Analysis of Catenary Action in Steel Beams under Fire Conditions

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OVERVIEW

- Introduction
- Numerical Simulations by ABAQUS
- Hand Calculation Method
- Conclusions
Introduction
Objectives

- Investigate the large deflection behaviour of steel beams at elevated temperatures

- Develop a simple hand calculation method for predicting the deflections and catenary forces in steel beams at elevated temperatures
Numerical Simulations by ABAQUS

- Shell element S4R

- Boundary conditions:
  - Stiff end plates applied to beam end sections
  - Spring elements applied at centre of beam end sections
  - Spring couple elements applied to the top and bottom flanges of beam end sections relative to section centre
Model validation

(4) 432x100 channel

(4) Rigid Connection

(2) Additional axial horizontal

(2) Columns 152x152x30UC

(2) Columns 203x203x60UC

Test Beam 178x102x19UB

(4) Pinned Connection
Fully axially restrained beams with lateral restraints

Temperature distributions

Uniform

Non-uniform
Uniform temperature distribution

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Non-uniform temperature distribution
Laterally restrained beams with different levels of axial restraint

![Graphs showing deflection and reaction forces for different levels of axial restraint](image)

- KA = 0.02EA/L
- KA = 0.05EA/L
- KA = 0.15EA/L
- KA = 0.30EA/L
- KA = EA/L

Fully restrained

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Laterally restrained beams with different levels of rotational restraint

![Diagram showing the effect of temperature on deflection and reaction for beams with different levels of rotational restraint.](image)

- **Fully restrained**
  - $KR = 2EI/L$
  - $KR = EI/L$
  - $KR = 0.6EI/L$
  - $KR = 0.1EI/L$
- **Free rotation**

**ABAQUS**

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Effect of lateral torsional buckling
Maximum temperature (°C)

Reaction (kN)

- Uniform, with L&A restraints
- Non-uniform, with L&A restraints
- Uniform, with only A restraints
- Non-uniform, with only A restraints
Hand Calculation Method

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Equilibrium equations

\[ F_T (\delta_m + \delta_l) + M_T + M_R + M_p = 0 \]

**First Equation:**

\[ F_T = K_A' \varepsilon_m = K_A' \frac{\Delta L_m}{L} \]

**Second Equation:**

\[ \frac{1}{K_A'} = \frac{1}{K_A} + \frac{L}{E_T A} + \frac{1}{K_A} \]

**Third Equation:**

\[ M_T = E_T I_y \phi_m \bigg|_{x = L/2} \]

**Fourth Equation:**

\[ M_R = K_R' \theta \bigg|_{x = 0} \]

**Fifth Equation:**

\[ \frac{1}{K_R'} = \frac{1}{K_R} + \frac{L}{E_T I_y} + \frac{1}{K_R} \]

**Notes:**

- \( M_p \) : the externally applied free bending moment

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Deflection profiles

\[ z(x) = z_m(x) + z_t(x) \]

\[ \Delta L_m = \Delta L - \Delta L_t \]

\[ \Delta L = \int_0^L \left[ 1 + \left( \frac{dz}{dx} \right)^2 \right]^{1/2} dx - L \]

\[ \Delta L_t = \alpha TL \]

\[ \varphi_m \bigg|_{x=L/2} = \frac{d^2 z_m}{dx^2} \bigg|_{x=L/2} \]

\[ \theta \bigg|_{x=0} = \frac{dz}{dx} \bigg|_{x=0} \]
Uniform temperature distribution

- Zero end rotational restraint
  - Under UDL
  
  \[ z_m = \frac{16\delta_{m,\text{max}}}{5L} \left( \frac{x^4}{L^3} - \frac{2x^3}{L^2} + x \right) \]

  - Under CPL
  
  \[ z_m = \text{free bend moment diagram} \]

- Complete end rotational restraint
  
  \[ z_m = \frac{16\delta_{m,\text{max}}}{L^2} \left( \frac{x^4}{L^2} - \frac{2x^3}{L} + x^2 \right) \]
Non-uniform temperature distribution

- **Zero end rotational restraint**
  
  \[ z_t = -\frac{\alpha \Delta T}{2h} (x^2 - Lx) \]

  Under UDL
  
  \[ z_m = z_{UDL,UT} \]

  Under CPL
  
  \[ z_m = \frac{z_{UDL,UT} + z_{CPL,UT}}{2} \]

- **Complete end rotational restraint**
  
  \[ z_t = 0 \]

  \[ z_m = \frac{16 \delta_{m,\text{max}}}{L^2} \left( \frac{x^4}{L^2} - \frac{2x^3}{L} + x^2 \right) \]

  \[ M_t = \frac{E_T I_y \alpha \Delta T}{h} \]
Axial load & bending moment interaction

\[ \frac{1 - \gamma}{(1 + \alpha)^2 \gamma^2} \frac{M}{M_p} + \frac{F}{F_p} = 1 \]

\[ 1 - \frac{\alpha[2(1 + \beta) + \alpha]}{\alpha[2(1 + \beta) + \alpha]} \]

PNA at web/flange junction

\[ \alpha = \frac{A_w}{2A_f} \]

\[ \beta = \frac{t}{h_o} \]

\[ \gamma = \frac{A_w}{2A_f + A_w} \]

\[ \frac{M}{M_p} + \frac{(1 + \alpha)^2}{\alpha[2(1 + \beta) + \alpha]} \left( \frac{F}{F_p} \right)^2 = 1 \]
Validation

- Complete axial restraint, zero rotational restraint
- Uniform temperature, UDL
Complete axial restraint, zero rotational restraint non-uniform temperature, central point load load
- Different levels of axial restraint, zero rotational restraint
- Uniform temperature, central point load, load ratio = 0.7
Different levels of axial restraint, zero rotational restraint, non-uniform temperature, central point load, load ratio = 0.7
Different levels of rotational restraint, complete axial restraint uniform temperature, UDL, load ratio = 0.7
Different levels of rotational restraint, complete axial restraint, uniform temperature, central point load, load ratio = 0.7
Conclusions

- If a steel beam is reliably provided with some axial restraints, catenary action will occur and will enable the beam to survive very high temperatures without a collapse.
- Whether a beam will experience lateral torsional buckling or not will only have some minor effects on its large deflection behaviour.
- A simplified hand calculation method is developed to predict the maximum deflection and catenary force in a steel beam, which can be used in design applications.
Thank you!