Tools for Performance and/or Objective Based Structural Fire Design

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Design Codes and Structural Fire Engineering

• Architect and Structural Engineer

• *EuroCode 2*:  
  – estimate the fire resistance of *structural elements*.  
  – 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

Temperature Distribution

Temperature $^\circ$C

Height (mm)

$T_1$ $f'_cT_1$

$T_2$ $f'_cT_2$

$T_3$ $f'_cT_3$

$T_{av}$ $f'_cT_{av}$

avg. Temp. (temperature)

avg. Temp. (strength)

Temperature $^\circ$C

( $t = 1$ hr)
\( \varepsilon = \varepsilon_{th} + \varepsilon_{st} + \varepsilon_c + \varepsilon_{tr} = \varepsilon_{th} + \varepsilon_{ct} \)

\( \psi_i \)

\( \bar{\varepsilon}_{th} \)

\( \varepsilon_{st} \)

Equivalent Thermal Strain

Self-induced Strain

Thermal Strain

\( \varepsilon_{th} \)
(3) Unrestrained Thermal Strains

\[
\varepsilon_i = f \text{ (ASTM-E119 Time, Width, Area of Steel Bars in Tension and Compression, Number of Layers of Tension Steel Bars, Aggregate Size)}
\]

\[
\psi_i = f \text{ (ASTM-E119 Time, Width, Height, Area of Steel Bars in Tension and Compression, Number of Layers of Tension Steel Bars, Aggregate Size)}
\]

- **M+ve**: Lower tension steel properties, need higher steel strain or lower curvature.
- **M-ve**: Tension steel unaffected and concrete in compression.
(4) Sectional Analysis at Elevated Temperatures

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 $\varepsilon_i$, $\psi_i$, $EA_{eff}$ and $EI_{eff}$.

3) Convert $\varepsilon_i$ and $\psi_i$ 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

- $\varepsilon_{c,\text{max}}$: concrete strain corresponds to Moment of Resistance $M_r$

- A parametric study is conducted to evaluate $\varepsilon_{c,\text{max}}$ at elevated temperatures

- Reasonable predictions are obtained at $r = 0.25$
Location of Critical Strain

a) four-face heated RC section

b) $\varepsilon_{cT}$ dist.

c) concrete forces

Fire (Left)

Fire (Top)

Fire (Right)

Fire (Bottom)

h = 0.6 m

b = 0.6 m

$c = 0.226$ m

$z_3 = 0.089$, $z_4 = -0.033$

concrete crushing

$\varepsilon_{cT max}$

$\varepsilon_{oT} + \varepsilon_{tr}$

$0.25 \times \Delta \varepsilon = 0.005$

$A$, $B$
(9) Axial Capacity of Fire-Exposed RC Columns

\[ C_c = \int_{y=0}^{h} (f_{cT}) b \, dy \]

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

Temperature dependant

\( f(\overline{T}_{avg}) \)

Closed Form Solution for Standard Fire Exposure
Temperature Distribution

Wickstrom’s Simple Method (1986)

\[ T_{xy} = \left[ n_w (n_x + n_y - 2n_x \cdot n_y) + n_x \cdot n_y \right] T_f \]

\[ z = \sqrt{e^{-45 t}} \]
Average Temperature

\[ T_{avg} = z_1 . e^{(z_2 \cdot y)} \]

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

\[ -0.45 T_f . n_w + 1.9 T_f . n_w . n_y - 0.45 T_f . n_y \]

\[ x = x_1 \rightarrow x_2 \]

\[ T_{avg 2} = T_f . n_w . n_y \]
Integration

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

**closed form solution to evaluate** \( f_{cT} \)

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

\[ f'_{cT} = 1.76 \times 10^{-9} T_{avg}^3 - 3.00 \times 10^{-6} T_{avg}^2 + 2.50 \times 10^{-1} T_{avg} + 1.00 \]

\[ \epsilon_{oT} + \epsilon_{tr} = 2.52 \times 10^{-5} T_{avg} \]

\[ T_{avg} = z_1 \cdot e^{(z_2 \cdot y)} \]
Validation (33 columns)

Lie and Wollerton [15]
Mean 1.117
SD 0.294
COV 0.263

Hass [17]
Mean 0.877
SD 0.258
COV 0.295

Dotreppe et al. [16]
Mean 0.782
SD 0.140
COV 0.179
(10) Validation RC Beams

![Diagram of RC Beam]

- **Validation RC Beams**
- **Fire duration (min)**: 0, 30, 60, 90, 120, 150
- **Sectional Analysis**
- **Curvature x 10^-3 (1/in)**
- **Moment (ft.lbf) x 10^10**
- **Curvature x 10^-6 (1/mm)**
- **Moment (kN.m)**
- **Prior to Fire**
- **1 hr fire exposure**

![Graphs of Curvature and Moment]

- **Prior to Fire**
- **1 hr fire exposure**

- **Tests Lin et al.**
- **FEM - Kodur et al.**
- **Sectional Analysis**

**Material Details**

- **Length**: 6.10 m [20.01 ft]
- **Stress**: 20 kN
- **Diameter**: 0.75 m
- **Depth**: 1.50 m
- **Reinforcement**: 2#19, 4#19

**Notes**

- **20 kN (4496 lb)**
- **4496 lb**
- **4.9 ft**
- **2.5 ft**

**Grid Reference**

- **Western Engineering**

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Validation for RC Walls

Experimental Results - Crozier and Sanjayan 2000
Calculated Results - Sectional Analysis
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
- $\Delta_1$ and $\Delta_2$ were monitored during the fire test
Fig. 1 - Beam-column subassemblage deformation after 3 hrs ISO-834 fire exposure

- a) Primary BMD
- b) Secondary BMD
- c) Total BMD (Stiffnesses in N.mm²)

\[ E_{Ie} = 8.26 \times 10^{12} \]

(23% error)

(10% error)

(5% error)

SAP2000

Fang et al. (2012)
Shear Capacity Validation

Experimental failure points
(Desai et al., 1998)

- B501
- B401
- B301
- B202
- B102
For additional details, please refer to:


Thank You !!