Analysis of Catenary Action in Steel Beams under Fire Conditions

Yingzhi Yin

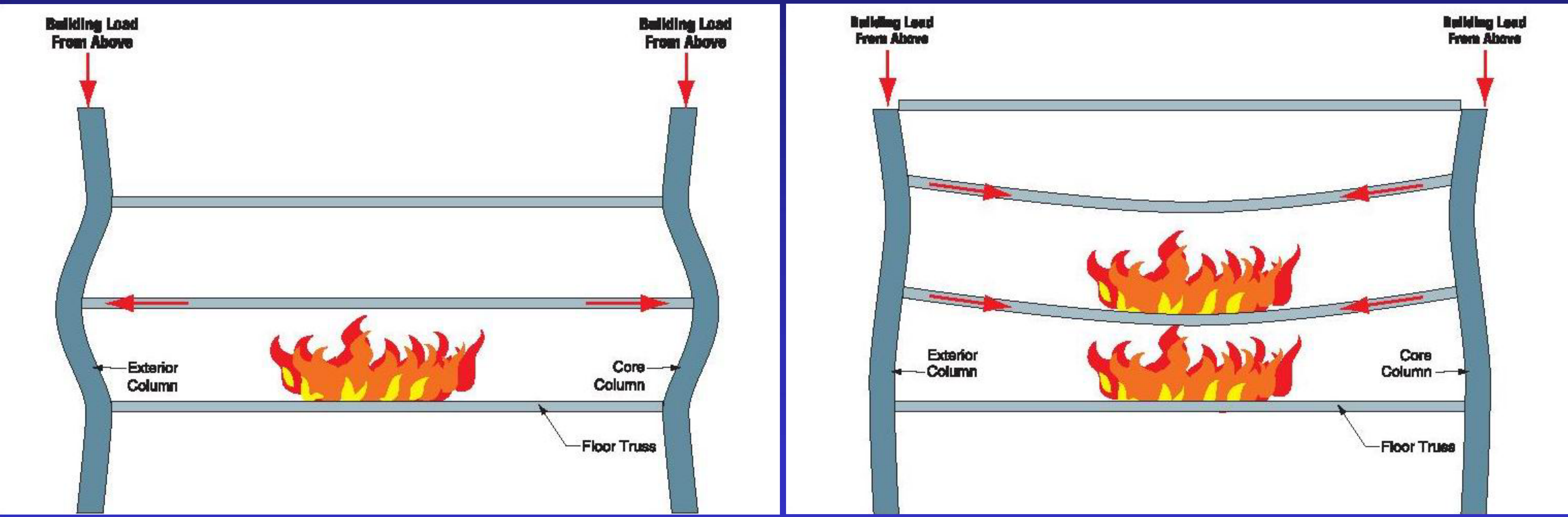
Manchester Centre for Civil and Construction Engineering

University of Manchester & UMIST

OVERVIEW

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

Introduction

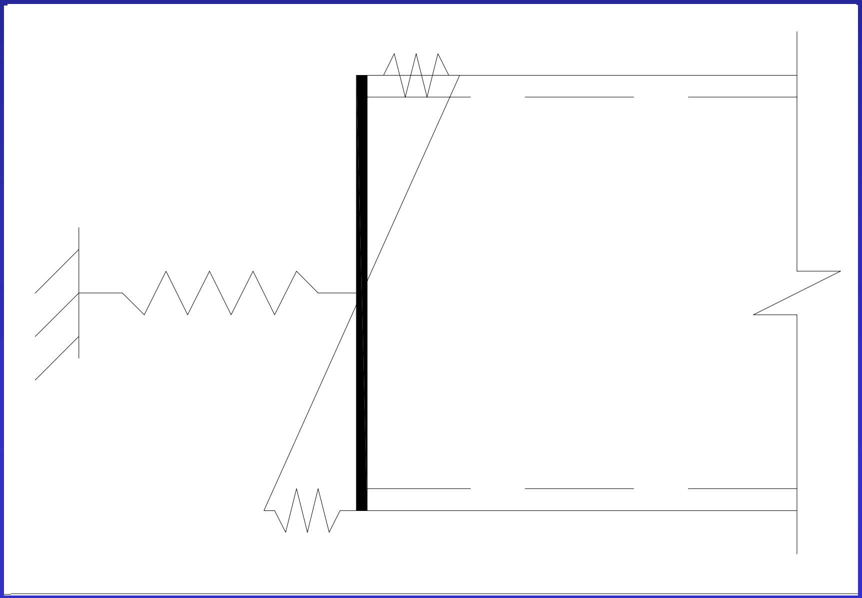


Objectives

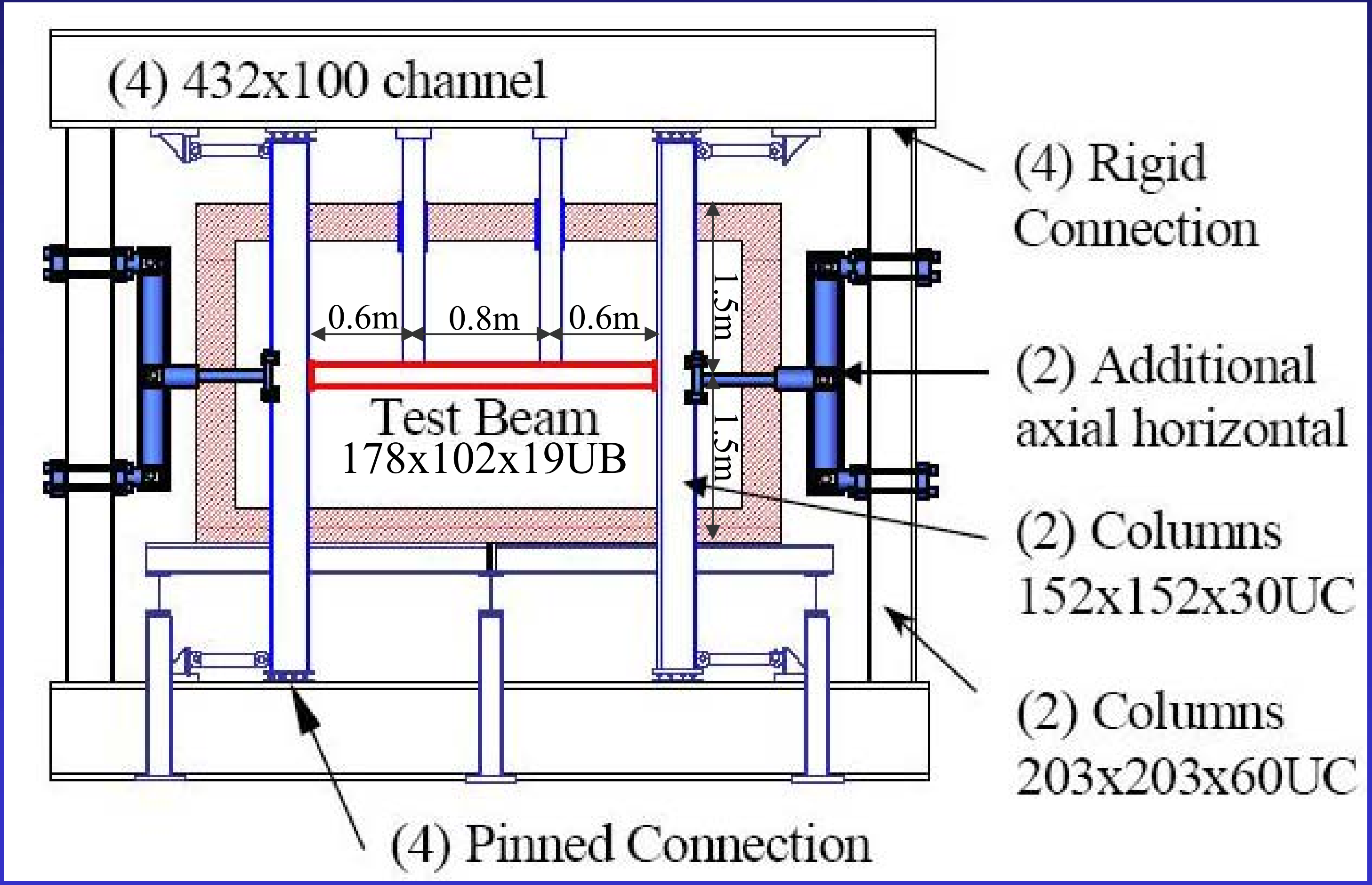
- Investigate the large deflection behaviour of steel beams at elevated temperatures
- Develop a simple hand calculation method for predicting the deflections and catenary forces in steel beams at elevated temperatures

Numerical Simulations by ABAQUS

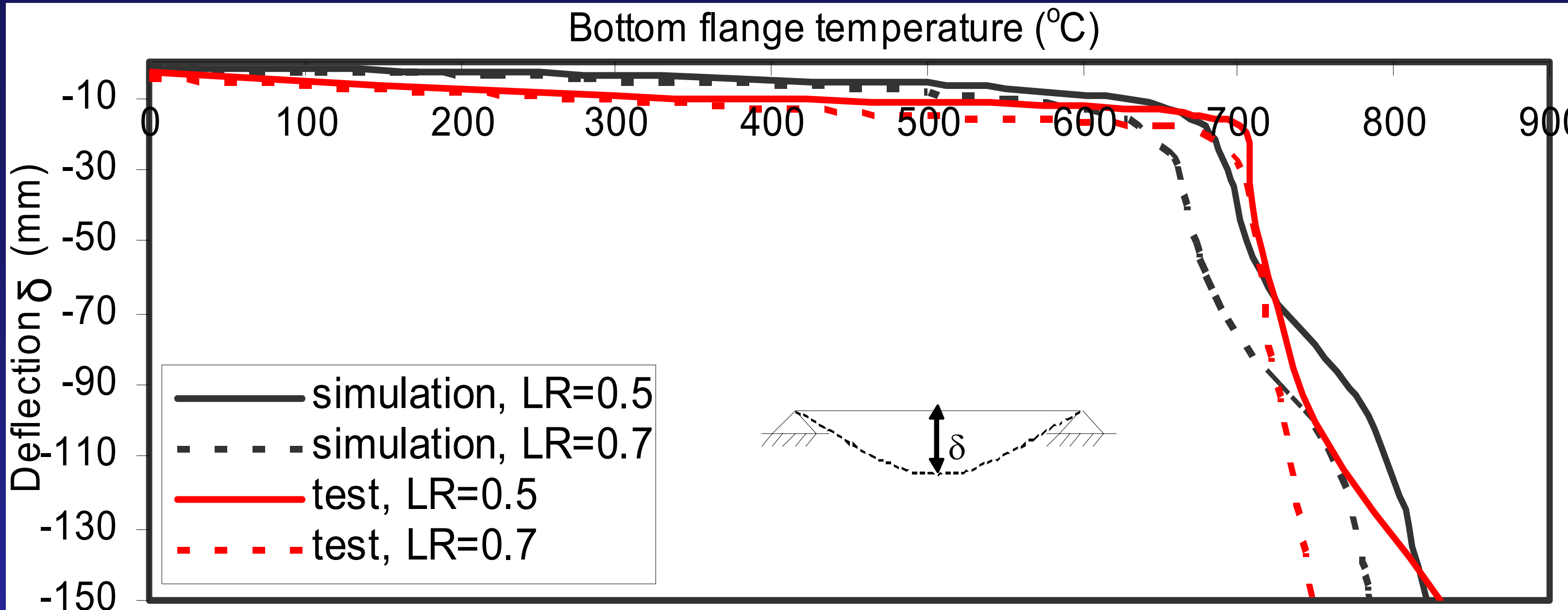
- Shell element S4R
- Boundary conditions:
  - Stiff end plates applied to beam end sections
  - Spring elements applied at centre of beam end sections
  - Spring couple elements applied to the top and bottom flanges of beam end sections relative to section centre

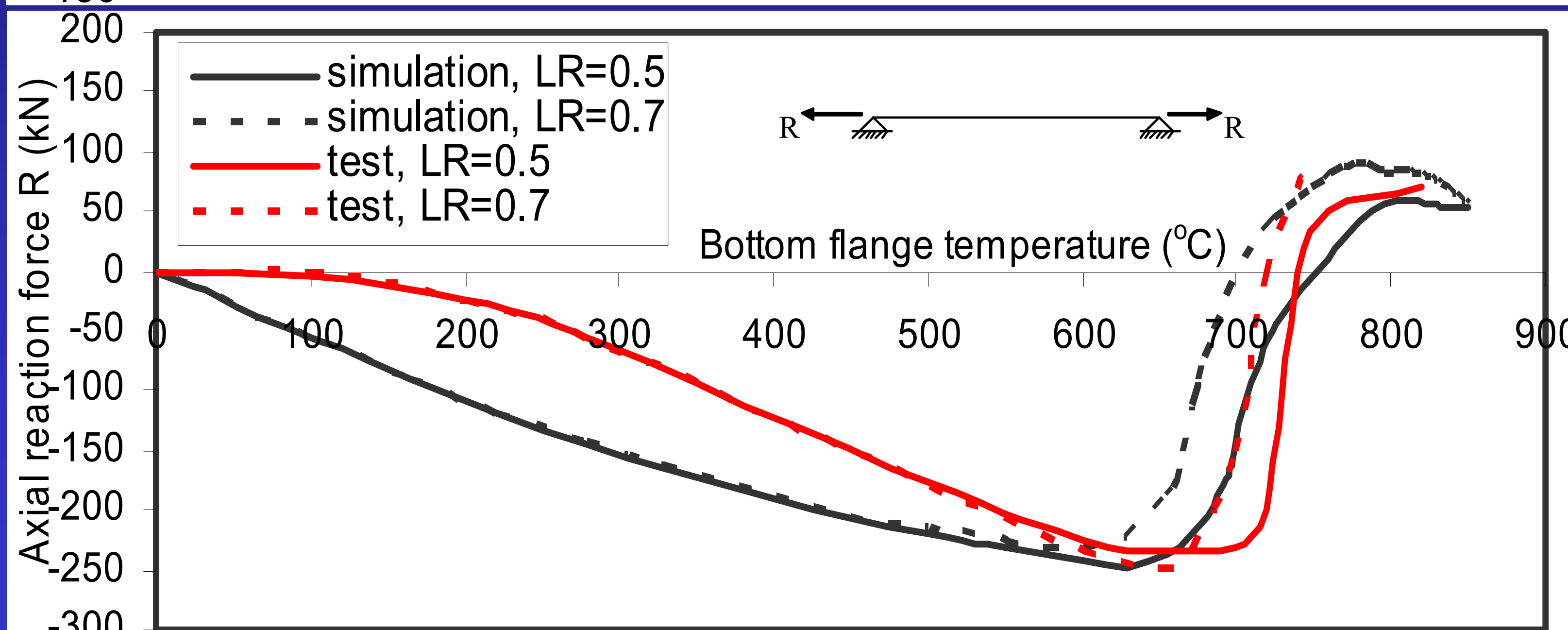


Model validation



ABAQUS

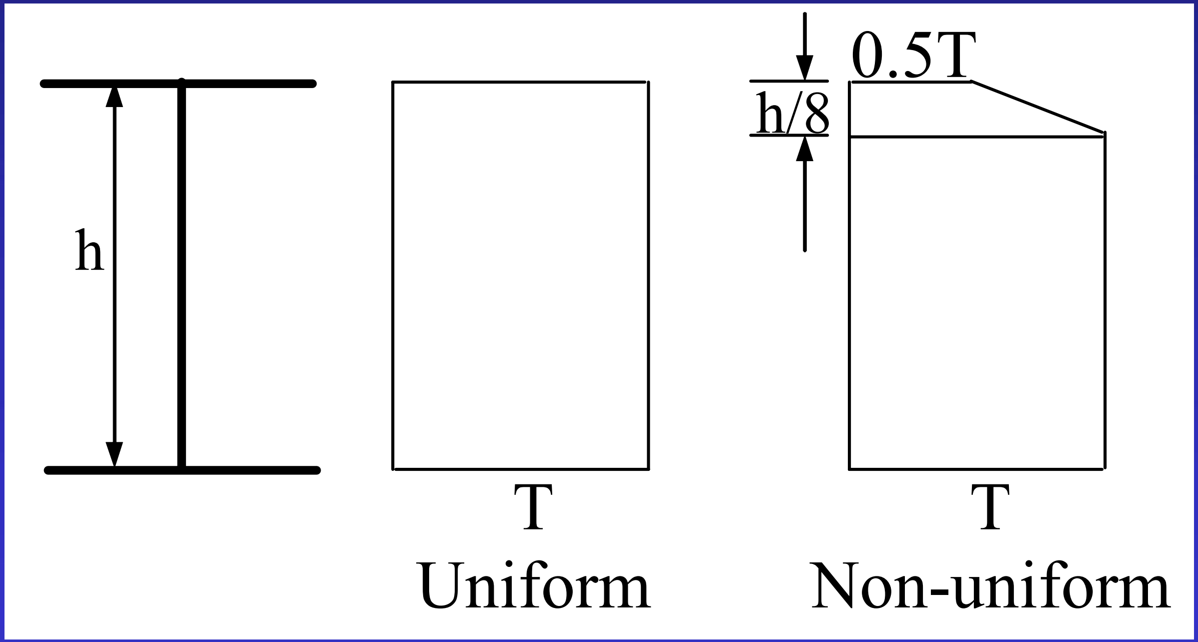

Bottom flange temperature (°C)
0
100
200
300
400
500
600
700
800
900
-10
-30
-50
-70
-90
-110
-130
-150
Deflection δ (mm)
simulation, LR=0.5
simulation, LR=0.7
test, LR=0.5
test, LR=0.7
δ


200
150
100
50
0
-50
-100
-150
-200
-250
-300
Axial reaction force R (kN)
simulation, LR=0.5
simulation, LR=0.7
test, LR=0.5
test, LR=0.7
R
R
Bottom flange temperature (°C)
0
100
200
300
400
500
600
700
800
900

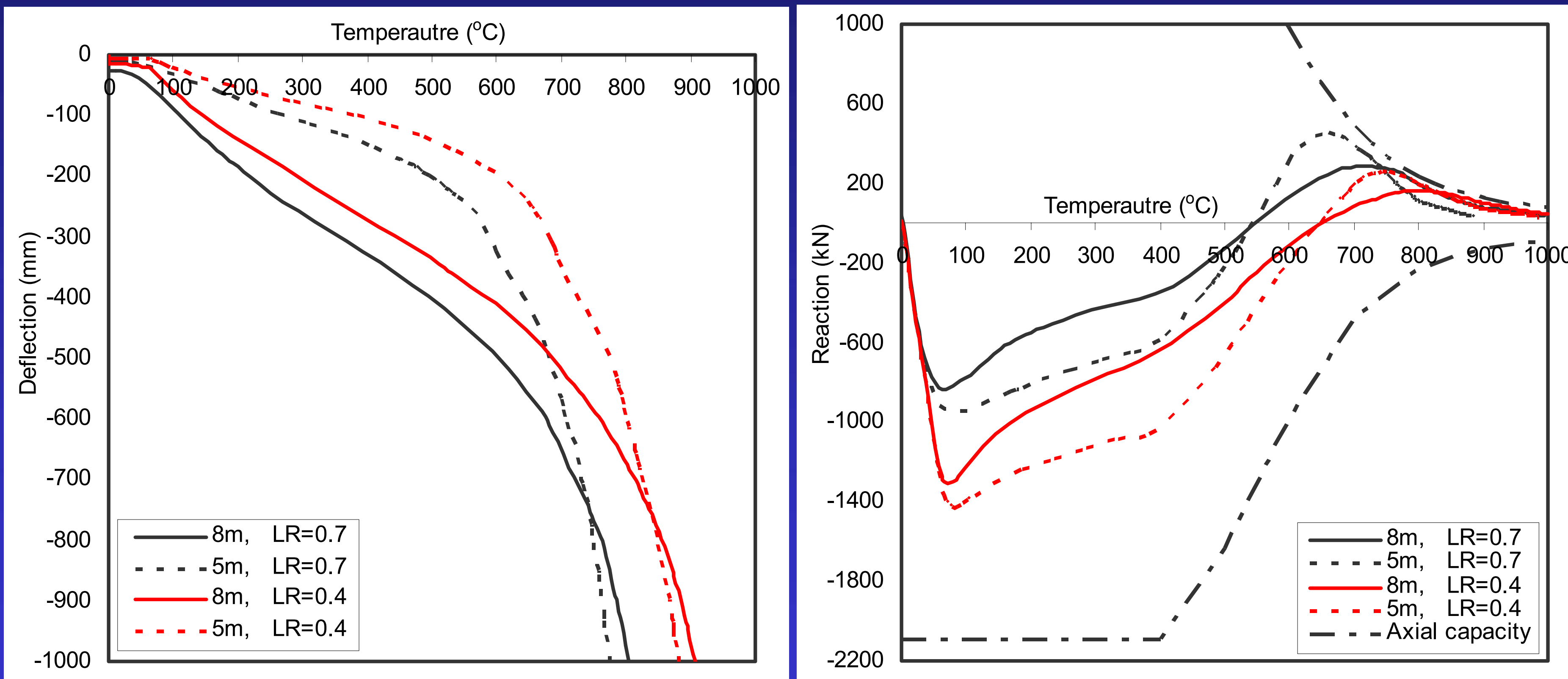
ABAQUS

Fully axially restrained beams with lateral restraints

Temperature distributions

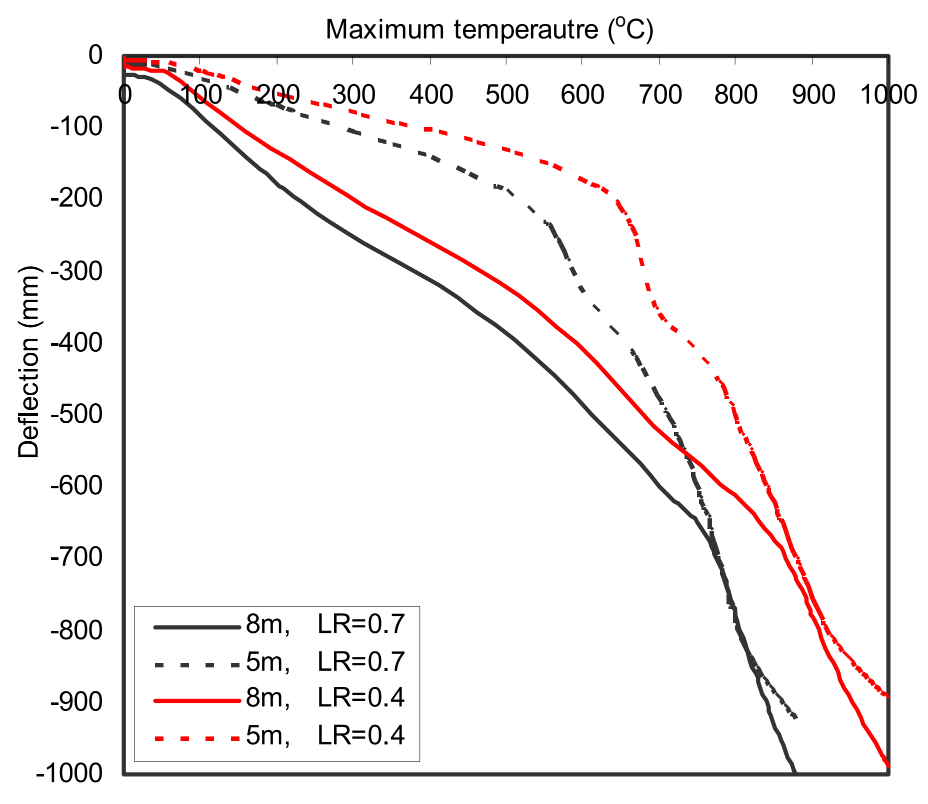


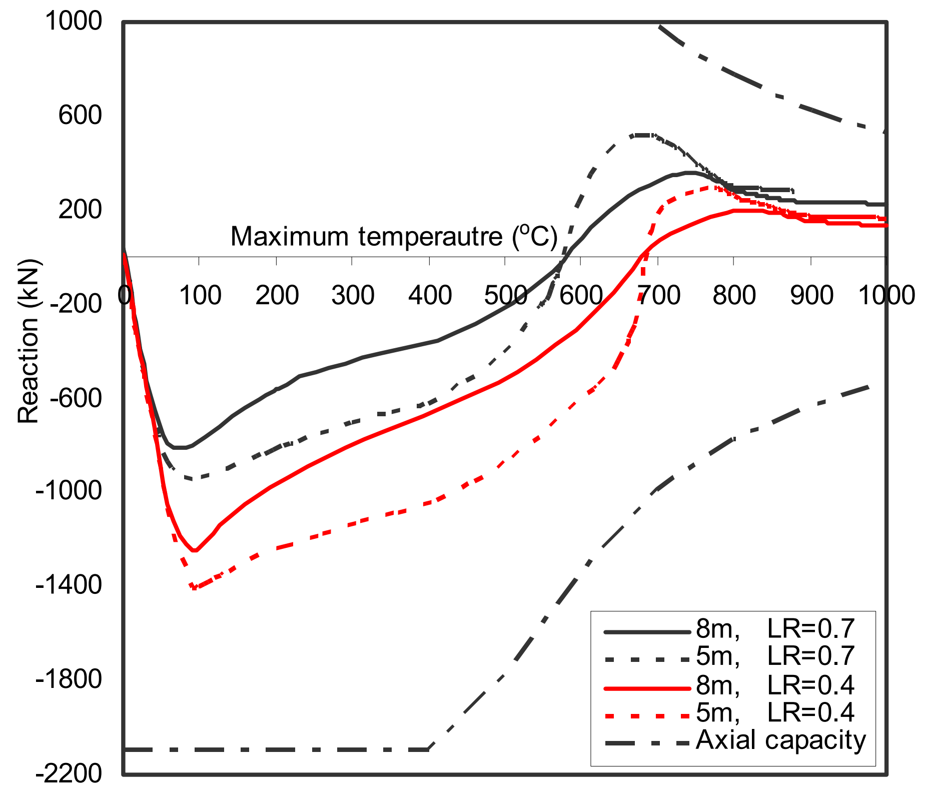
● Uniform temperature distribution



ABAQUS

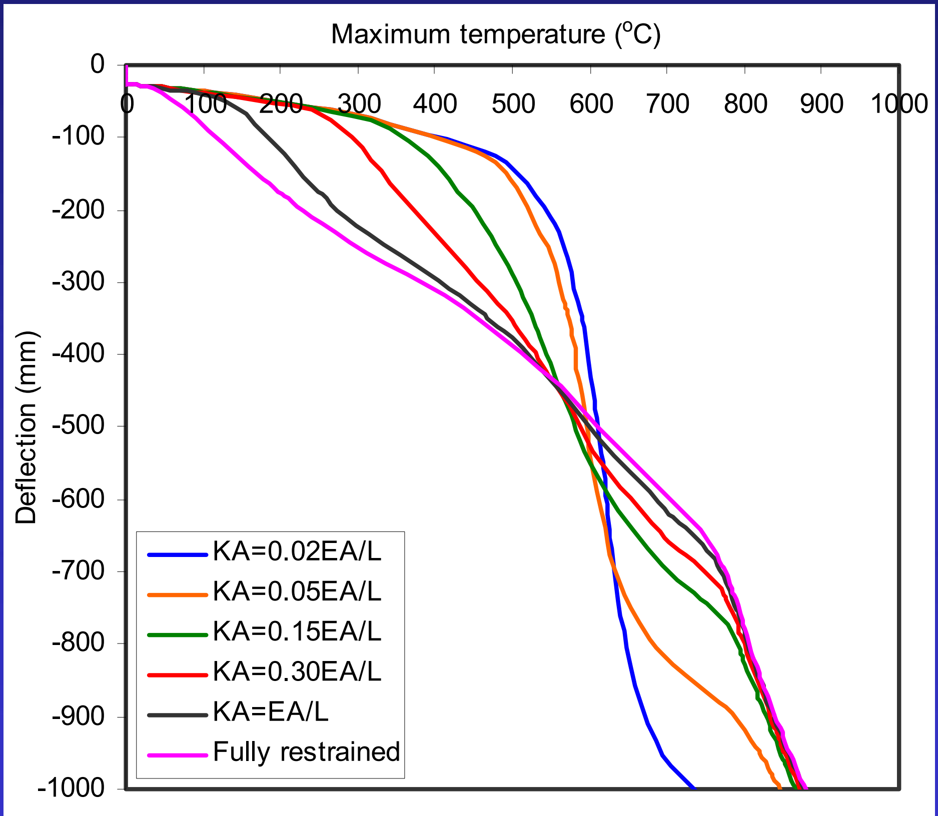
● Non-uniform temperature distribution

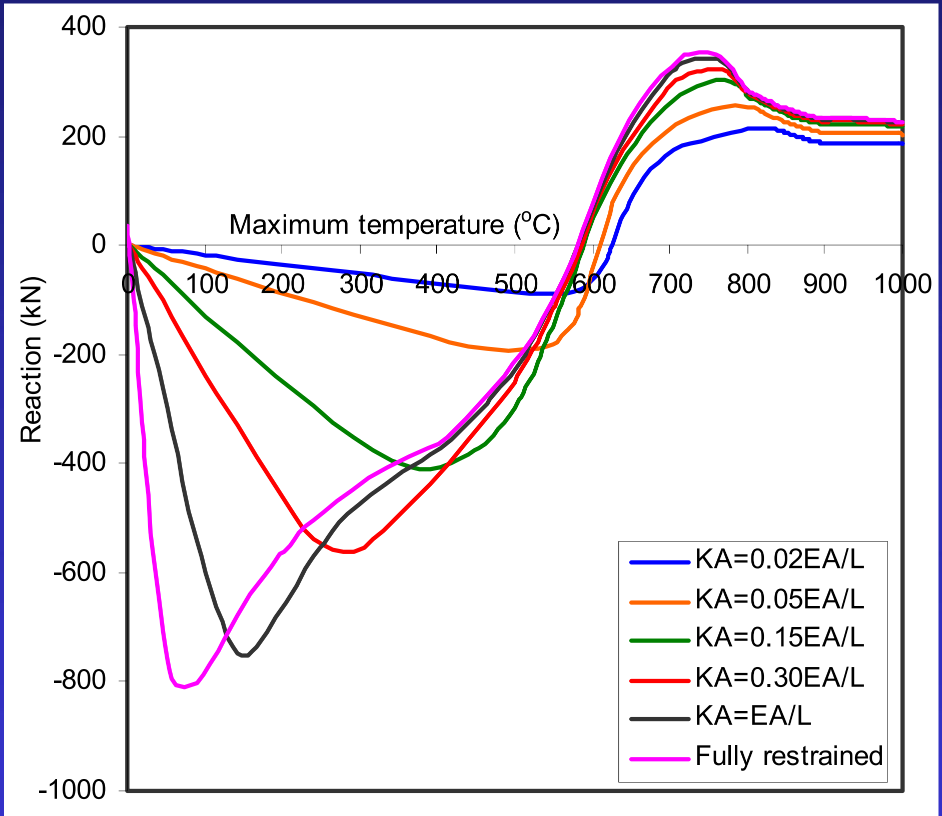




ABAQUS

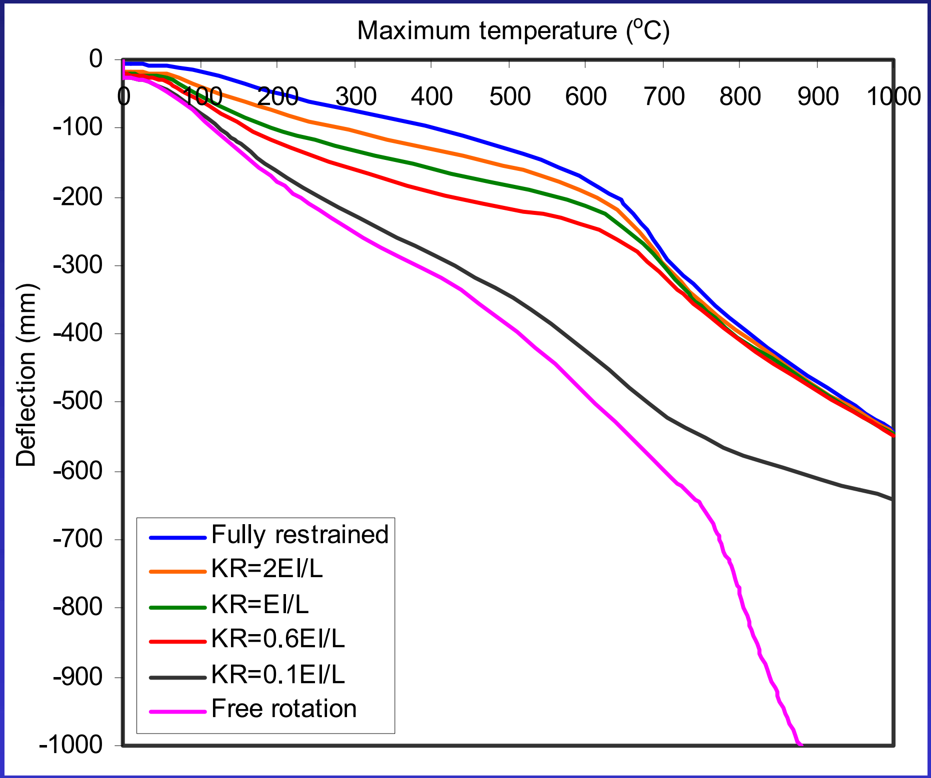
Laterally restrained beams with different levels of axial restraint

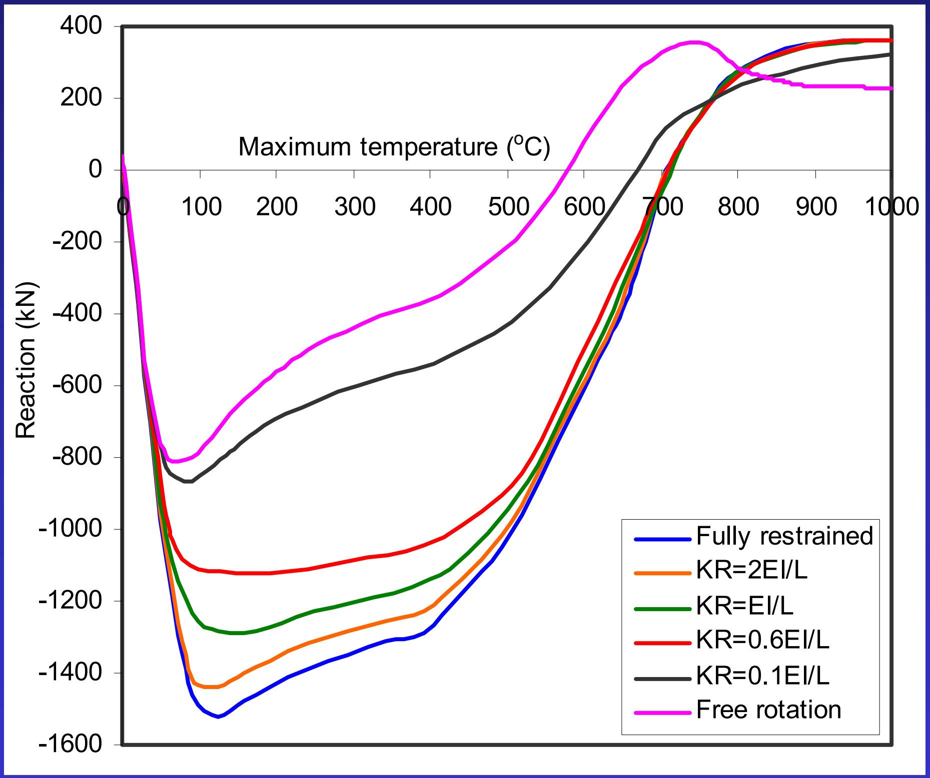




ABAQUS

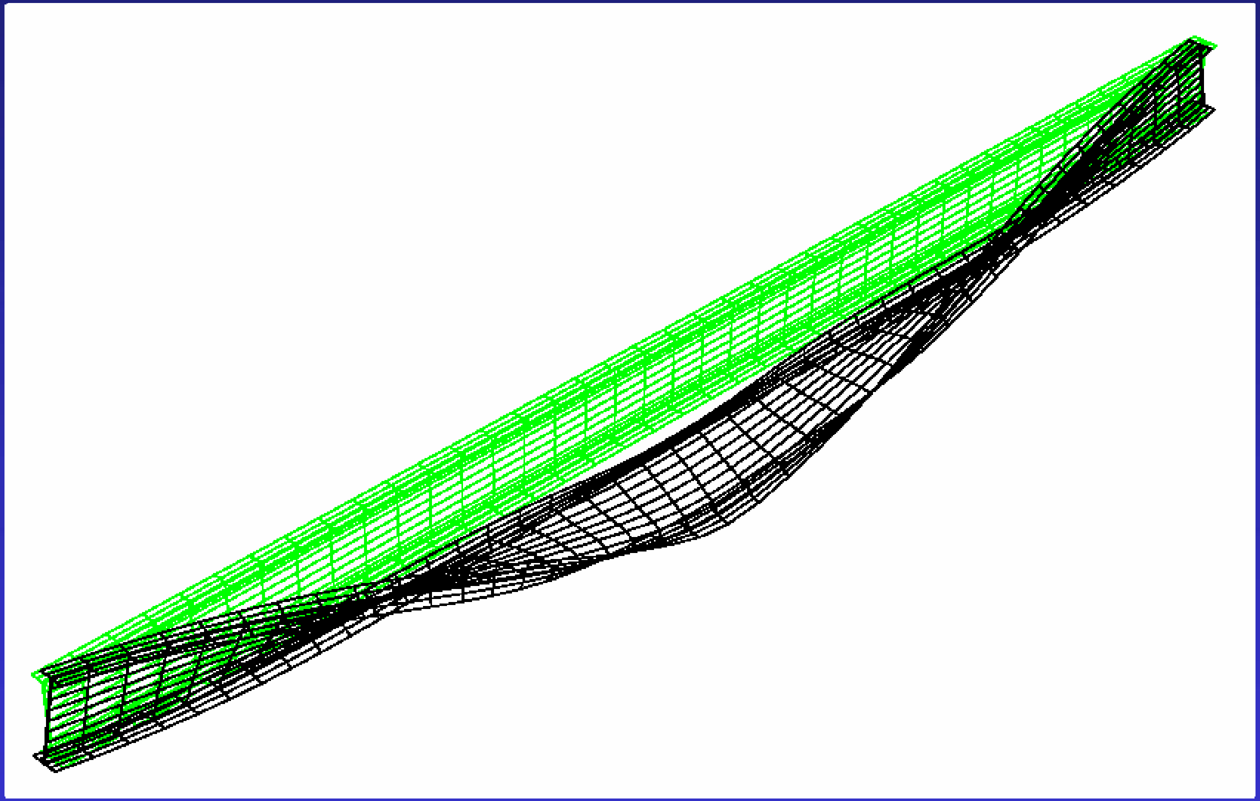
Laterally restrained beams with different levels of rotational restraint



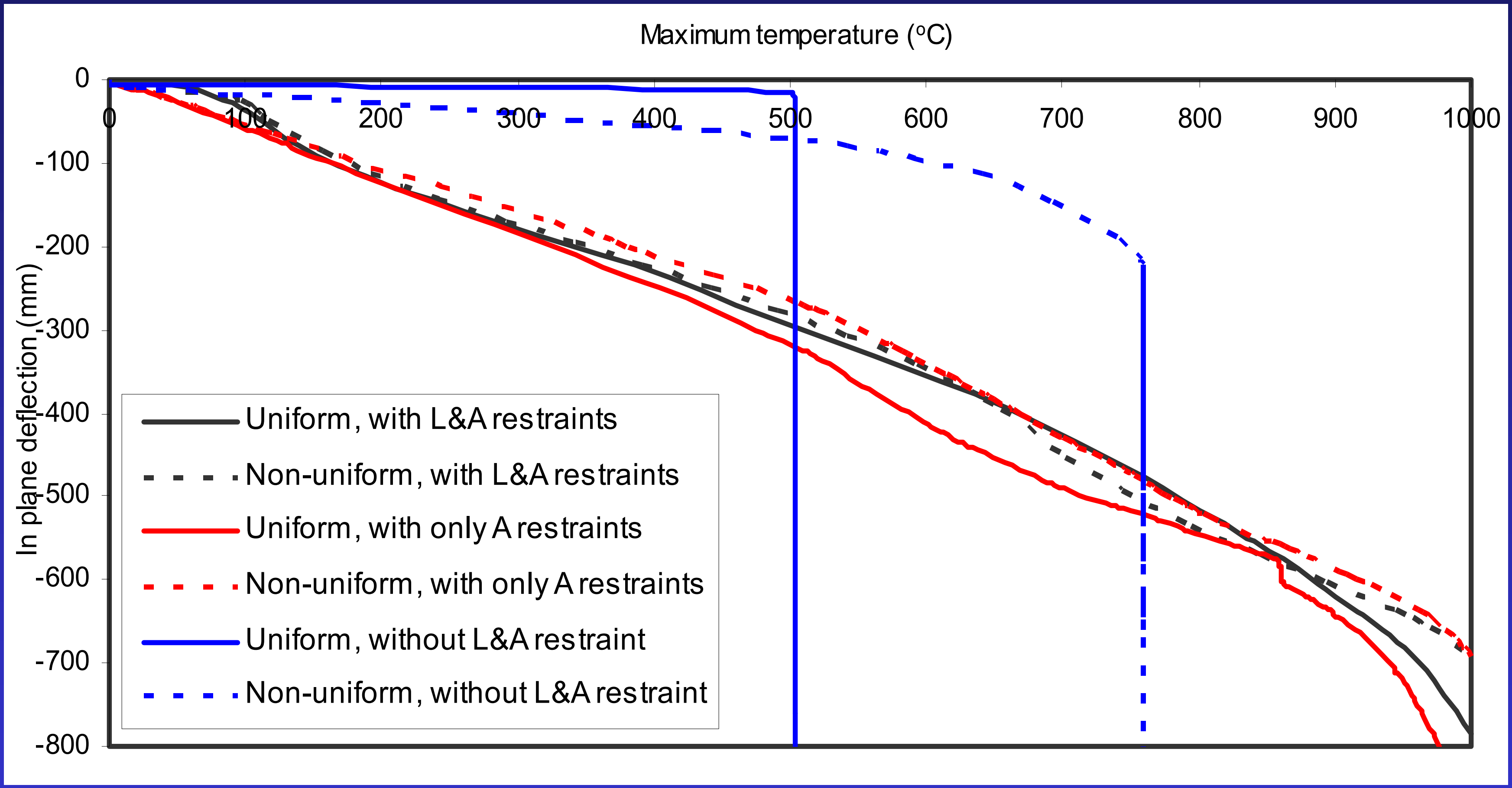


ABAQUS

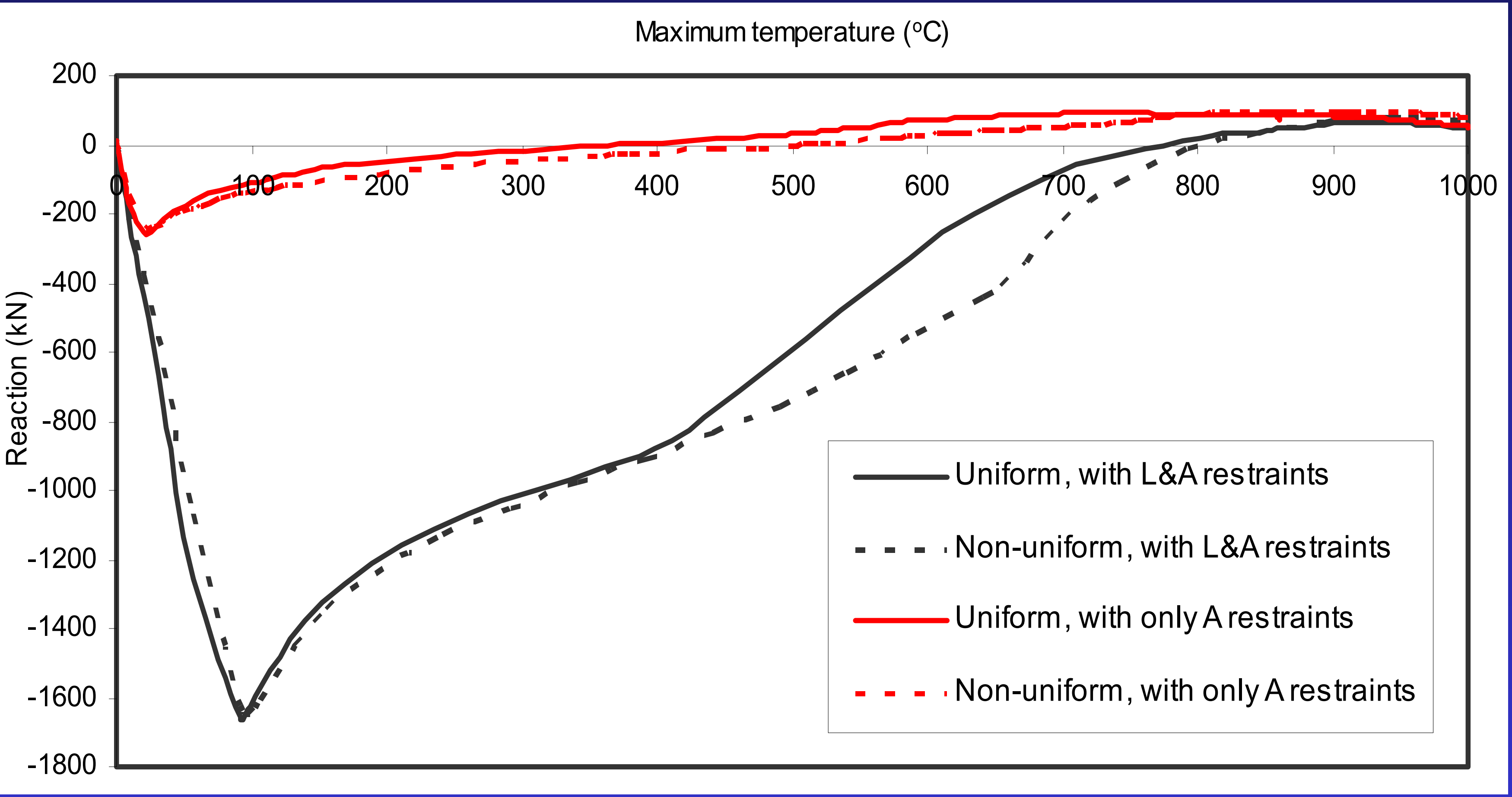
Effect of lateral torsional buckling



ABAQUS

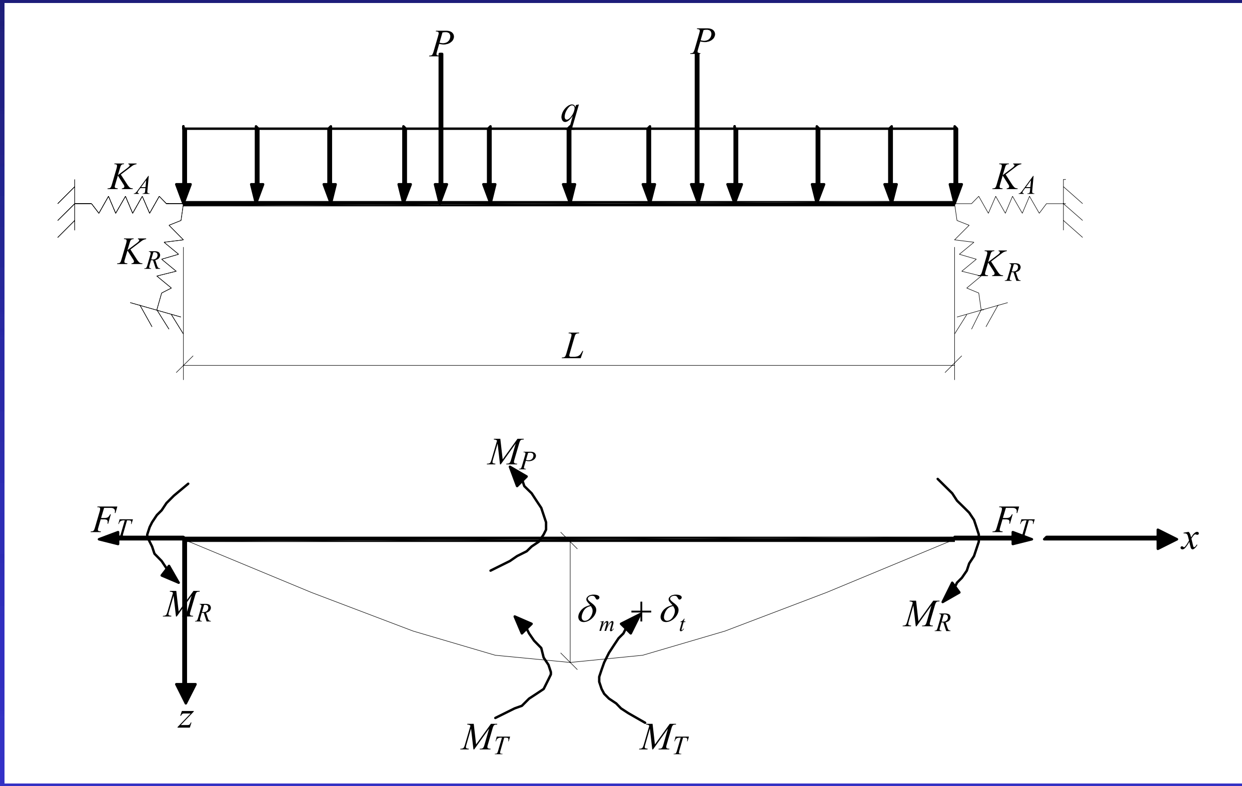

Maximum temperature (°C)
0
100
200
300
400
500
600
700
800
900
1000
0
-100
-200
-300
-400
-500
-600
-700
-800
In plane deflection (mm)
Uniform, with L&A restraints
Non-uniform, with L&A restraints
Uniform, with only A restraints
Non-uniform, with only A restraints
Uniform, without L&A restraint
Non-uniform, without L&A restraint

ABAQUS


Maximum temperature (°C)
Reaction (kN)
200
0
-200
-400
-600
-800
-1000
-1200
-1400
-1600
-1800
0
100
200
300
400
500
600
700
800
900
1000
Uniform, with L&A restraints
Non-uniform, with L&A restraints
Uniform, with only A restraints
Non-uniform, with only A restraints

ABAQUS

Hand Calculation Method



Equilibrium equations

$$F_T(\delta_m+\delta_t)+M_T+M_R+M_P=0$$

$$F_T=K'_A\varepsilon_m=K'_A\frac{\Delta L_m}{L}$$

$$\frac{1}{K'_A}=\frac{1}{K_A}+\frac{L}{E_TA}+\frac{1}{K_A}$$

$$M_T=E_TI_y\varphi_m\Big|_{x=\frac{L}{2}}$$

$$M_R=K'_R\theta\Big|_{x=0}$$

$$\frac{1}{K'_R}=\frac{1}{K_R}+\frac{L}{E_TI_y}+\frac{1}{K_R}$$

M_P :the externally applied free bending moment

Deflection profiles

$$z(x) = z_m(x) + z_t(x)$$

$$\Delta L_m = \Delta L - \Delta L_t$$

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

$$\Delta L_t = \alpha T L$$

$$\varphi_m \Big|_{x=\frac{L}{2}} = \frac{d^2 z_m}{dx^2} \Bigg|_{x=\frac{L}{2}}$$

$$\theta \Big|_{x=0} = \frac{dz}{dx} \Bigg|_{x=0}$$

- Uniform temperature distribution

$$z_t = 0$$

- Zero end rotational restraint

Under UDL

$$z_m = \frac{16\delta_{m,\max}}{5L}\left(\frac{x^4}{L^3} - \frac{2x^3}{L^2} + x\right)$$

Under CPL

z_m=free bend moment diagram

- Complete end rotational restraint

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

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

$$z_m = \frac{z_{UDL,UT} + z_{CPL,UT}}{2}$$

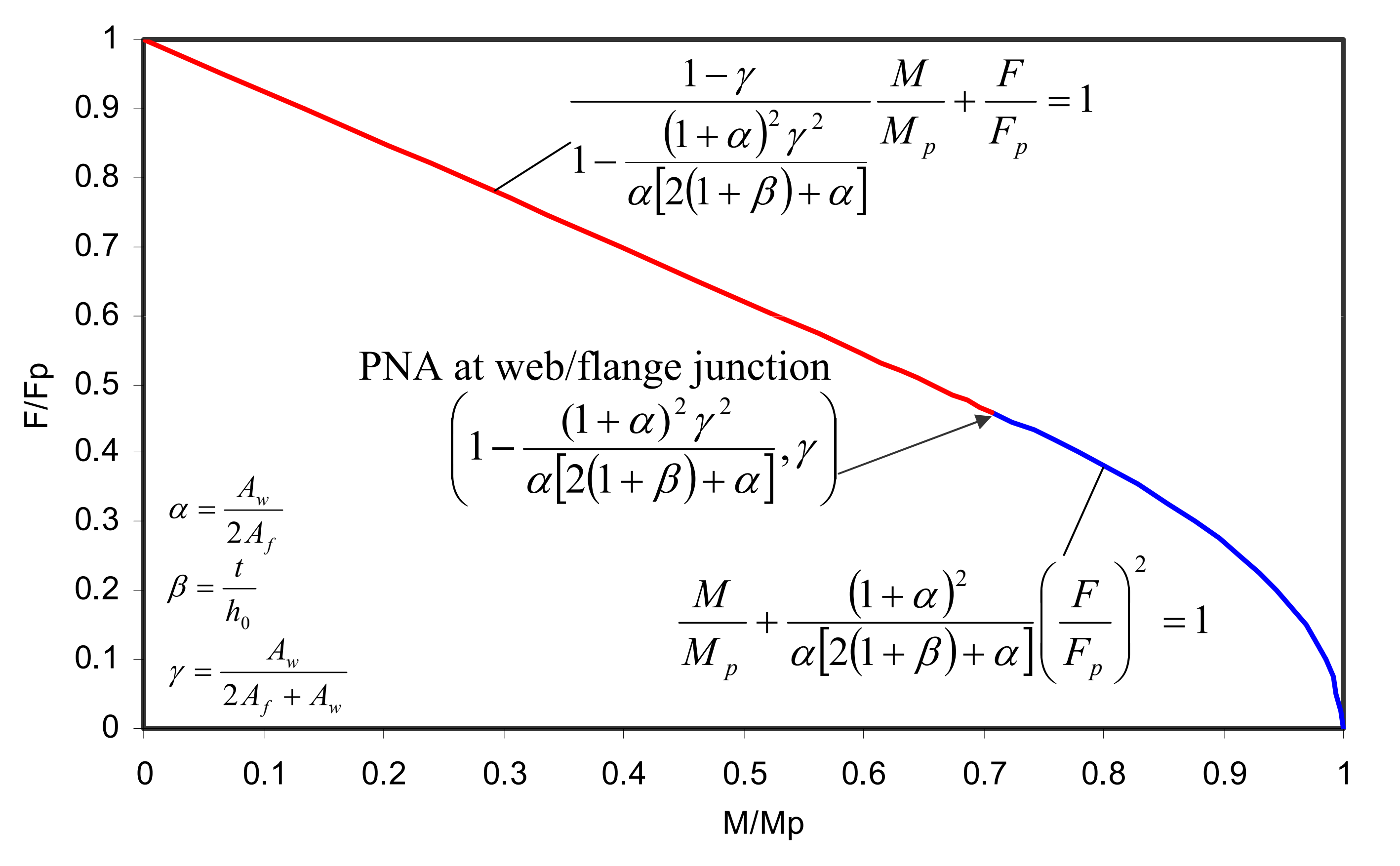
- Complete end rotational restraint

$$z_t = 0$$

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

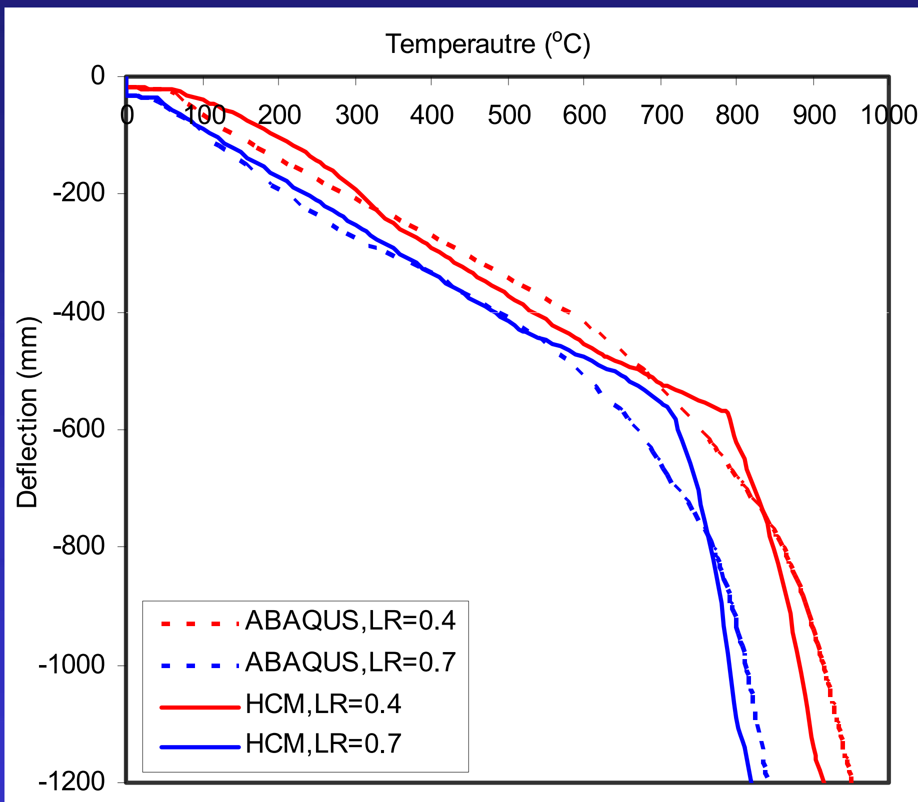
$$M_t = \frac{E_T I_y \alpha \Delta T}{h}$$

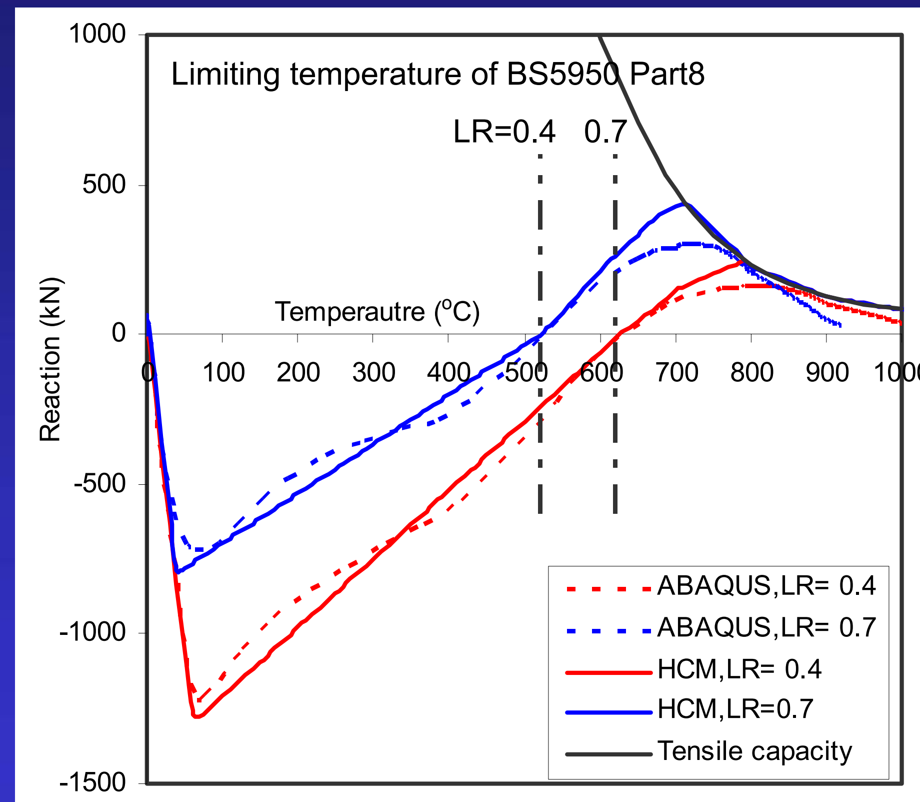
Axial load & bending moment interaction



Validation

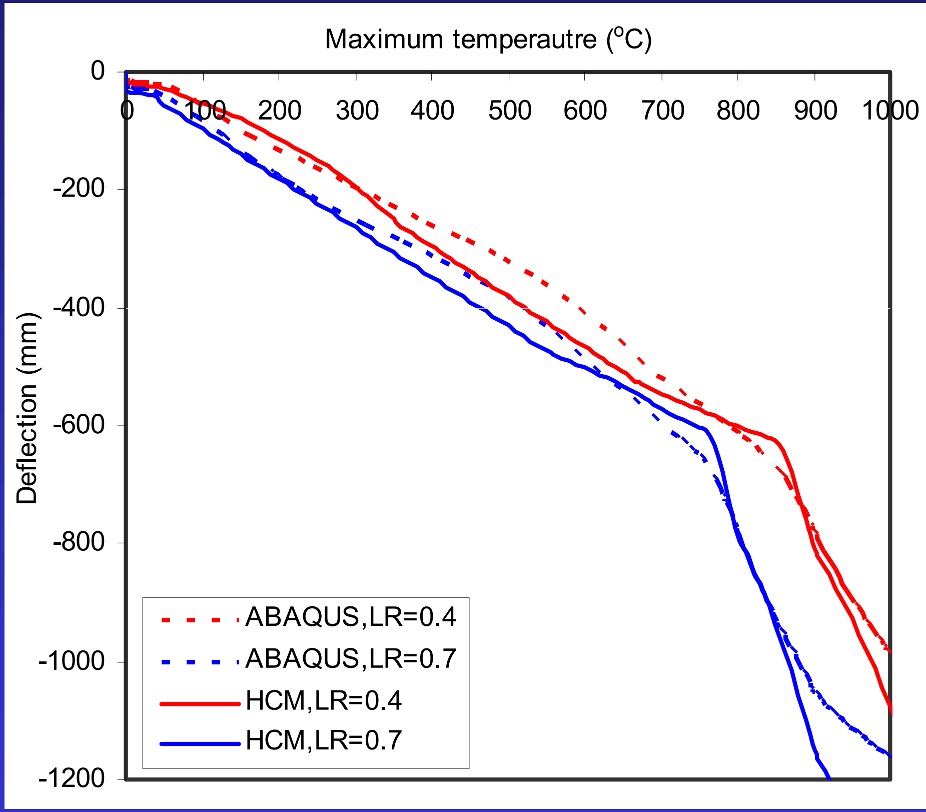
- Complete axial restraint, zero rotational restraint uniform temperature, UDL

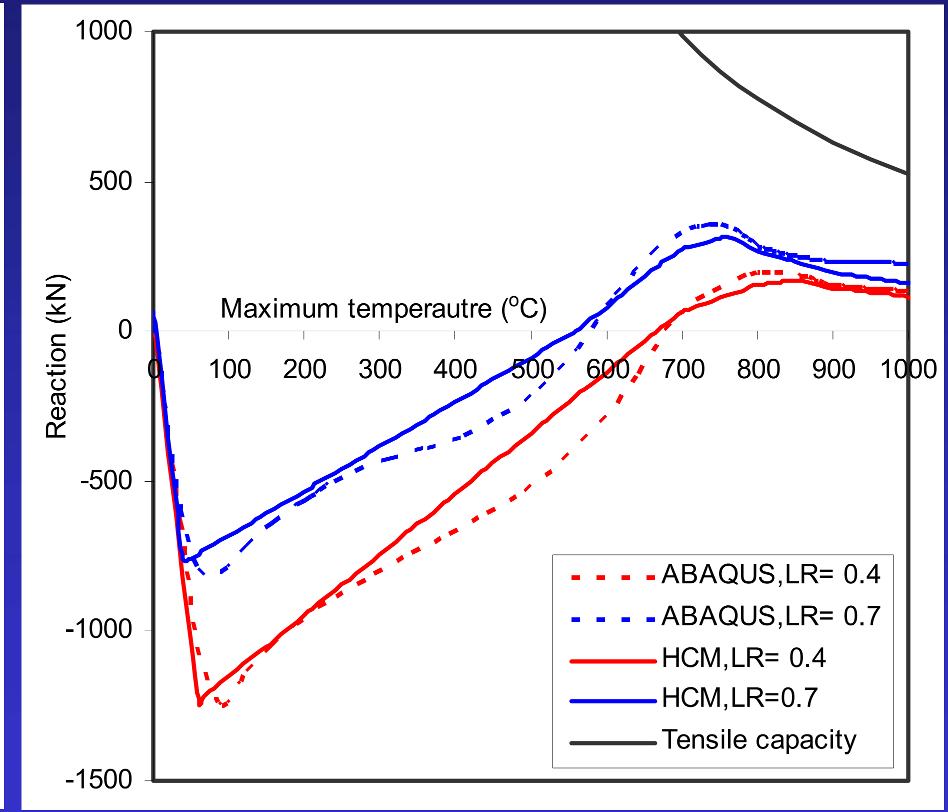




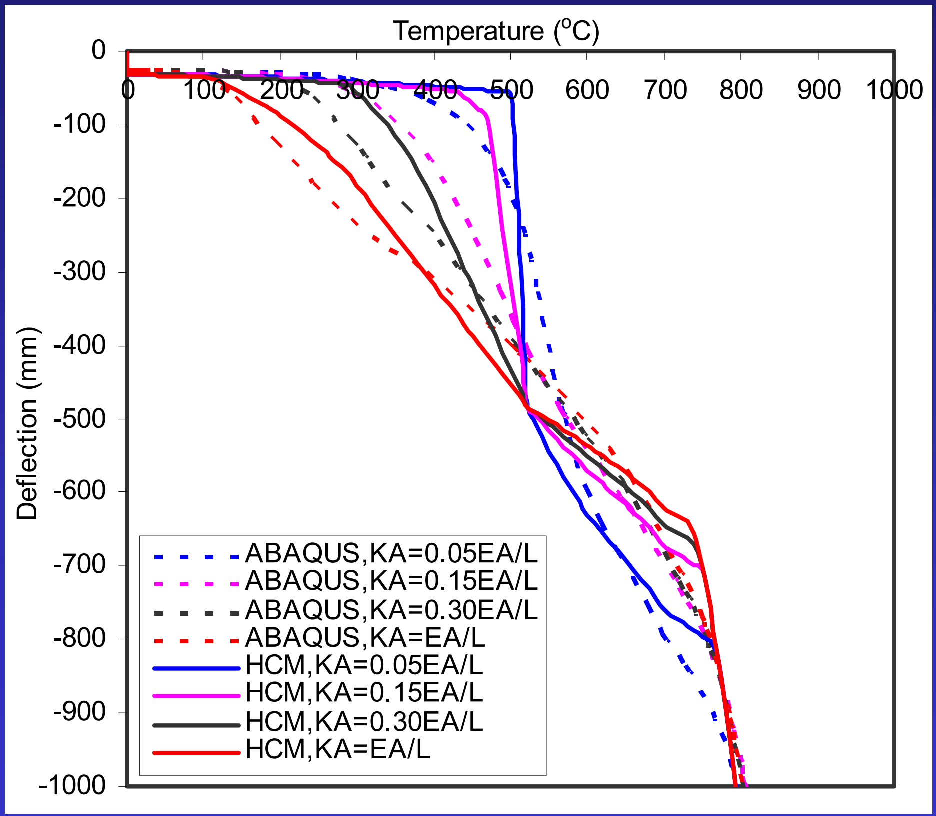
HCM

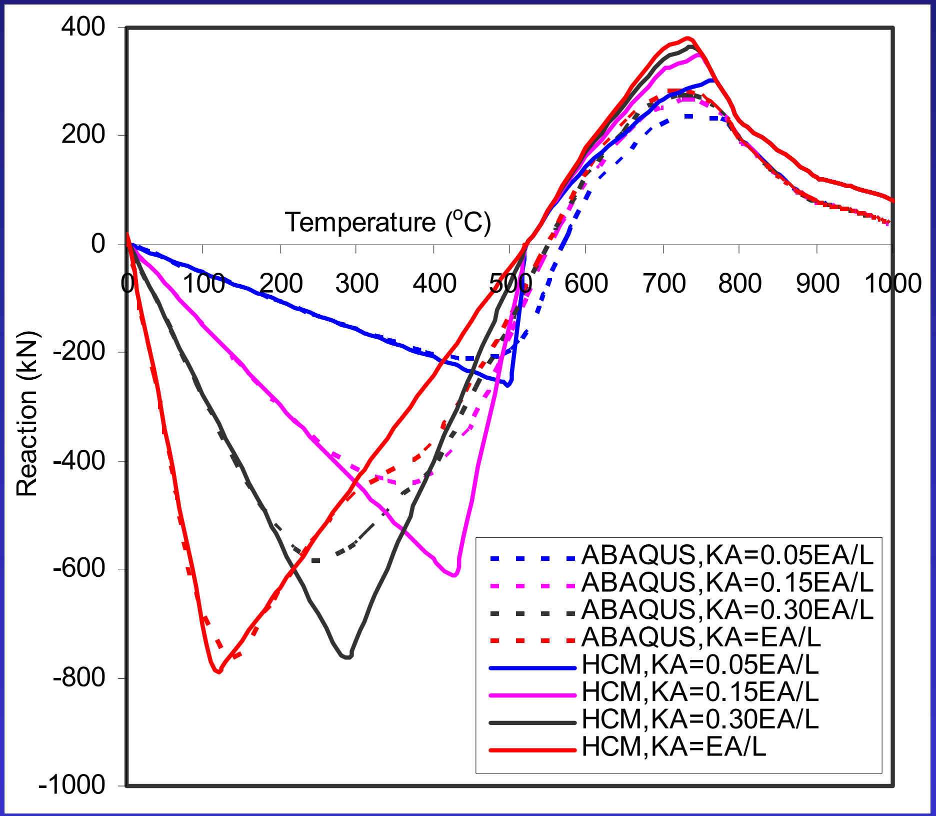
- Complete axial restraint, zero rotational restraint non-uniform temperature, central point load





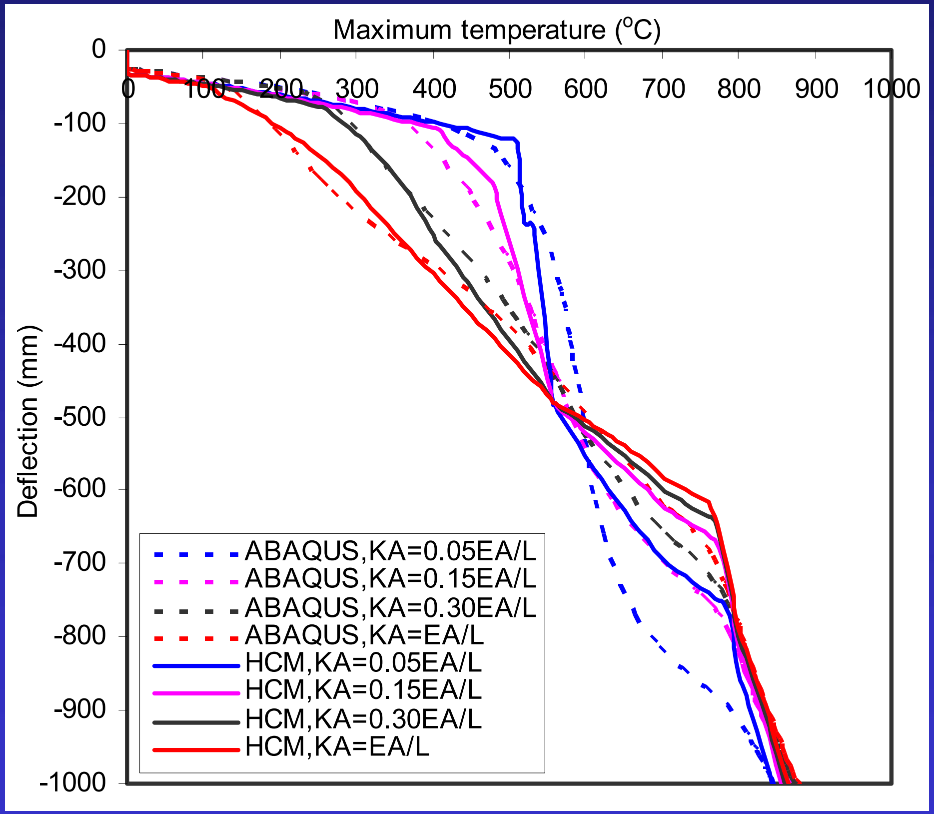
- Different levels of axial restraint, zero rotational restraint uniform temperature, central point load, load ratio = 0.7

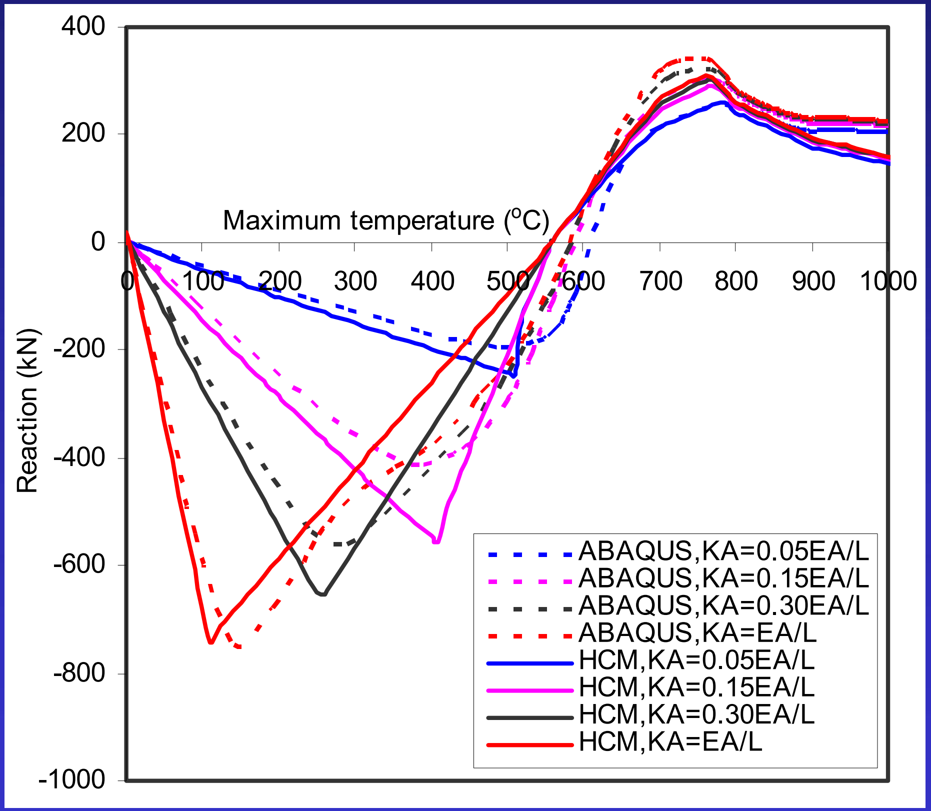




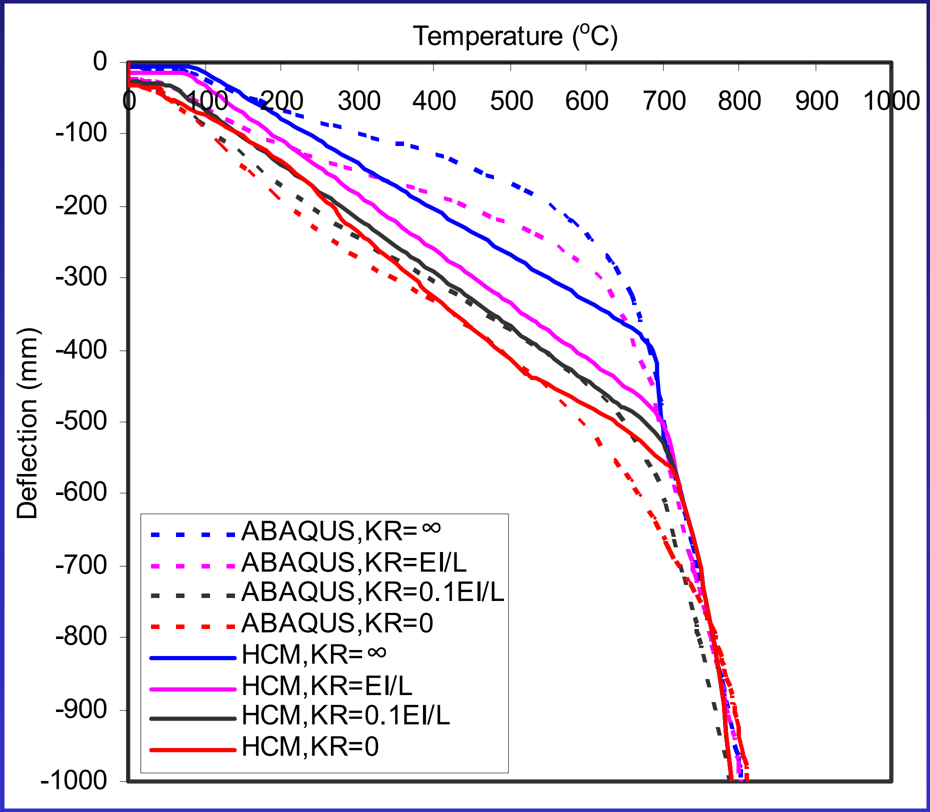
HCM

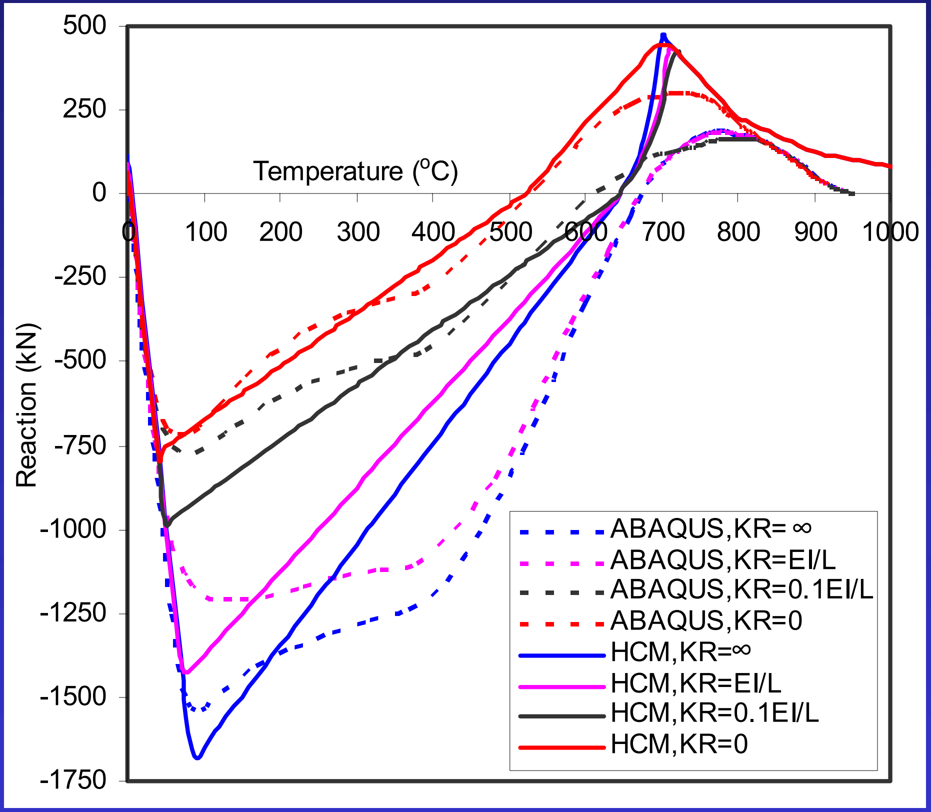
- Different levels of axial restraint, zero rotational restraint non-uniform temperature, central point load, load ratio = 0.7



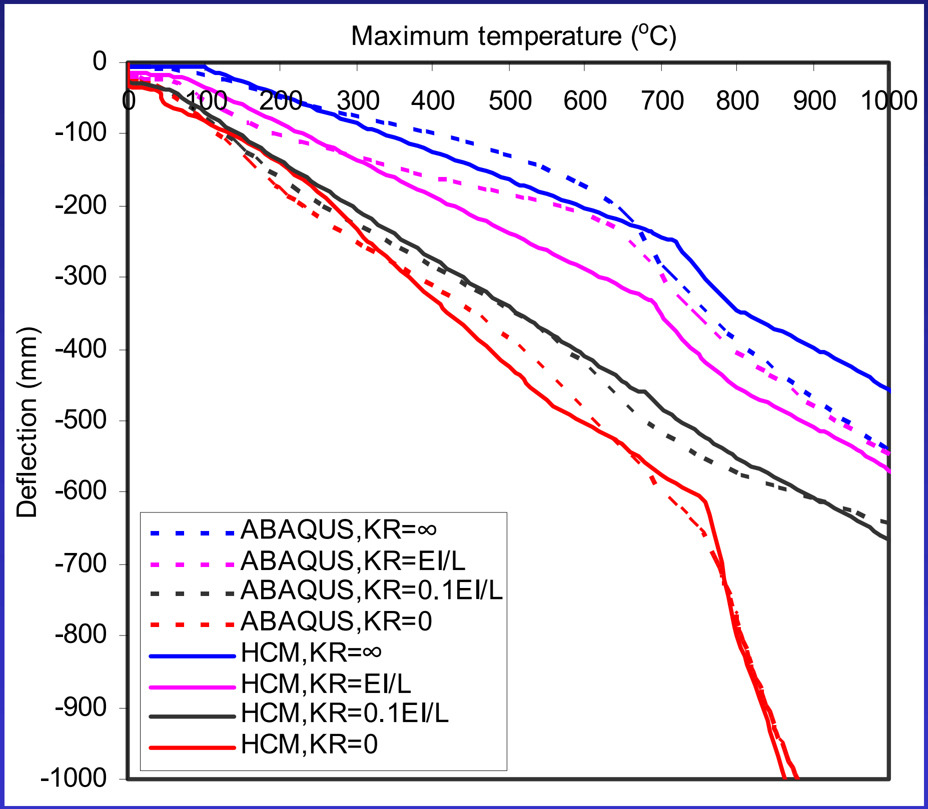


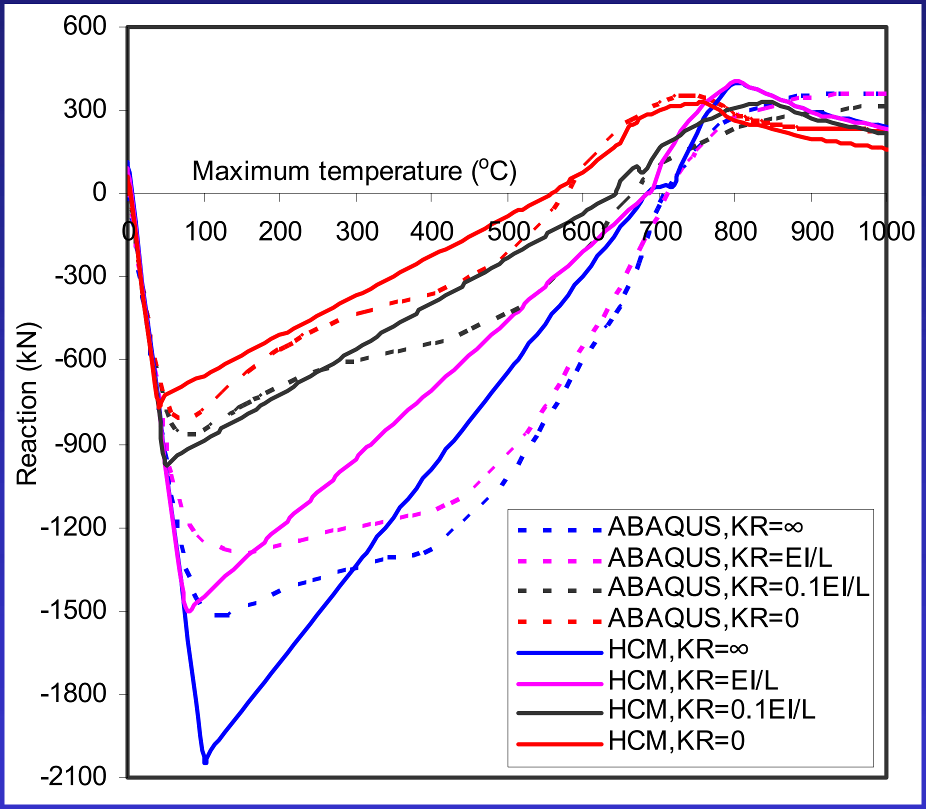
- Different levels of rotational restraint, complete axial restraint uniform temperature, UDL, load ratio = 0.7





- 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!