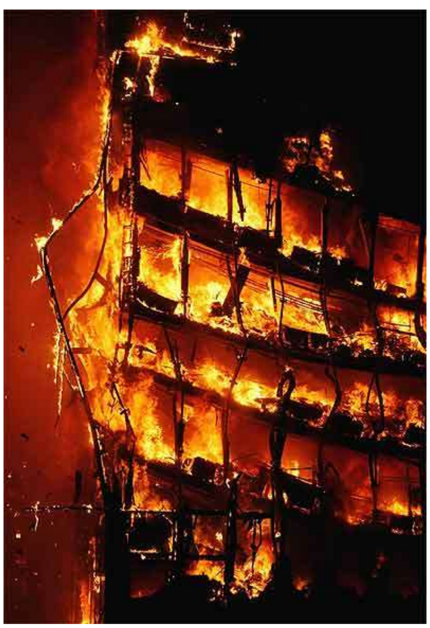

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Fire Safety

- Annual fire occurrence in high-rise buildings exceeds 10,000 incidents in US.
- Fire Safety:
  – Automatic fire sprinklers
  – Systems for fire detection
  – Safe travel (Egress) paths
  – Barriers to control the fire spread, and
  – Fire-resistant structures

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Outline

- Fire Modeling.
- Design for Fire.
- Constitutive Models at Elevated Temperatures
- Analysis Tools
- Simplified Analysis
- Design Tools for Flexural and Shear

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Fire Stages

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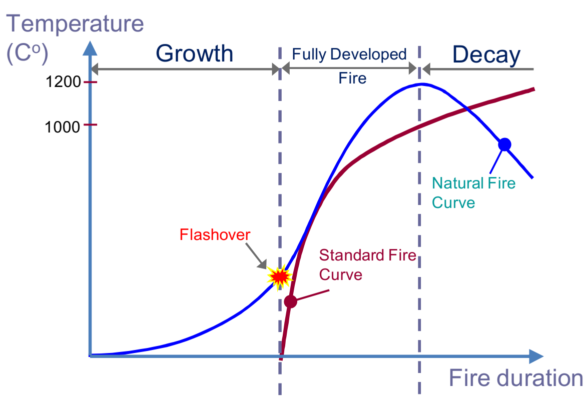
Fire Modeling



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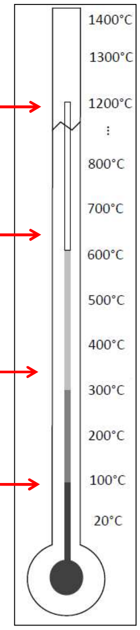
Effect of Fire on Concrete

- Melting starts.

- Calcium carbonate dissociates.
- Total loss of water hydration.

- Calcium hydroxide dissociates.
- Gravels breaks up.

- Free water lost.
- Permeability increases.



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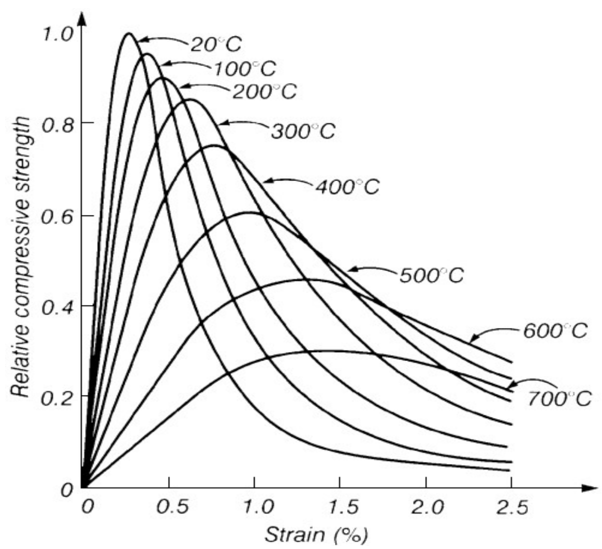
Concrete Stress-Strain Relationship at Elevated Temperatures



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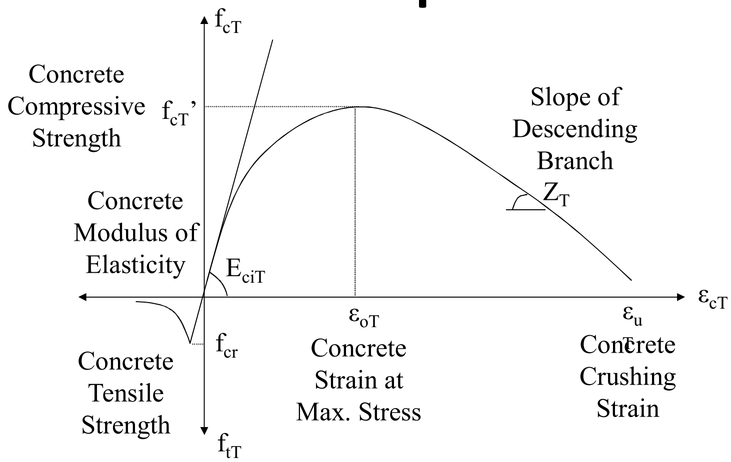
Concrete Stress-Strain Model at Elevated Temperatures



Chosen Models

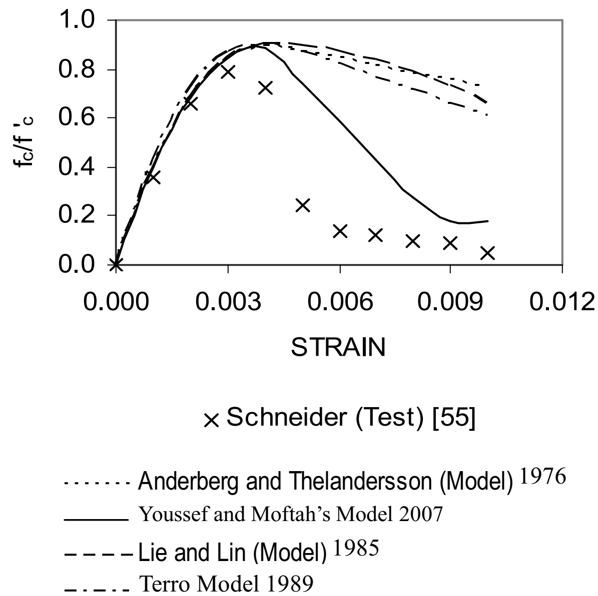
Property	Selected Model	Advantages
Compressive Strength	Hertz (2005)	A, L
Modulus of Elasticity	Anderberg (1976)	A, L
Transient Creep Strain	Terro (1998)	A, L, V_A
Strain at Peak Stress	Terro (1998)	L
Tensile Strength	Terro (1998)	A
Free thermal strain	Eurocode (1992)	A

A = Accounts for Aggregate Type

V_A = Accounts for Volume of Aggregates

L = Accounts for Preloading Compressive Stresses

Youssef and Moftah's Model



Accounts for:

Temperature,

Preloading,

Transient Creep strain,

Cracking,

Confinement.

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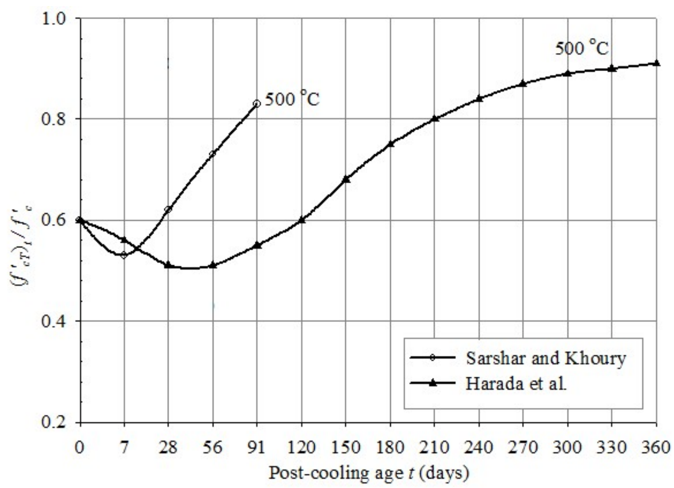
Residual Concrete Compressive Strength

Concrete continues loosing strength following the fire



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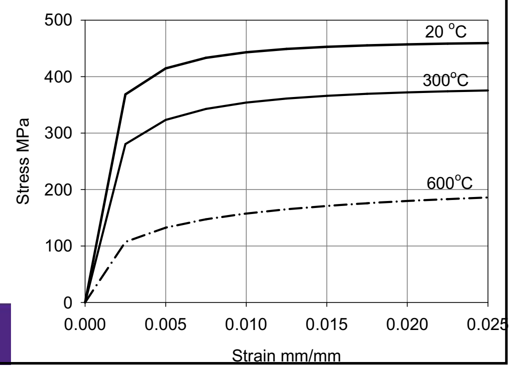
Steel Stress-Strain Relationship at Elevated Temperatures

$$f_{yT} = \left[1 + \frac{T}{900\ln(T/1750)}\right] \times f_y \qquad 0 < T \le 600^o C$$

Lie's model

$$f_{yT} = \left[\frac{340 - 0.34T}{T - 240}\right] \times f_y \qquad T > 600^o C$$



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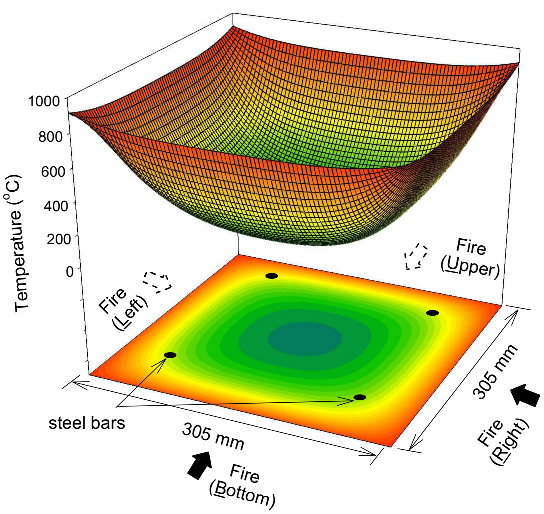
Heat Transfer Analysis

- Finite Element.
- Finite Difference.
- Approximate

  Example:

  Wickstrom's method



$$T_{xy} = \left[\eta_w\left(\eta_x + \eta_y - 2\eta_x.\eta_y\right) + \eta_x.\eta_y\right] T_f$$

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Design for Fire

- Prescriptive Methods:
  - Simple and empirical but limited in applicability.
- Performance Based Design (PBD) evaluates the performance of the structure under realistic fire loads. It has many advantages:
  - allow engineers to achieve innovative solutions.
  - cost-effectiveness and flexibility in design
  - harmonization between regulations/codes
  - changes in construction technology

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Potential Methods to Achieve PBD

- Fire Tests (costly, limits).
- Nonlinear Finite Element Analysis

  (can be accurate, computationally expensive and complex)

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Simplified Tools for PBD of Structures Exposed to Fire

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

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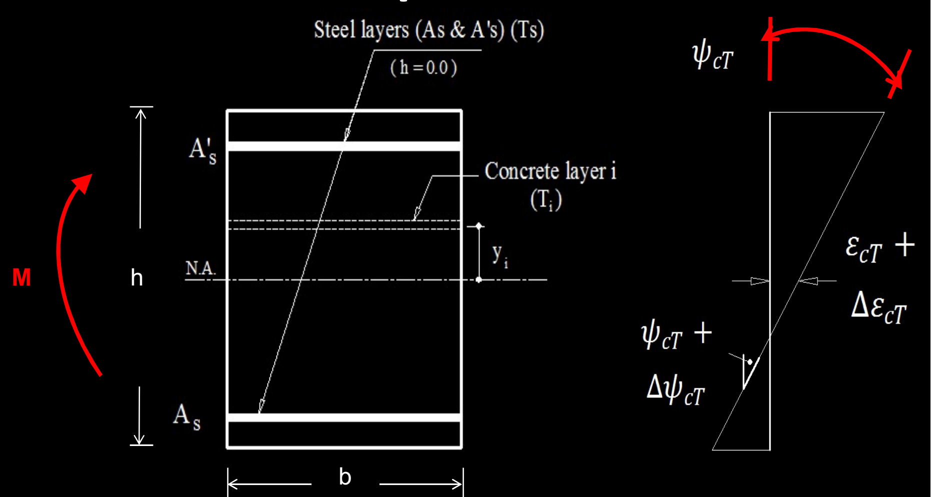
Sectional Analysis at Ambient Temperature



Sectional Analysis at Elevated Temperatures

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

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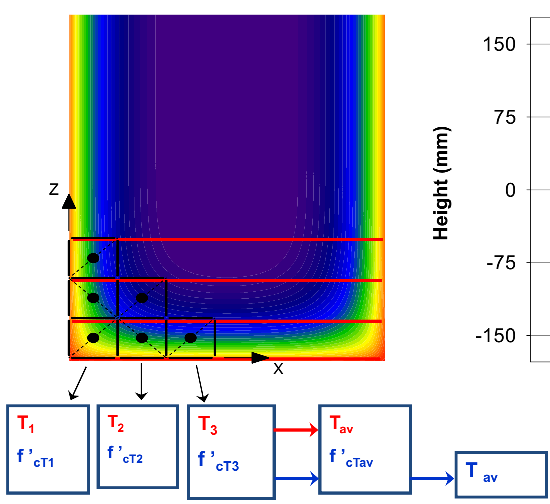
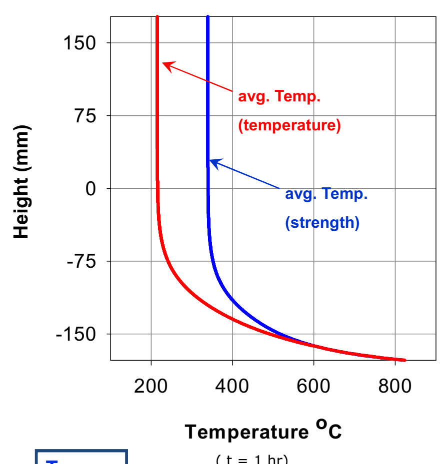
Temperature Distribution





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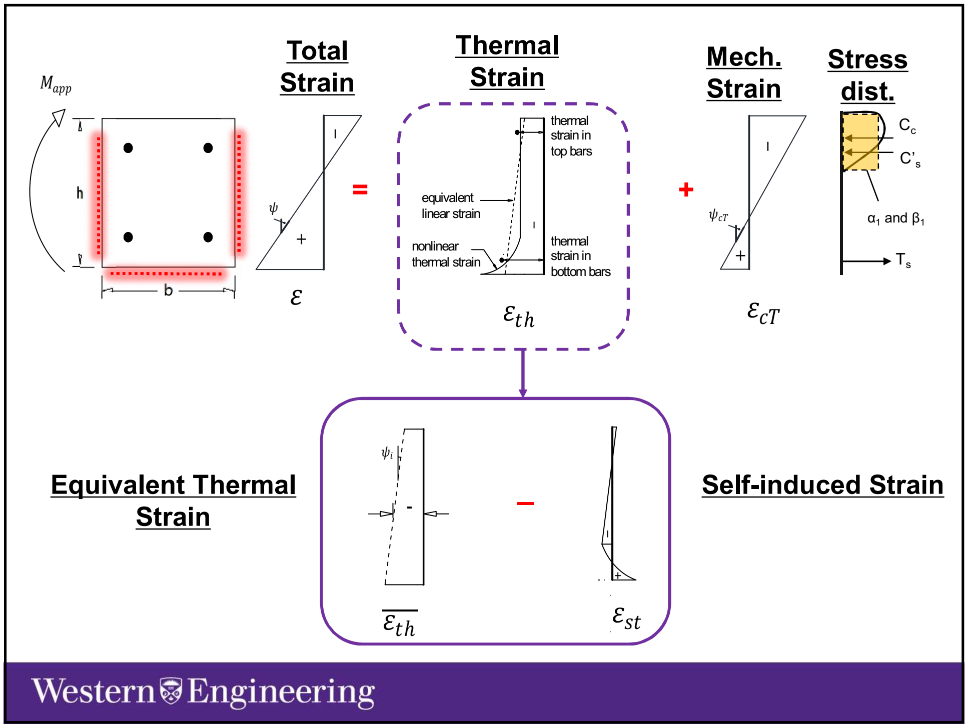
Total Strain
Thermal Strain
Mech. Strain
Stress dist.
M_{app}
h
b
ε
thermal strain in top bars
equivalent linear strain
nonlinear thermal strain
thermal strain in bottom bars
ε_{th}
ε_{cT}
C_c
C'_s
α_1 and β_1
T_s
Equivalent Thermal Strain
Self-induced Strain
$\overline{\varepsilon_{th}}$
ε_{st}
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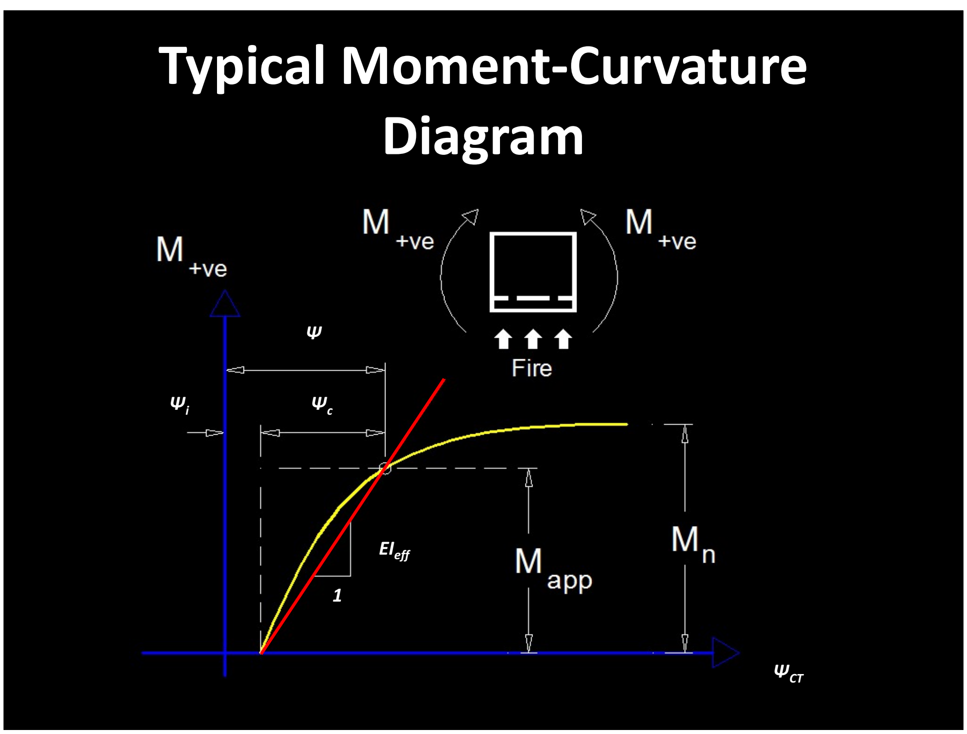
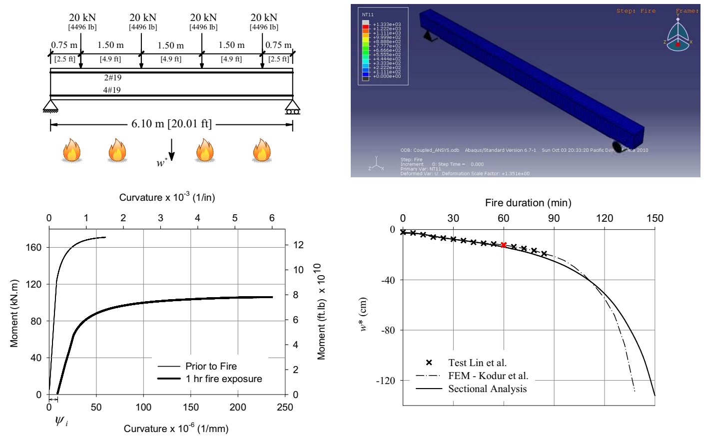
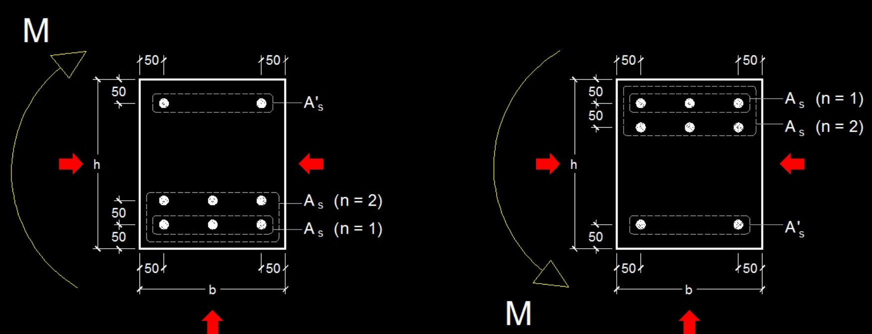

Typical Moment-Curvature Diagram
M +ve
M +ve
M +ve
Fire
ψ
ψ_i
ψ_c
EI_{eff}
1
M_{app}
M_n
ψ_{CT}

Validation

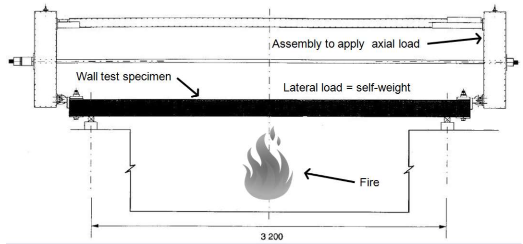


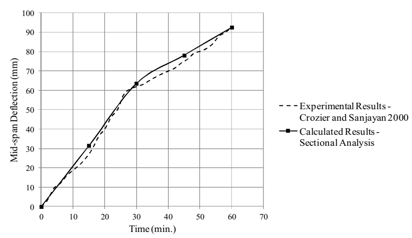
Parametric Study

- Moment-Curvature diagrams are studied for 35 beams heated up to 2.5 hrs ASTM-E119
- Studied parameters (b, h, As , A's, Aggregate Type)



Validation for RC Walls





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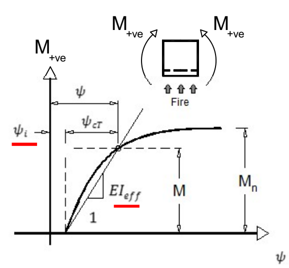
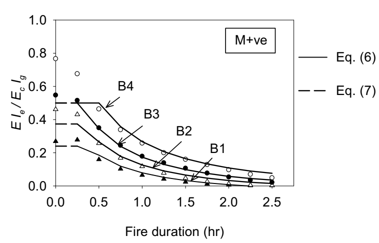
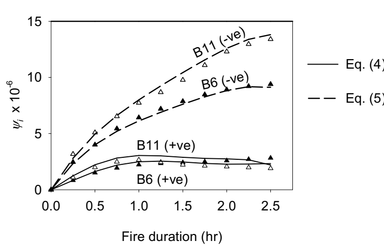
Initial Thermal Curvature and Effective EI







Proposed Equations

$\psi_i = f\,(\ldots.\, t\,,\ b\,,\ As,\ A's\,,\ n\,,\ Agg\ \ldots)$

$EI_{eff} = f\,(\ldots.\, t\,,\ \lambda,\ As,\ A's\,,\ Agg\ \ldots)$

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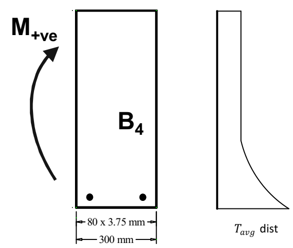
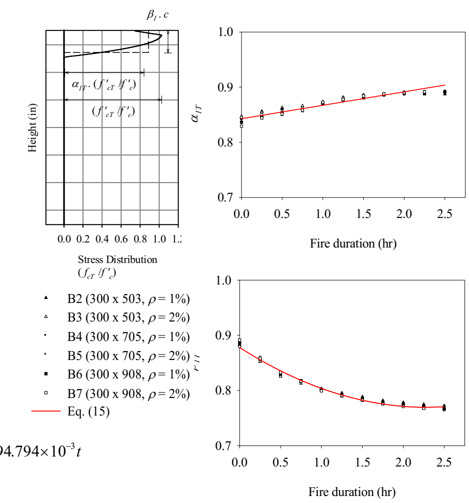
Stress Block Parameters (+ve Bending)

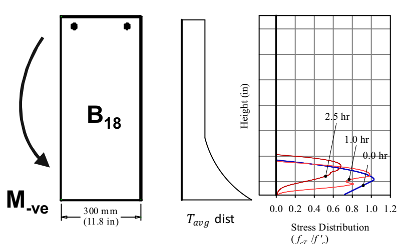




$$\alpha_{1T} = \alpha_1 - 1.533\times10^{-2} + 24.397\times10^{-3}t + 15.758\times10^{-4} f'c - 10.089\times10^{-5} b$$

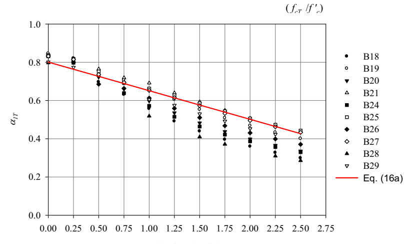
$$\beta_{1T} = \beta_1 - 2.907\times10^{-2} + 20.734\times10^{-3}t^2 - 94.794\times10^{-3}t - 75.057\times10^{-5} f'_c + 15.413\times10^{-5} b$$

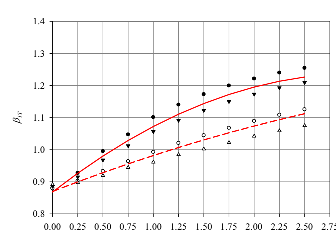
Stress Block Parameters (-ve Bending)



$$\alpha_{1T} = \alpha_1 - 2.735\times10^{-2} - 1.497\times10^{-1}t + 7.579\times10^{-2} F_{agg.}$$

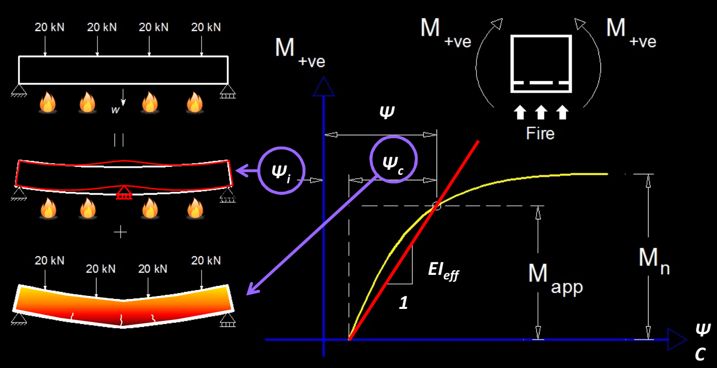
$$\beta_{1T} = \beta_1 - 1.965\times10^{-1} - 4.054\times10^{-2}\left(\frac{t}{\rho}\right)^2 + 2.448\times10^{-1}\left(\frac{t}{\rho}\right) - 3.456\times10^{-2} F_{agg.} + 3.687\times10^{-3} f'_c + 2.342\times10^{-4} b$$





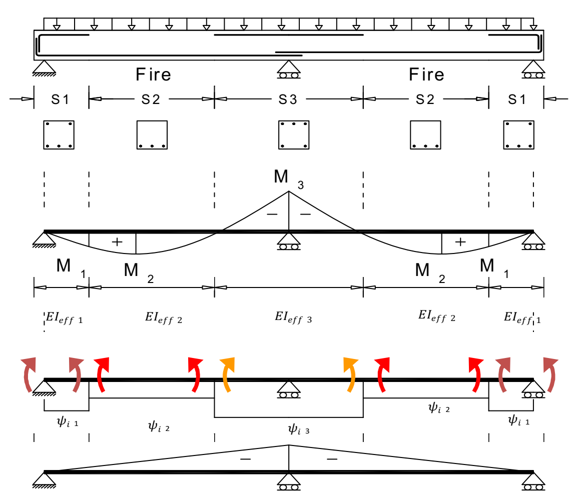
Restrain Action

Total curvature (Ψ) = thermal curvature (Ψ_i) + mechanical curvature (Ψ_c)



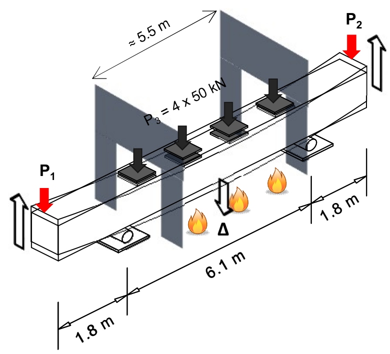
Proposed Method

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



Validation

1. Loaded prior to test
2. Ends restrained in Vl. dir.
3. ASTM-E119 (5.5 m only)
4. Δ , P_1 , and P_2 were monitored during fire



Validation Analysis

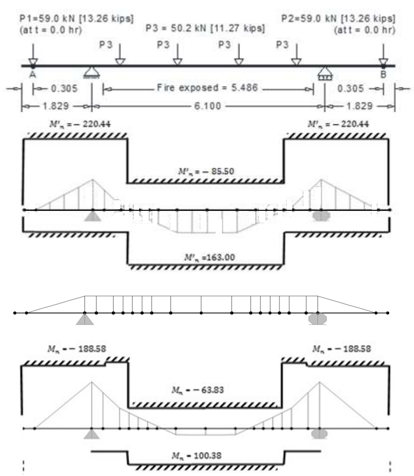
- ❑ **Primary BMD**

  +

- ❑ **Secondary BMD**

  =

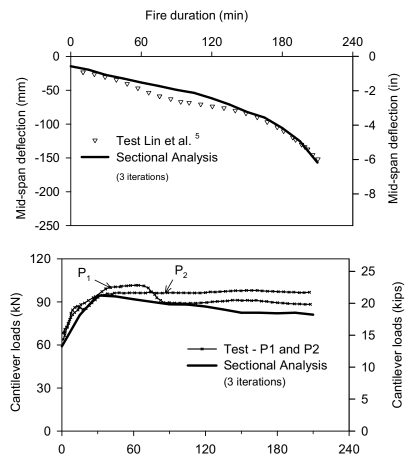
- ❑ **Total BMD**



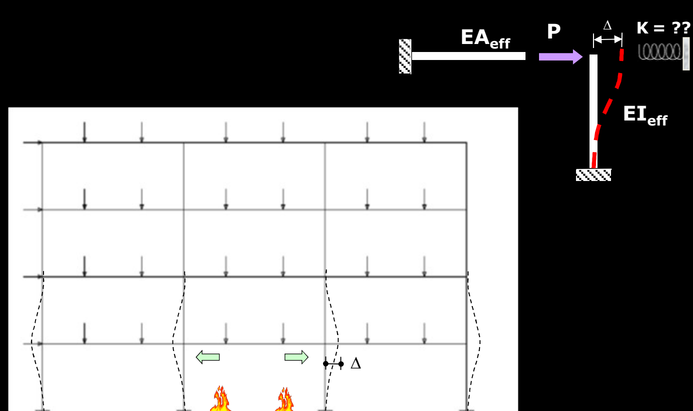
Validation Results

TEST RESULTS

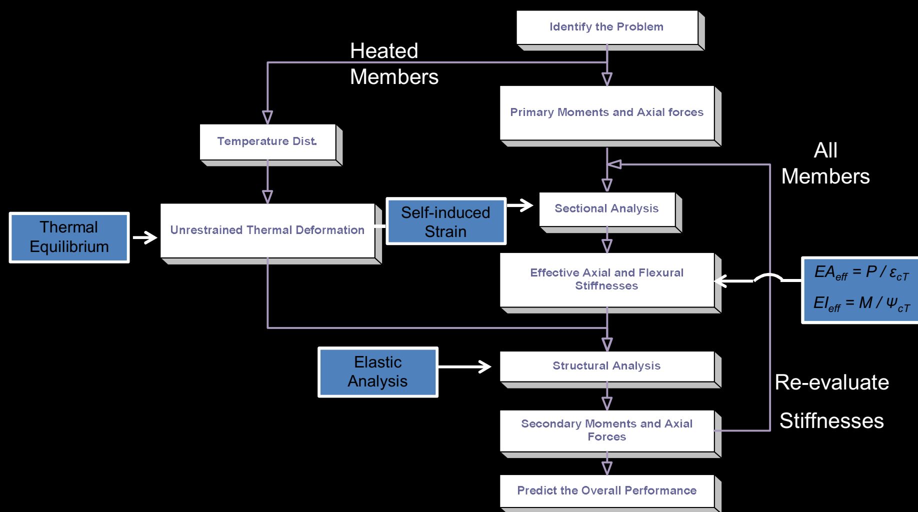
- Theoretically fail after 160 min
- Load redistribution extended the failure > 180 min
- Good agreement with test results



Frame Analysis (Challenges)

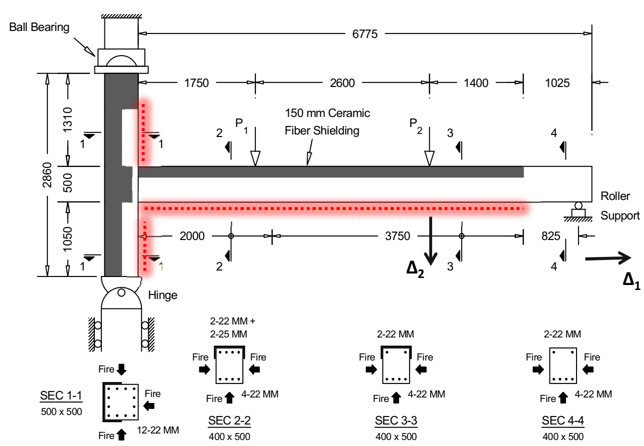


Youssef and El-Fitiany Method



Validation 1

- Axial load on column = 1727 kN
- Vl. loads on the beam = 78 & 49 kN
- 3 hrs ISO834
- The top 150 mm was shielded t (floor slab)
- Δ_1 and Δ_2 were monitored during the fire test



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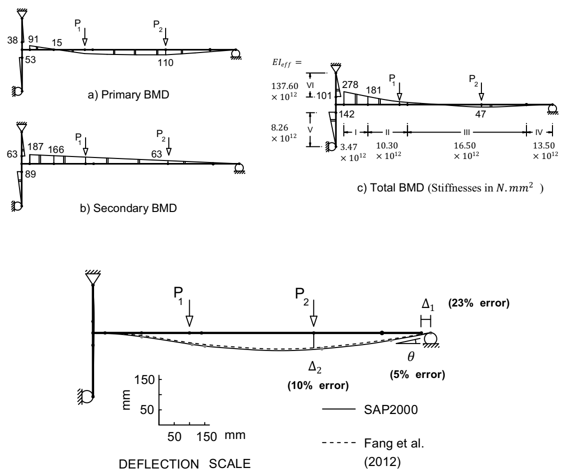
Validation 1 Results

- SAP2000
- Rigid links at the joints
- Unrestrained thermal deformation → Linear temperature loading
- The reduced flexural stiffness is assigned to each segment based on the applied moment



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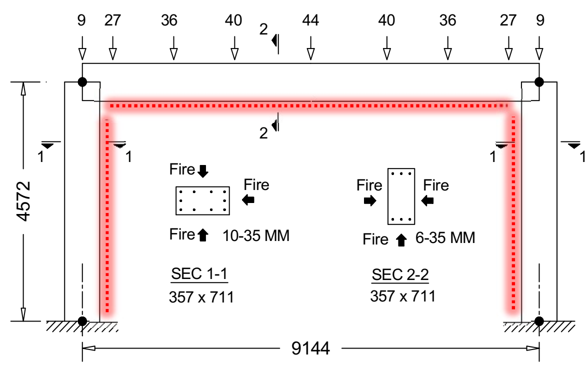
Validation 2

- A comprehensive FE software developed at University of California, Berkeley
- 1 hr ASTM-E119



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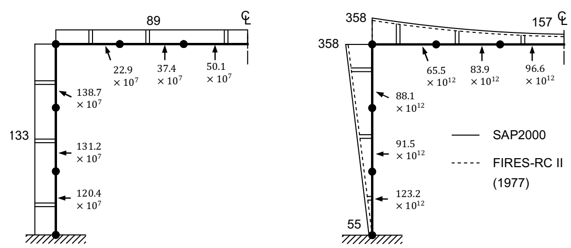
Validation 2 Results

- External forces / moments

  (1 hr ASTM-E119)

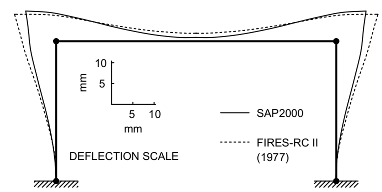


a) Axial (compression) force diagram (Stiffnesses in $N.mm^2$)

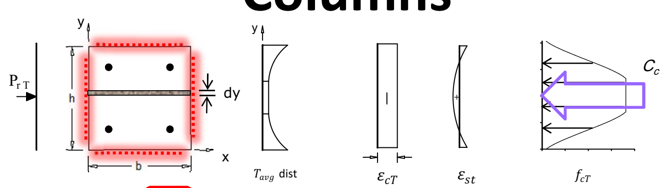
b) Total BMD (Stiffnesses in $N.mm^2$)

- RC frame deflection

  (1 hr ASTM-E119)



Axial Capacity of Fire-Exposed RC Columns

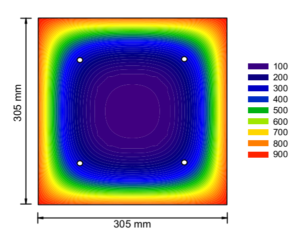


$$C_c = \int_{y=0.0}^{h} (f_{cT})\, b\ dy$$

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

Temperature dependant

$f\,(T_{avg})$



** t = 1 hr ASTM-E119

Temperature Boundaries

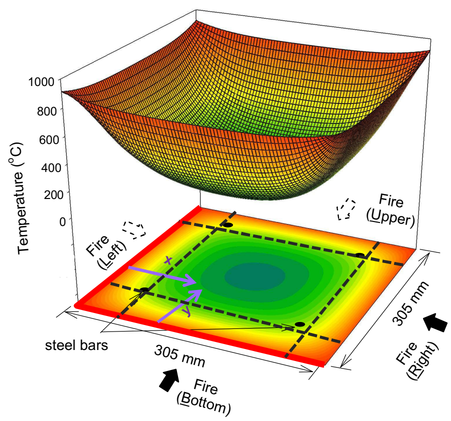
Wickstrom's Simple Method (1986)

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

= 0.0

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

(e.g. t = 1 hr → z = 0.105 m)



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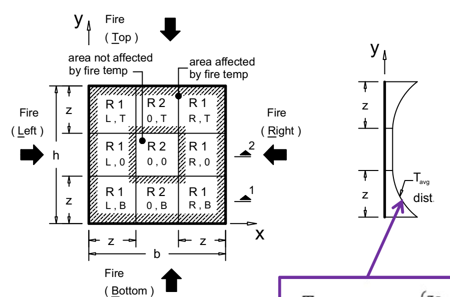
Average Temperature Distribution

- Identify heated regions R1, R2, R3
- Calculate $T_{avg\ R}$ for each region
- T_{avg} dist. is the weighted average



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

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

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

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

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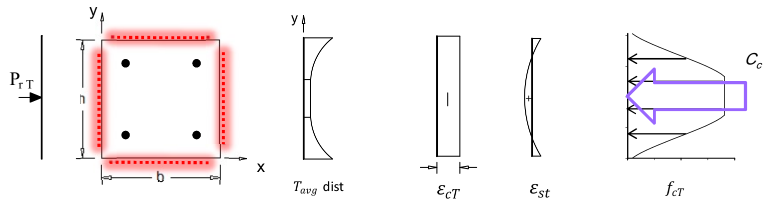
Closed Form Solution



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

closed form solution to evaluate f_{cT}

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

$$\varepsilon_{oT} + \varepsilon_{tr} = 2.52 \times 10^{-5}\, T_{avg}$$

$$\frac{f'_{cT}}{f'_c} = 1.76 \times 10^{-9}\, T_{avg}^{\,3} - 3.00 \times 10^{-6}\, T_{avg}^{\,2} + 2.50 \times 10^{-4}\, T_{avg} + 1.00$$

$$T_{avg} = z_1 \cdot e^{(z_2 \cdot y)}$$ ✓

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Axial Capacity of Fire-Exposed RC Columns

1. The heated section is divided into variable and constant temperature regions.
2. Average temperatures are evaluated.
3. The failure strain for the section is identified.
4. The average concrete stresses are predicted.
5. The axial capacity is evaluated.

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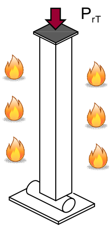
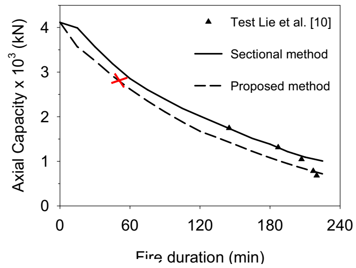
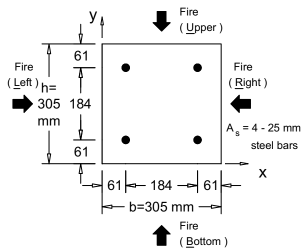
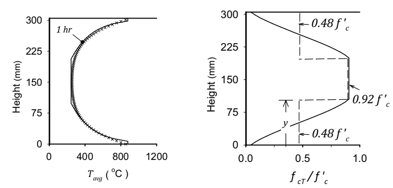
Validation

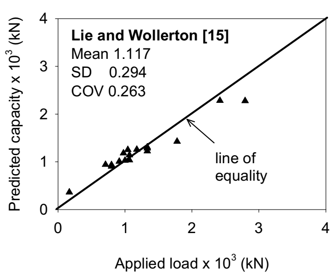


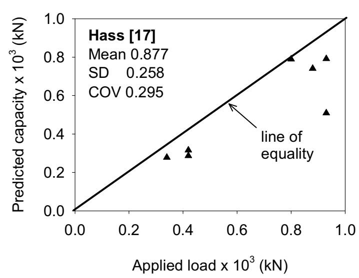


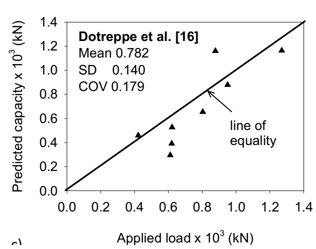




Validation (33 columns)



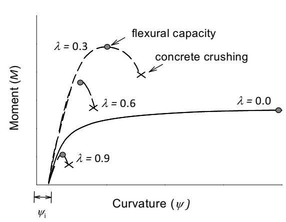


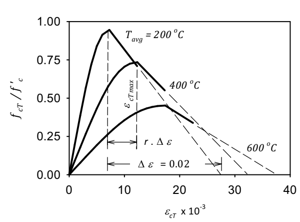


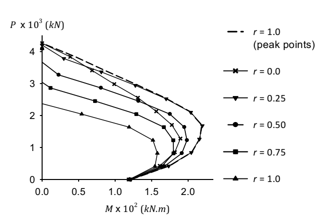
Interaction Diagrams at Elevated Temperatures

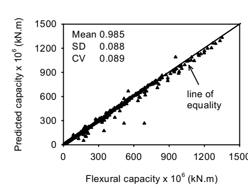
Strain Defining Moment Capacity of the Section

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





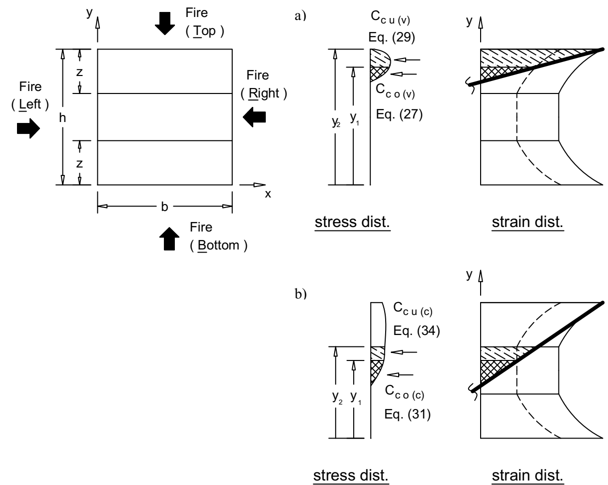




b)) $r = 0.25\,\Delta\varepsilon$

Internal Concrete Forces

- Variable T_{avg}
  - $\varepsilon_{cT} < \varepsilon_{oT} + \varepsilon_{tr}$
  - $\varepsilon_{cT} > \varepsilon_{oT} + \varepsilon_{tr}$
- Constant T_{avg}
  - $\varepsilon_{cT} < \varepsilon_{oT} + \varepsilon_{tr}$
  - $\varepsilon_{cT} > \varepsilon_{oT} + \varepsilon_{tr}$



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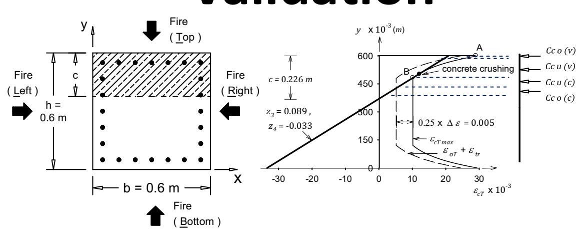
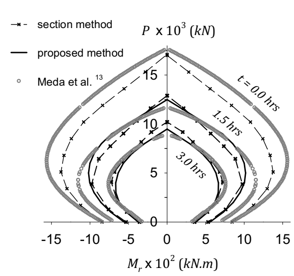
Validation



a) four-face heated RC section

b) ε_{cT} dist.

c) concrete forces



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Shear Capacity of Fire-Exposed RC Sections

Average Temperature of Shear Reinforcement

$$Temp\ (shear\ RFT) = \frac{A(y_v) - A(c) + B}{h - 2c}$$

$A = f(c, t)$

$B = f(h, c, t)$

Average Temperature of Concrete

$$Temp\ (Conc) = \frac{A'(x_v)(h - y_v) + B' + (0.5b - x_v)A'(y_v)}{(b)(h)/2}$$

$A' = f(t)$

$B' = f(h, b, t)$

h = beam height (m)

b = beam width (m)

c = cover (m)

t = fire duration (hr)

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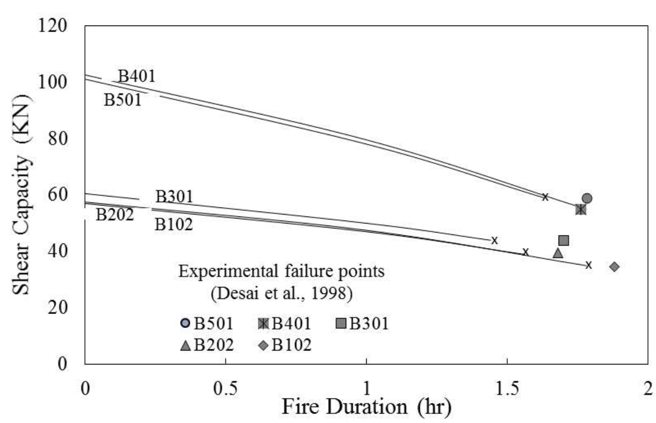
Validation



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- **For additional details, please refer to:**

- El-Fitiany SF, **Youssef MA**, in-press, "Interaction Diagrams for Fire-Exposed Reinforced Concrete Sections", ***Engineering Structures***, accepted March 2014.
- El-Fitiany S.F., **Youssef M.A**., 2014, "Simplified Method to Analyze Continuous Reinforced Concrete Beams during Fire Exposure", ***ACI Structural Journal***, Vol. 111, No. 1, pp. 145-155.
- El-Fitiany S.F., **Youssef M.A**., 2011, "Stress-Block Parameters for Reinforced Concrete Beams during Fire Events", ***ACI SP-279: Innovations in Fire Design of Concrete Structures***, ACI-TMS Committee 216: Fire Resistance and Fire Protection of Structures, Paper No. 1, pp. 1-39.
- El-Fitiany S.F., **Youssef M.A.**, 2009, "Assessing the Flexural and Axial Behaviour of Reinforced Concrete Members at Elevated Temperatures using Sectional Analysis", ***Fire Safety Journal***, Vol. 44, No. 5, pp. 691-703.
- **Youssef M.A**., El-Fitiany S.F., Elfeki M., 2008, "Flexural Behavior of Protected Concrete Slabs after Fire Exposure", ***ACI SP-255: Designing Concrete Structures for Fire Safety***, ACI-TMS Committee 216: Fire Resistance and Fire Protection of Structures, Paper No. 3, pp. 47-74.
- **Youssef M.A.** and Moftah M., 2007, "General Stress-Strain Relationship for Concrete at Elevated Temperatures", ***Engineering Structures***, Vol. 29, No. 10, pp. 2618-2634.

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Thank You !!

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