Restrained Behaviour of Beams in a Steel Frame Exposed to Fire

Comparison of FEM to HCM

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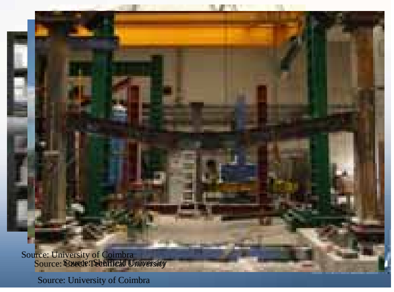
Introduction

Background of the Study

The study presented here has been performed as part of a European project called COMPFIRE.

During the project fire tests were conducted on:

- Connection Components
- Isolated Joints
- Sub-frames
- Full scale buildings



Source: University of Coimbra

Introduction

Hand caclulation model

- A proposed method for hand calculation by Yin and Wang* (2005)
- 4 point concentrated loading of the beam (as in the sub-frame tests)
- The supports provide flexible rotational and axial restraints to the beam

* Yin, Y. Z., Wang, Y. C.,: "Analysis of catenary action in steel beams using a simplified hand calculation method, Part 1: theory and validation for uniform temperature distribution", Journal of Constructional Steel Research, Vol. 61: pp. 183 – 211, 2005

State of the art

Steel Structures in Fire

- Loss of Strength and Stiffness
- Thermal expansions
- Excessive deformations

Engineering approach (design codes)

- All Structural components i.e. connections, beams and columns are designed as isolated components in Fire
- For a beam the flexural resistance determines the design resistance in the absence of any interaction with surrounding structure

State of the art

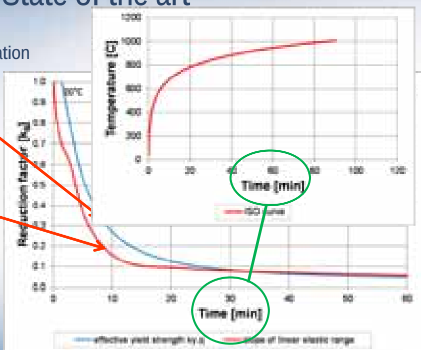
Material properties degradation

- Yield Strength

$$f_{y,\theta} = k_{y,\theta} f_y$$

- Modulus of Elasticity

$$E_\theta = k_{E,\theta} E$$



State of the art

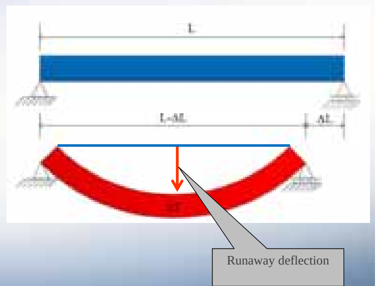
Conventional design

- Failure Criterion

$$M_{fi,d} \le M_{Ed,fi}$$

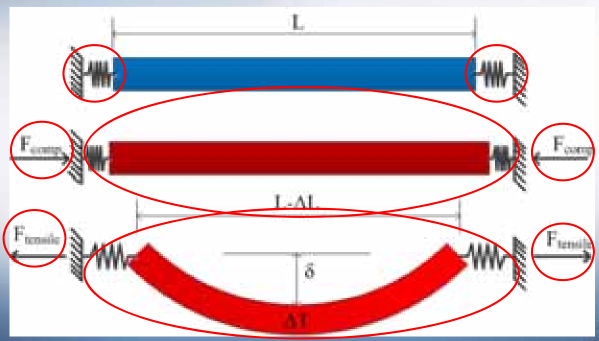
- Moment resistance

$$M_{fi,d} = k_{y,\theta} \frac{W_{pl} f_y}{\gamma_{M,fi}}$$



State of the art

Restrained Beam



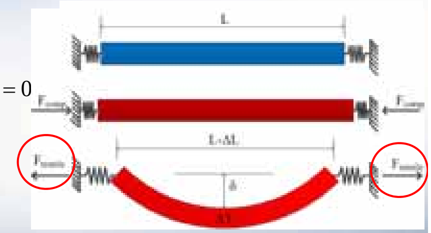
State of the art

Equilibrium at elevated temperature

- Isolated beam

$$M_{Ed,fi} + M_{fi,Rd,t} = 0$$

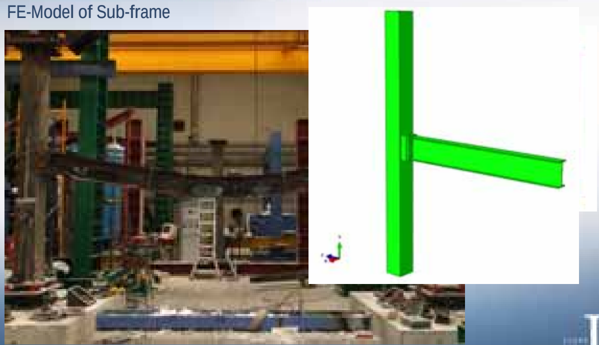
- Restrained Beam



$$M_{Ed,fi} + M_{fi,Rd,t} + F_{axial} \times \delta = 0$$

Benchmarking of FE-Models

FE-Model of Sub-frame



Source: University of Coimbra

Benchmarking of FE-Models

Material model
From EN 1993 part 1-2

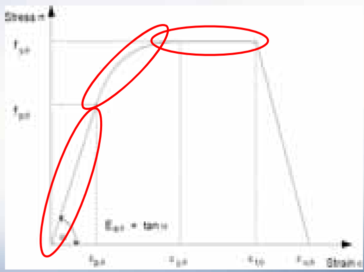
- Yield strength

$$f_{y,\theta} = k_{y,\theta} f_y$$

- Modulus of Elasticity

$$E_\theta = k_{E,\theta} E$$

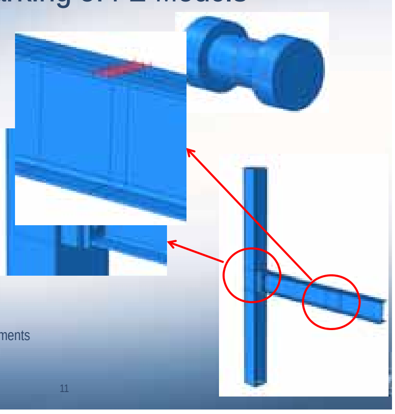
Reduction factors provided in EN 1993-1-2



Benchmarking of FE-Models

Simulation Steps

- Pretensioning of the bolts
  - Displacement adjustment
  - To initialize contact
- Loading of the beam
  - Pressure load
  - Area same as loading plate
- Application of heat
  - Predefined field
  - Magnitude according to measurments
  - Time vs. Temperature relation



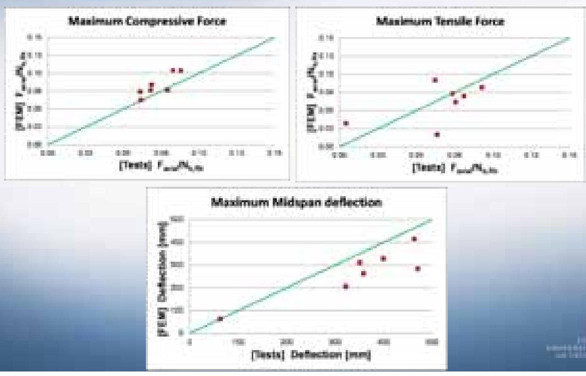
Benchmarking of FE-Models

Artificial damping

- Matrial softening often causes convergence problems
- Artificial damping through 'Dissipated energy fraction'
- An optimum value for the 'Dissipated energy fraction' is required to avoid over damping
- Ratio between 'artificial strain energy' and 'total strain energy' is kept below 5 %
- The results are therefore reliable since there is no artificial increase in the total strain evergy of the system
- The alternative is to use Explicite analysis in ABAQUS

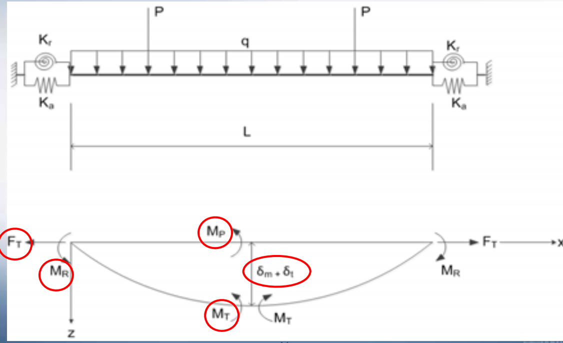
Benchmarking of FE-Models

Results:



Hand Calculation Method

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



Hand Calculation Method

Deflection profile at elevated temperature

$$z_{flexible} = (1 - c_f) \times z_{zero} + c_f \times z_{fixed}$$

Where

$$c_f = \frac{K'_R}{EI/L}$$

- For Uniform temperature

$$z = z_m = (1 - c_f) \times z_{zero} + c_f \times z_{fixed}$$

- For temperature gradient

$$z = z_m + z_t$$

where

$$z_t = -\frac{\alpha \Delta T}{2h}(x^2 - Lx)$$

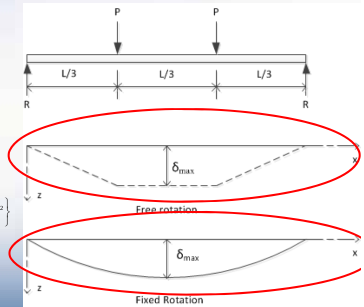
Hand Calculation Method

Deflection profile at elevated temperature

$$z_{zero} = \begin{cases} \frac{3\delta_{m,max}}{L}x & 0 \le x \le \frac{L}{3} \\ \delta_{m,max} & \frac{L}{3} \le x \le \frac{2L}{3} \\ \frac{3\delta_{m,max}}{L}(L-x) & \frac{2L}{3} \le x \le L \end{cases}$$

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

$$z = (1-c_f)\begin{cases} \frac{3\delta_{m,max}}{L}x & 0 \le x \le \frac{L}{3} \\ \delta_{m,max} & \frac{L}{3} \le x \le \frac{2L}{3} \\ \frac{3\delta_{m,max}}{L}(L-x) & \frac{2L}{3} \le x \le L \end{cases} + c_f \frac{16\delta_{m,max}}{L^2}\left\{\frac{x^4}{L^2} - \frac{2x^3}{L} + x^2\right\}$$



Hand Calculation Method

Axial force calculation

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

Axial deformation depending on deflection profile and thermal expansion

Measure of the level of axial restraint at the support

Where

K'_A Effective axial stiffness

$\Delta L_m = \Delta L - \Delta L_t$ Net axial deformation

Contraction

Thermal expansion

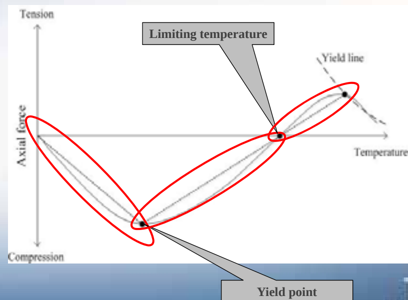
$$\Delta L = \int_0^L \left[1 + \left(\frac{dz}{dx}\right)^2\right]^{1/2} dx - L$$

$$\Delta L_T = \alpha \Delta T L$$

Hand Calculation Method

Variation of Axial force with temperature

- Elastic stage
- Non-linear stage
- Catenary stage



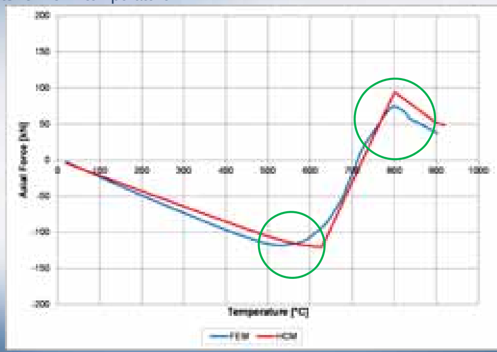
Comparison between HCM and FEM

Test Models

Sub-frame setup	Column	Beam	Connection	Beam span [m]
Setup 1	SHS 250x8	UB 178x102 x19	UK SHS 180x42.7	2
Setup 2	SHS 250x10	IPE300	U200x90x10	5
Setup 3	SHS 250x10	IPE300	U200x90x8	5
Setup 4	SHS 250x10	IPE300	U200x90x12	5

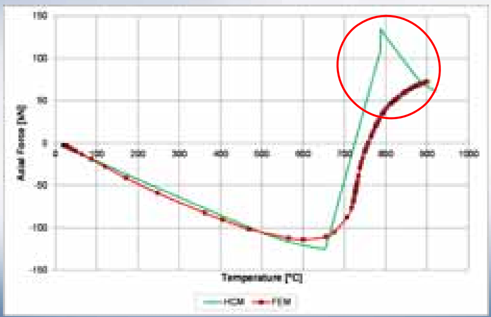
Comparison between HCM and FEM

Results: Uniform temperature



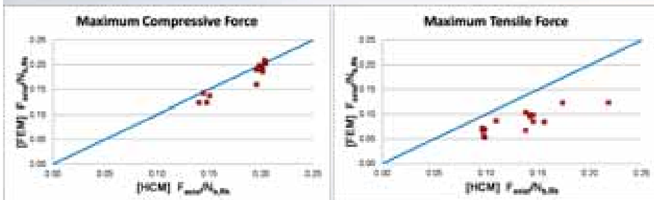
Comparison between HCM and FEM

Results: Temperature gradient



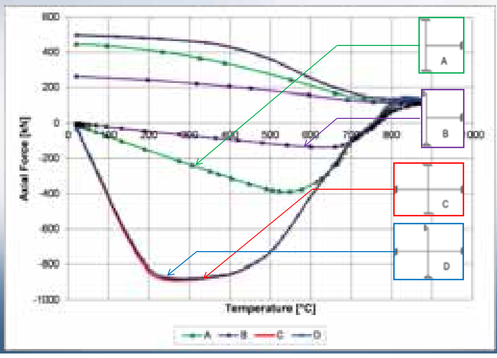
Comparison between HCM and FEM

Results



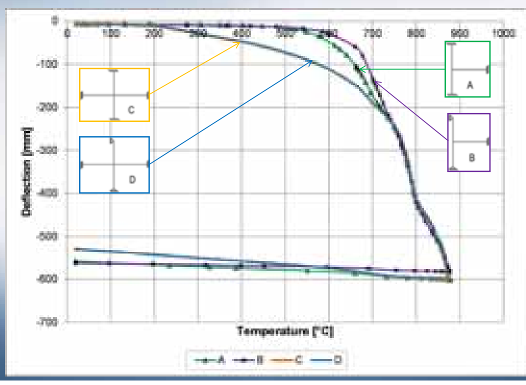
Parametric Study

Different boundary conditions



Parametric Study

Different boundary conditions



Conclusions

- Catenary action in restrained beam provides additional resistance approx. 100°C beyond the conventional limiting temperature.
- Very high midspan deflections approx. 500 mm could be observed in the restrained beam but still be below the limit state.
- The FE-models accurately depict the axial stiffness and the maximum compression force measured in the tests, about 10% maximum difference.
- Accuracy of the maximum tensile force is slightly lower in the FE- models due to interaction with bending moment, about 25% maximum difference.
- Smaller midspan deflection in FE-Models due to slightly stiffer connections and stiffer behaviour of the FE-model in general.