SHORT TERM SCIENTIFIC MISSION – COST ACTION TU0904

BENCHMARK STUDIES FOR STEEL BEAMS, STEEL FRAMES AND COMPOSITE STEEL BEAMS

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1. INTRODUCTION

The response of structures in fire is a complex process. Response of the structure can be determined experimentally or estimated with calculation procedures. Experiments are in most cases extremely difficult and expensive therefore many researchers are dedicated to the development of efficient computational procedures for the analysis of mechanical response of structures exposed to fire. For this purpose in the University of Sheffield in the Department of Civil and Structural Engineering the *Vulcan* software was developed. Vulcan is software which allows determining the response of the structure during the fire. It focuses primarily on the response of steel and composite steel-concrete structure in fire. Similarly, in the University of Ljubljana software to determine response of structure during the fire was also developed. At the Faculty of Civil and Geodetic Engineering software named *Fire* and *CompositeFire* were developed. Software allows us to determine the response of steel and composite concrete-steel elements during the fire.

The aims of short term scientific mission are benchmark studies which will focus primarily on the fire analysis of simply supported steel and composite steel-concrete elements.

2. DESCRIPTION OF THE WORK

We shall consider different cases:

- Simply supported steel beam,
- fully restrained steel beam,
- steel frame and
- simply supported composite steel-concrete beam.

Fire analysis determined with software developed at the University of Ljubljana is divided in two independent phase. The first step comprises the determination of temperature field in steel elements subject to the given temperature regime in fire department. For the concrete part of composite beam moisture and pore pressure are determined. In the second step of the fire analysis, the stress and strain fields due to combined effects of mechanical and thermal loads are obtained.

In the Vulcan the temperature field of steel and composite elements is determined in simplified manner. Therefore this part of the fire analysis is not specifically calculated.

3. THERMAL ANALYSIS

3.1. Standard BS 476 fire curve

For all benchmark studies the standard BS 476 fire curve was considered. Time-temperature development is shown on Figure 1.

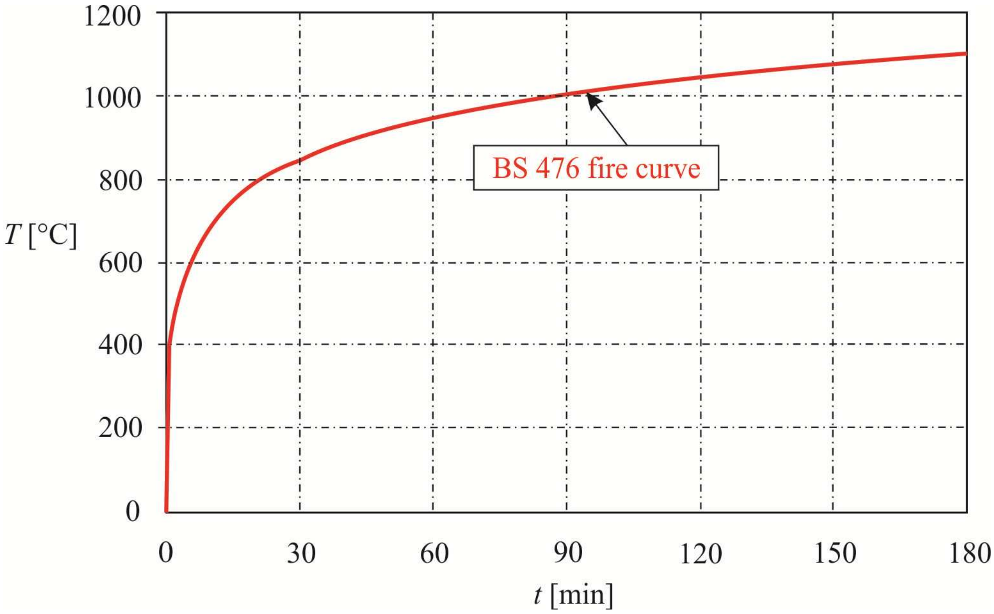

Figure 1: Standard BS 476 fire curve

3.2. Temperature pattern in accordance with EC3

The increase of temperature in an unprotected steel member during a time interval Δt can be calculated in accordance with EN 1993-1-2 (2005).

$$\Delta\theta_{a,t} = k_{sh} \frac{A_m / V}{c_a \rho_a} \dot{h}_{net} \, \Delta t, \tag{1}$$

where:

k_{sh}	is correction factor for shadow effect,
A_m / V	is the section factor for unprotected steel members [m^{-1}],
A_m	is the surface area of the member per unit length [m^2/m],
V	is the volume of the member per unit length [m^3/m],
c_a	is specific heat of steel [J/kgK],
ρ_a	is the unit mass of steel [kg/m^3],
$\dot{h}_{net}$	is the design value of the net heat flux per unit area,
Δt	is the time interval [s].

For I-sections the correction factor for the shadow effect under the influence of fire such as BS 476 is determined as:

$$k_{sh} = 0.9[A_m / V]_b / [A_m / V], \tag{2}$$

where $[A_m / V]_b$ is a section factor for an imaginary box that embraces the I-section. In all other cases, the value of ksh should be taken as:

$$k_{sh} = [A_m / V]_b / [A_m / V]. \tag{3}$$

Figure 2 shows the difference between section factor and box value of section factor.

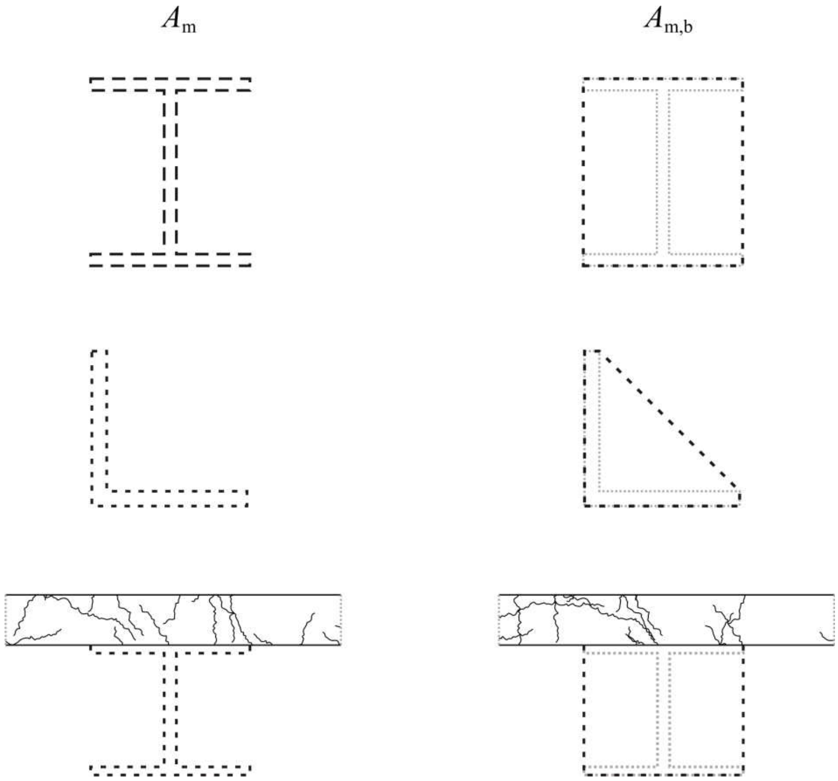

Figure 2: Section factor and box value of section factor

3.3. Temperature pattern in Vulcan

In Vulcan temperature field of steel elements in usually determined in accordance with EN 1993-1-2 (2005). Temperature field for the concrete part of composite beam is usually determined by bilinear pattern shown in figure 3.

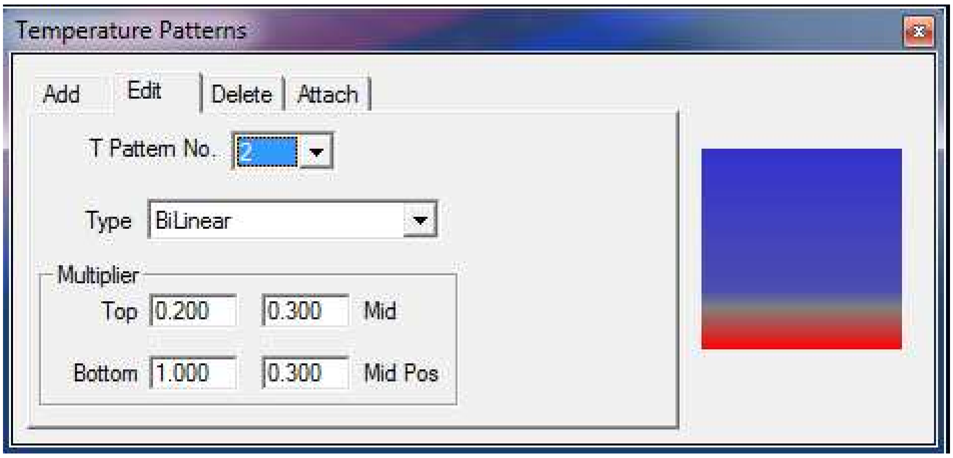

Figure 3: Bilinear temperature pattern in Vulcan

3.4. Thermal analysis with HeatMoisture

HeatMoisture is software to determine moisture and temperature within the steel and concrete as a coupled problem, where temperatures, vapour pressure, free water, and mixture of dry air and water vapour content in concrete are treated as a coupled heat and moisture transfer. The model takes into account evaporation of free water, the liquefaction of water vapour and the dehydration of chemically bond water. Following Tenchev et al. (2001) the mathematical model of a coupled heat and moisture transfer in concrete exposed to fire is described with a system of mass conservation equations for each phase of concrete separately and with the energy conservation equation. More details are presented in Hozjan et al (2010).

4. MECHANICAL ANALYSIS

4.1. Fire and CompositeFire

Fire and *CompositeFire* are software to determine the stress–strain state in the steel element and steel–concrete composite beam. Software is based on finite element method. For each time interval $[t^{i-1},t^{i}]$, employed previously in the heat or in the heat and moisture transfer analysis, we determine iteratively the stress and strain state at time station t^{i} based on a given mechanical results at t^{i-1} and thermal and hygro-thermal results at t^{i}. Each material component (the layer) of the steel–concrete beam are modeled by its own beam using Reissner's beam theory (1972), but with the effect of shear deformations being neglected. We also assume that only the tangential slip can occur at the interface between the two beams, and neglect any transverse separation (uplifts) between the components. We also propose that the geometrical strain increment in a point is the sum of the strain increments due to the change of temperature, stress and creep and for concrete only, of the transient strain increment.

4.1.1. Mechanical characteristic of steel at elevated temperatures

Stress-strain relationship

In numerical analysis we consider stress-strain relationship of steel at elevated temperatures as proposed by standard EN 1993-1-2 (2005) or bilinear steel material model proposed by Srpčič (1991). Let us mention that in stress-strain relationship proposed by EN 1993-1-2 (2005) creep of steel is implicitly considered.

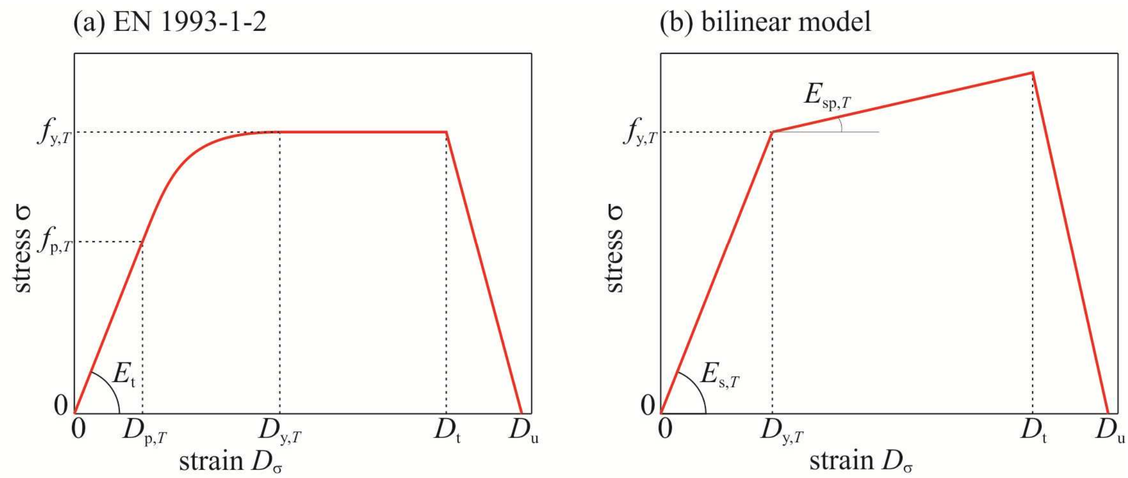

Figure 4: (a) Stress-strain relationship of steel at elevated temperature (EN 1993-1-2, 2005). (b) Bilinear material model of steel.

It is well known that with the increase in temperature the rigidity of steel elements significantly lowers. Modulus of elasticity as well as yield tension declines non-linear with temperature. For the first stress-strain model (Figure 4a) we assume the variation of material parameters of steel as determined by reduction factors $k_{p,T}$, $k_{y,T}$ and $k_{E,T}$ in accordance with EN 1993-1-2 (2005). For bilinear constitutional model the reduction factors $k_{y,T}$ and $k_{E,T}$ are considered in accordance with French regulations (Construction metallique, 1976).

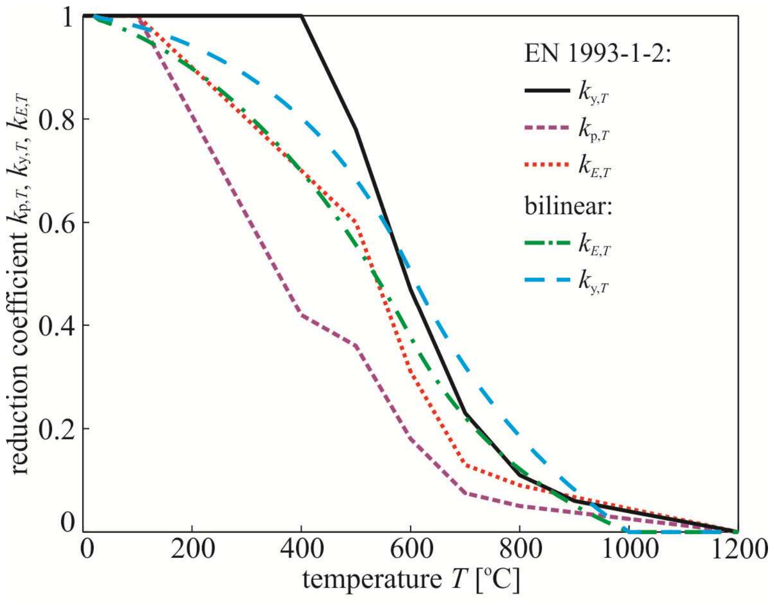

Figure 5: Change of reduction factors with temperature.

Creep of steel

Creep of steel is at normal temperatures almost negligible. At elevated temperatures (T > 400°C) creep cannot be neglected. The mathematical model used for the mechanical part of fire analysis is considered according to model that was suggested by Williams-Leir (1983):

$$\Delta\varepsilon_{\mathrm{cr,s}} = sign(\sigma_{\mathrm{s}}) \cdot b_1 \cdot \coth^2\left(b_2 \cdot \left|\varepsilon_{\mathrm{cr,s}}\right|\right) \cdot \Delta t \qquad (4)$$

where b_1 and b_2 are the functions of stress σ_s and temperature T.

4.2. Vulcan

Vulcan is a finite element analysis (FEA) program, which is capable of modeling the global 3-dimensional behavior of composite steel-framed buildings under fire conditions. The analysis considers whole structure action and includes geometrical and material non-linearity within its beam-column and slab elements, with full membrane action in the slabs. Standard stress-strain curves and full thermal expansion characteristics are incorporated as functions of temperature for both steel and concrete, with uniform or non-uniform temperature distributions. The orthotropic nature of composite deck slabs is represented using an effective-stiffness concept, and options for semi-rigid connections and partial interaction between steel sections and slabs are provided. Vulcan software has been developed specifically for the analysis of building performance in fire conditions (http://www.vulcan-solutions.com/software.html)

5. RESULTS

5.1. Simply supported steel beam

First we deal with simply supported steel beam with span of 8 m. The cross-section that we consider is UB 406×178×67. The analysis is performed with the load of 20 and 40 kN/m. The Figure 6 shows model for simply supported beam and its cross-section.

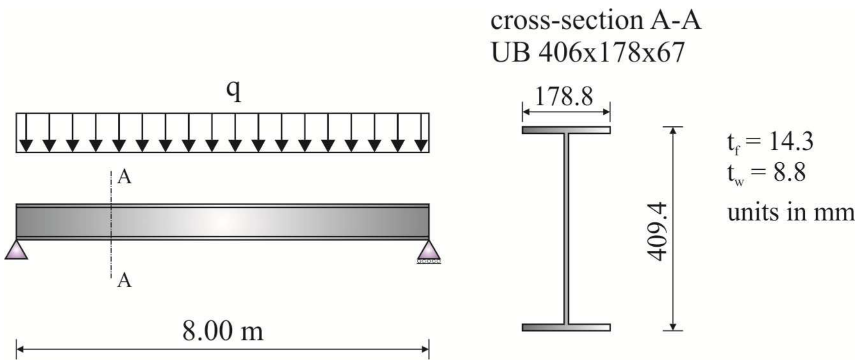

Figure 6: Simply supported steel beam

5.1.1. Input data

Table 1: Input data for simply supported beam

	Vulcan	**Fire**
Span	8m	
Cross-section	UB 406×178×67	
Load	20 and 40 kN/m	
Temperature pattern	EN 1993-1-2 (2005)	
Strength of steel	S275	
Modulus of elasticity	21000 kN/cm^2	
Stress-strain relationship	EC3	EC3 and Bilinear + Creep

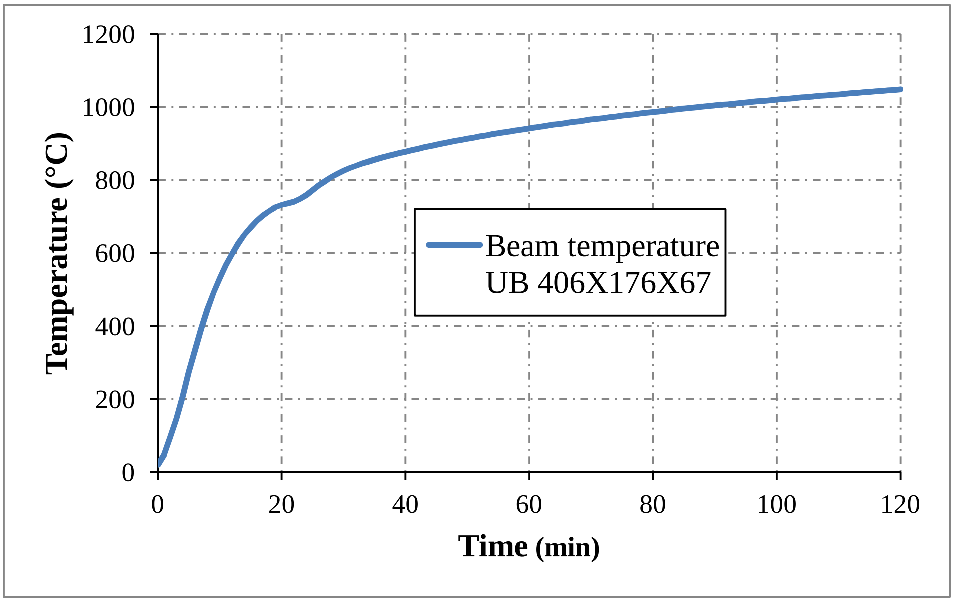

Figure 7: Beam temperature

5.1.2. Vertical displacement in the mid-span of the beam

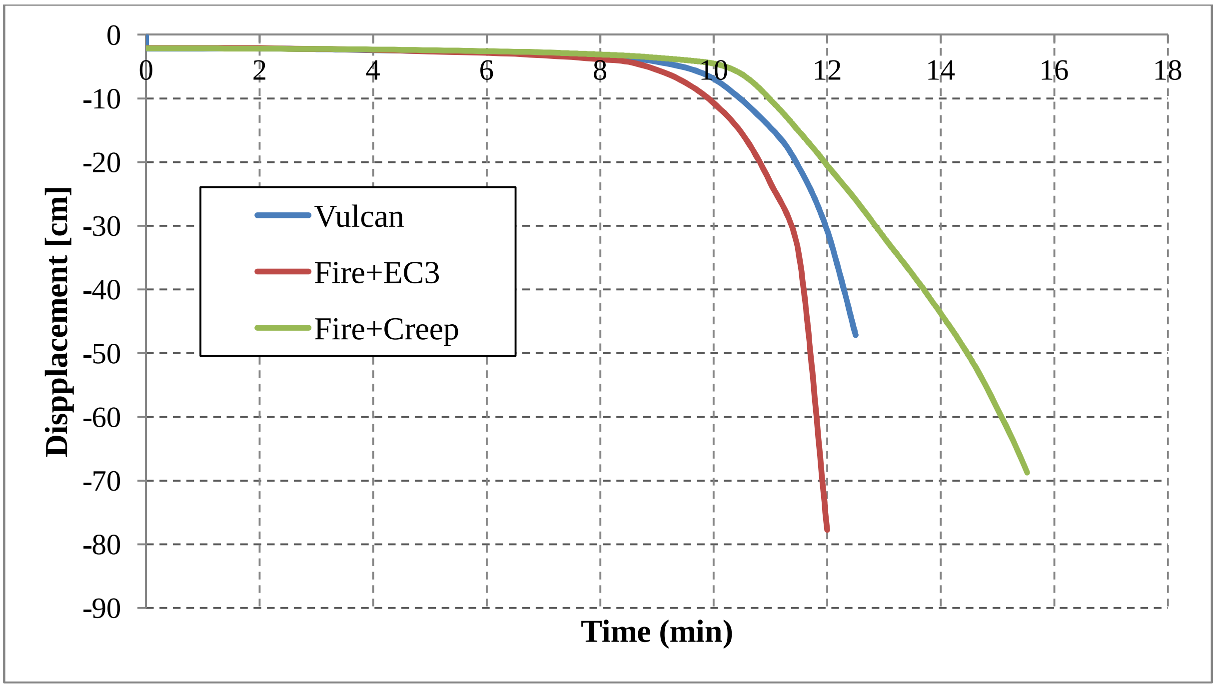

Figure 8: Displacement in the mid-span of the beam, load q = 20kN/m

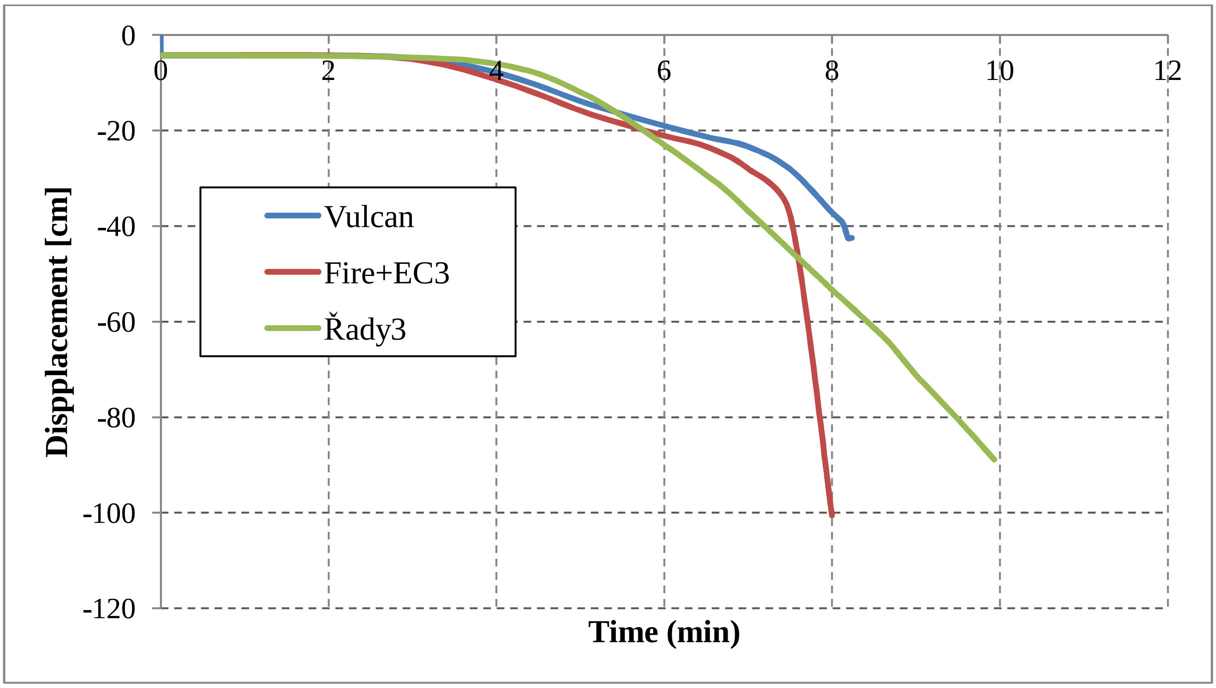

Figure 9: Displacement in the mid-span of the beam, load q = 40kN/m

5.2. Fully restrained steel beam

Second part of our benchmark study was fully restrained steel beam. It differs from simply supported beam only in supports. Ends of beam are fully supported (both translations and rotation). The input data is the same as in chapter 5.1 therefore we skip this chapter here.

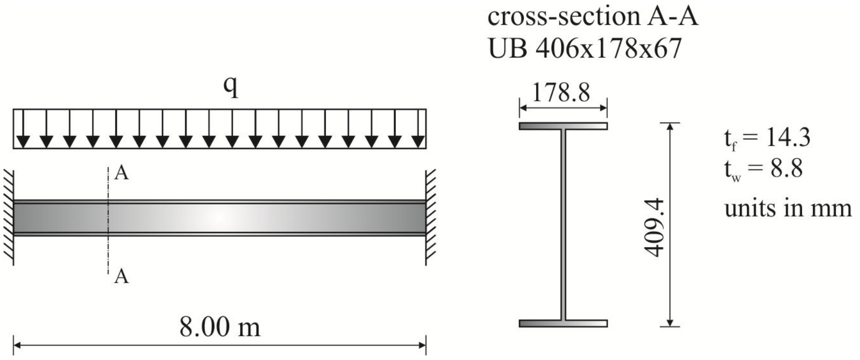

Figure 10: Fully restrained steel beam

5.2.1. Vertical displacement in the mid-span of the beam

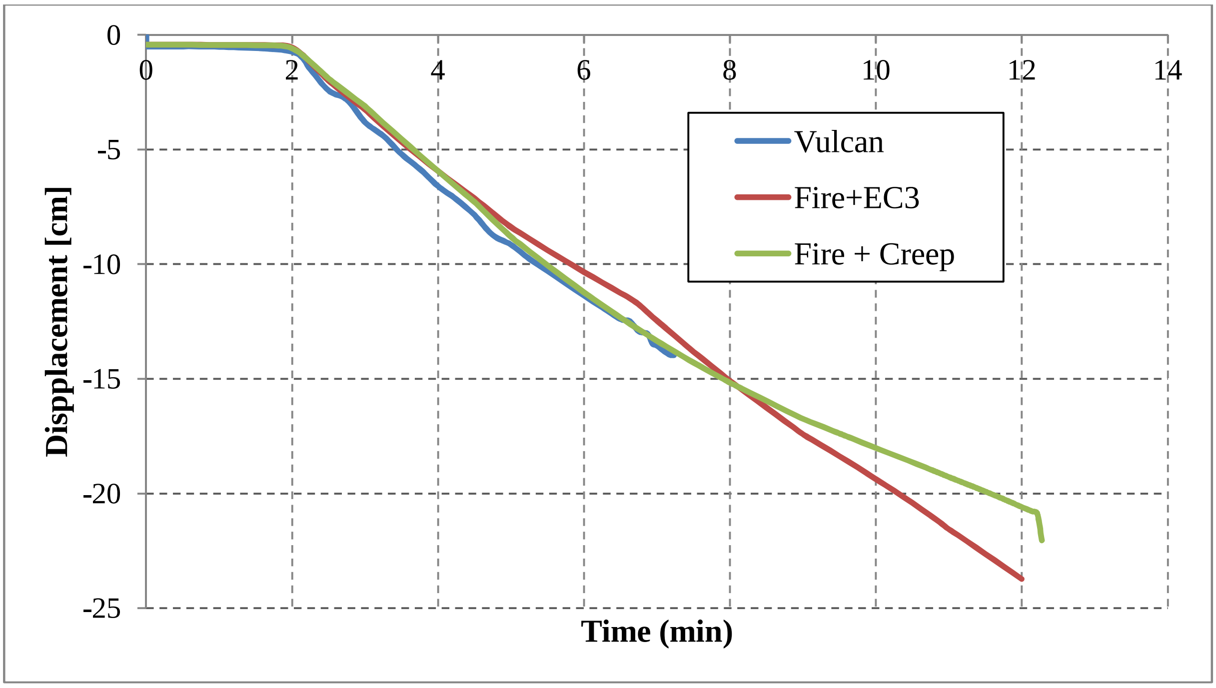

Figure 11: Displacement in the mid-span of the beam, load q = 20kN/m

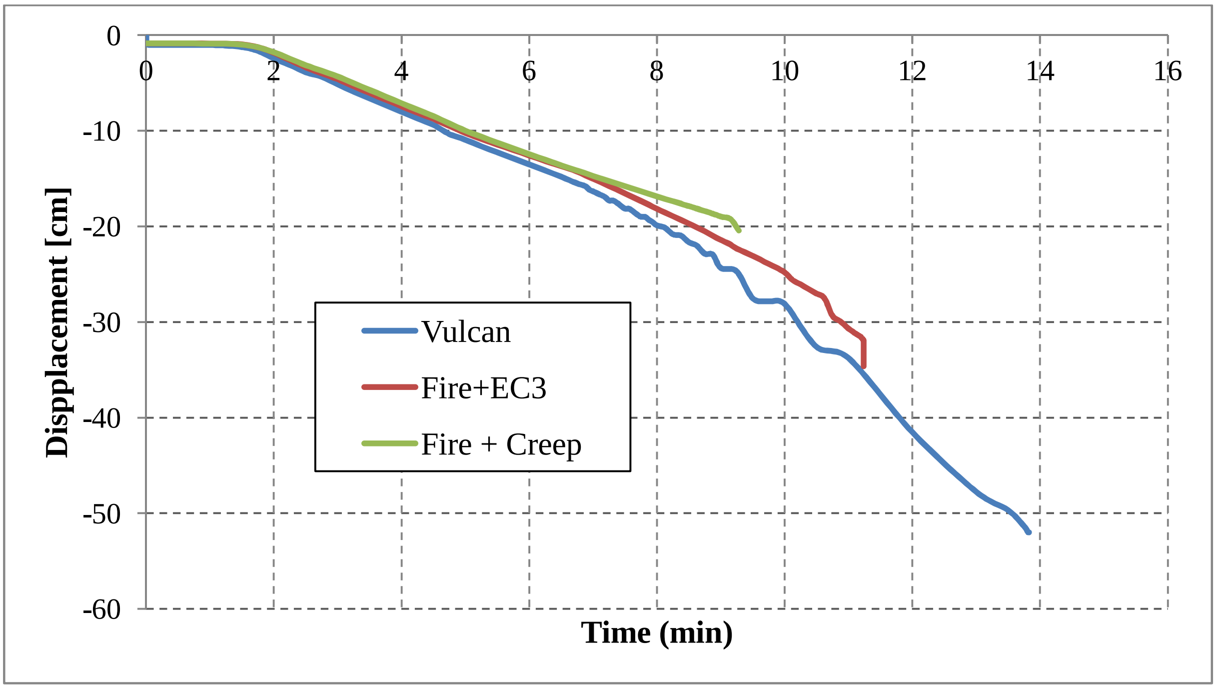

Figure 12: Displacement in the mid-span of the beam, load q = 40kN/m

5.2.2. Axial force

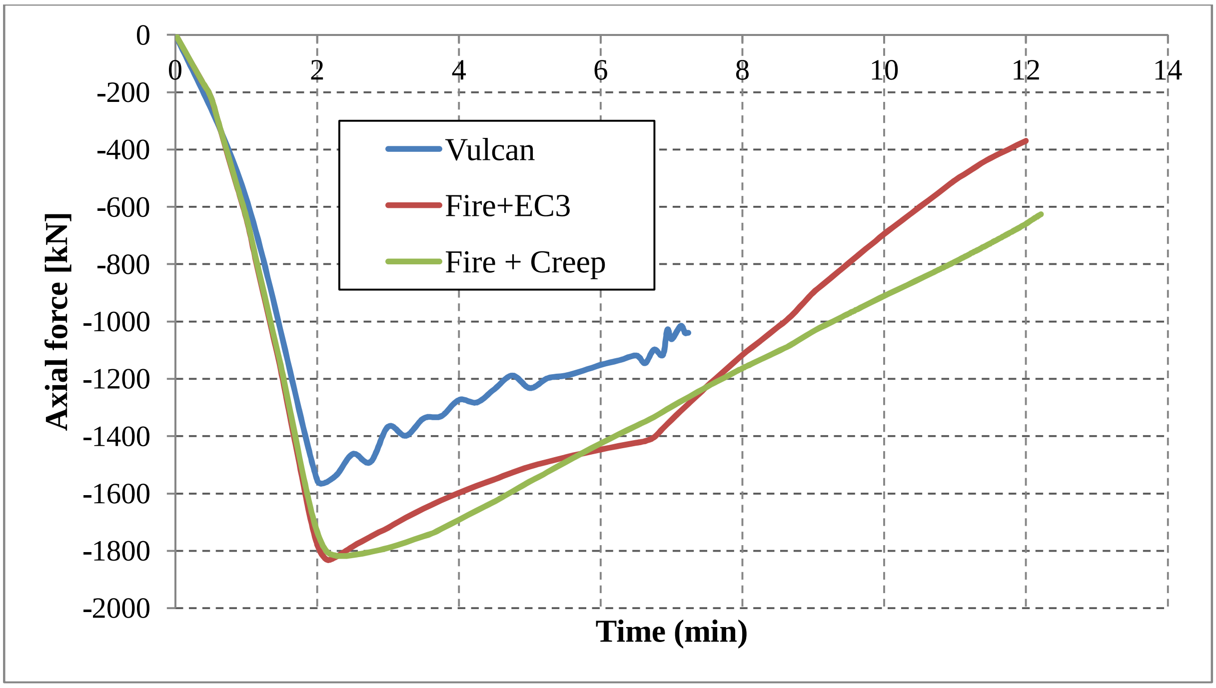

Figure 13: Axial force in the mid-span of the beam, load *q* = 20 kN/m

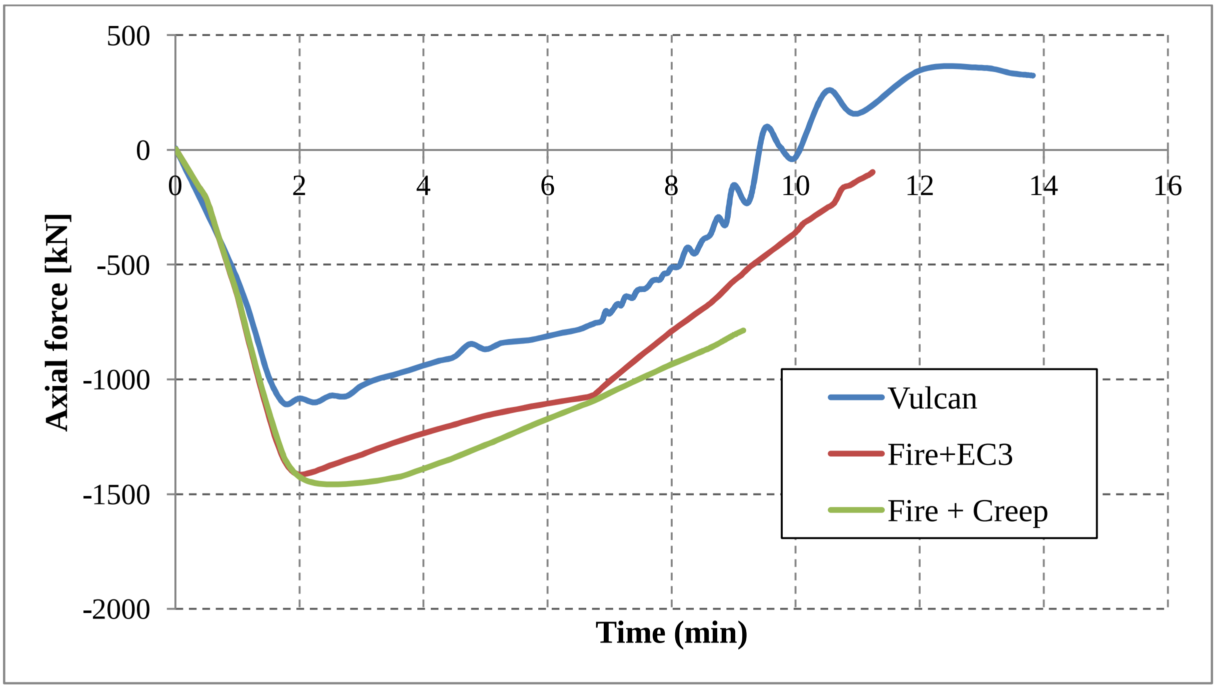

Figure 14: Axial force in the mid-span of the beam, load *q* = 40 kN/m

5.3. Steel frame

Next subject of our benchmark study was simple steel frame. The frame consists of two steel columns and steel beam that is connecting them. The span of the beam is 5 m and the height of the columns is 3.5 m. Columns are at the bottom supported with a pin support. Cross section of all elements is HEA 300.

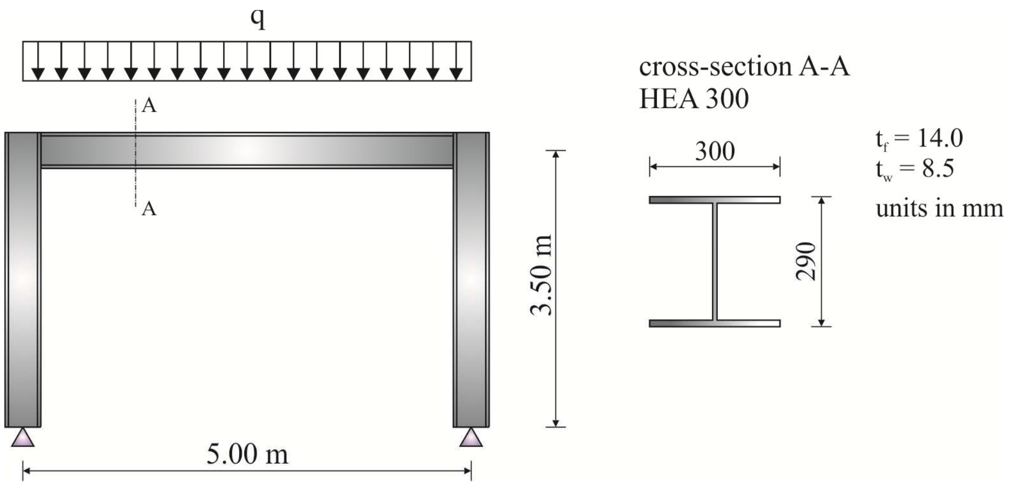

Figure 15: Steel frame

5.3.1. Input data

Table 1: Input data for steel frame

	Vulcan	**Fire**
Width	5 m	
Height	3.5 m	
Cross-section	HEA 300	
Load	30 kN/m	
Temperature pattern	EN 1993-1-2 (2005)	
Strength of steel	S275	
Modulus of elasticity	21000 kN/cm^2	
Stress-strain relationship	EC3	EC3 and Bilinear + Creep

5.3.2. Displacement in the mid-span of the beam

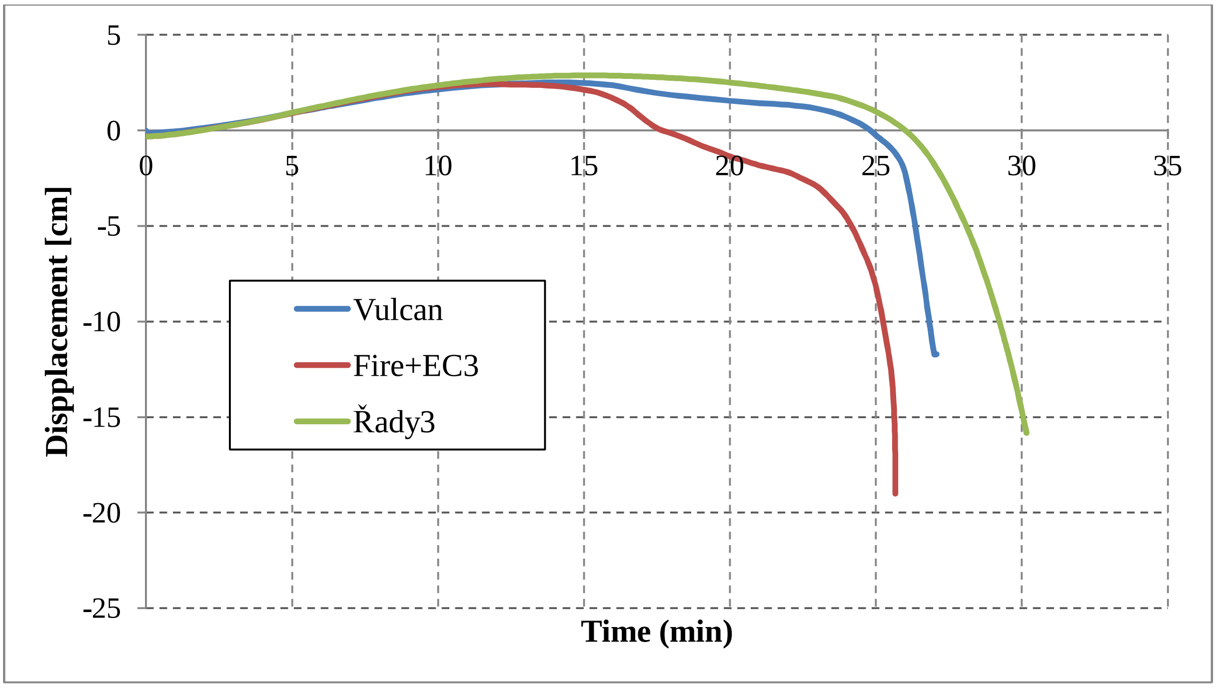

Figure 16: Displacement in the mid-span of the beam, load q = 40kN/m

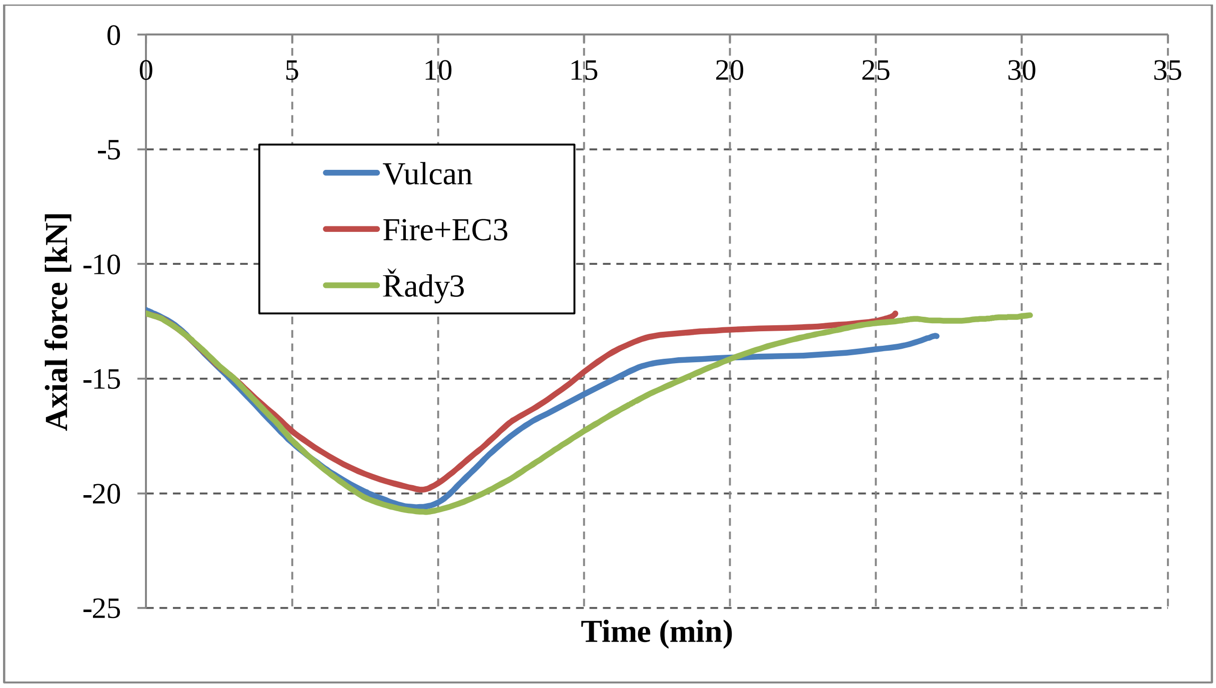

Figure 17: Axial force in the mid-span of the beam, load q = 30 kN/m

5.4. Composite steel beam

The last part of our benchmark study was simply supported composite steel-concrete beam. The span of the beam is 5m. The beam is loaded with tree point loads.

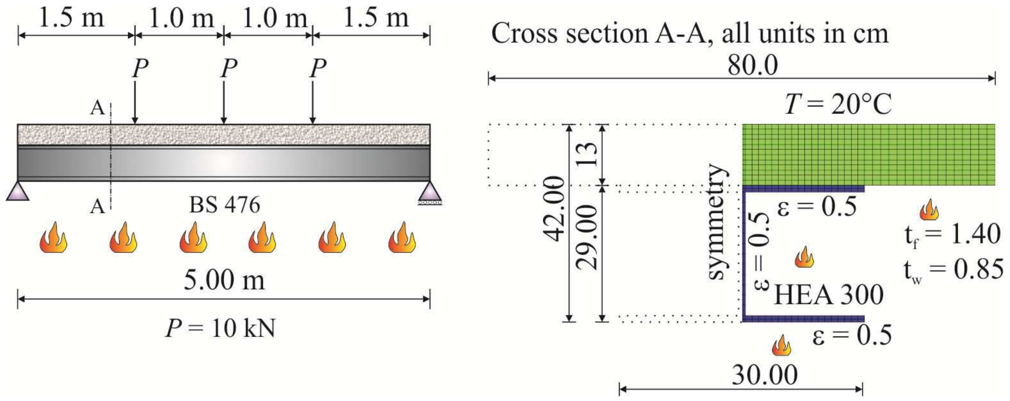

Figure 18: Composite steel-concrete beam

5.4.1. Input data

Table 1: Input data for composite beam

	Vulcan	**CompositeFire**
Span	5 m	
Steel cross-section	HEA 300	
Concrete cross-section	13 × 80 cm	
Load	3 × 10 kN	
Temperature pattern	EC3 - steel Bilinear model - concrete	HeatMoisture
Strength of steel	S275	
Modulus of elasticity of steel	21000 kN/cm^2	
Strength of concrete	3.5 kN/cm^2 (compression)	
Modulus of elasticity of concrete	3300 kN/cm^2	
Stress-strain relationship	EC3	
Shear connection	Rigid	

5.4.2. Displacement in the mid-span of the beam

Due to different temperature field in composite beam is displacement in the mid-span of the beam shown as a function of temperature. The reference temperature is the temperature of the bottom flange of steel section.

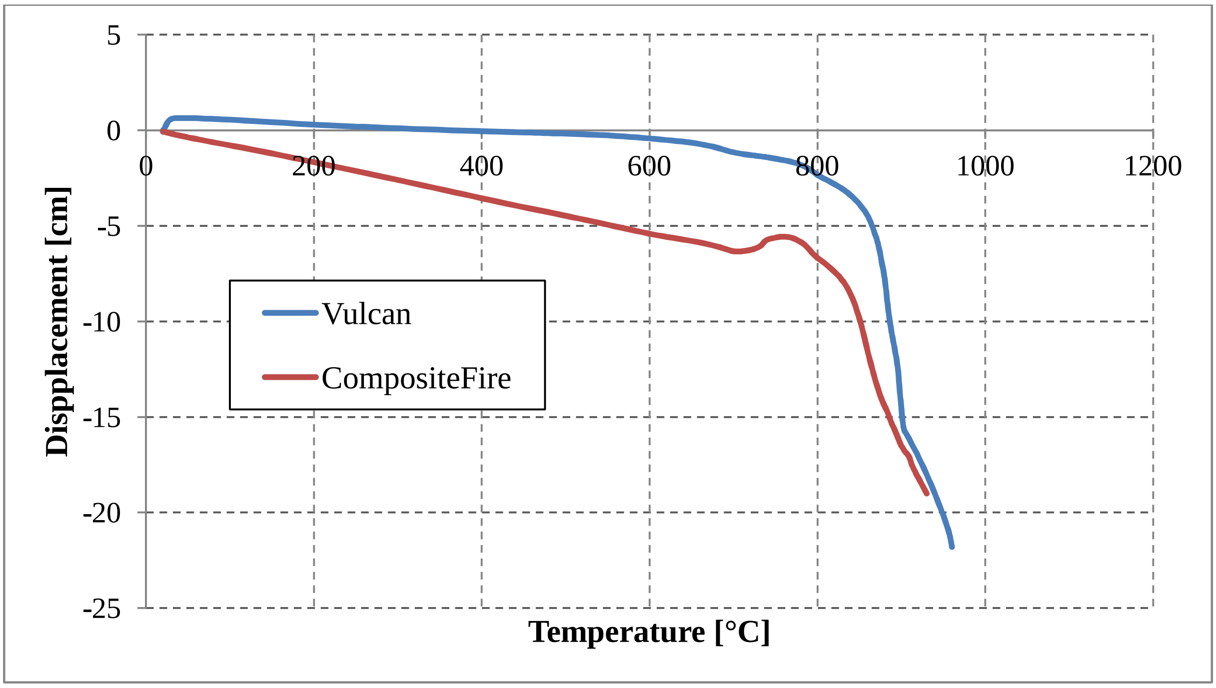

Figure 19: Displacement in the mid-span of the composite beam

6. CONCLUSIONS

In the short term scientific mission we provided benchmark studies for steel beams, steel frame and composite steel-concrete beam. The results were obtained with different software. First software was developed in the University of Sheffield and the second was developed in the University of Ljubljana. The results were compared with each other. The comparison shows good agreement between the results, small deviation can be observed only in the vertical displacement of composite beam. The study also revealed that the model used for creep of steel is s suitable for determining the response of steel elements in fire.

7. REFERENCES

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