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Joint Component Behaviour in Fire

Florian M. Block

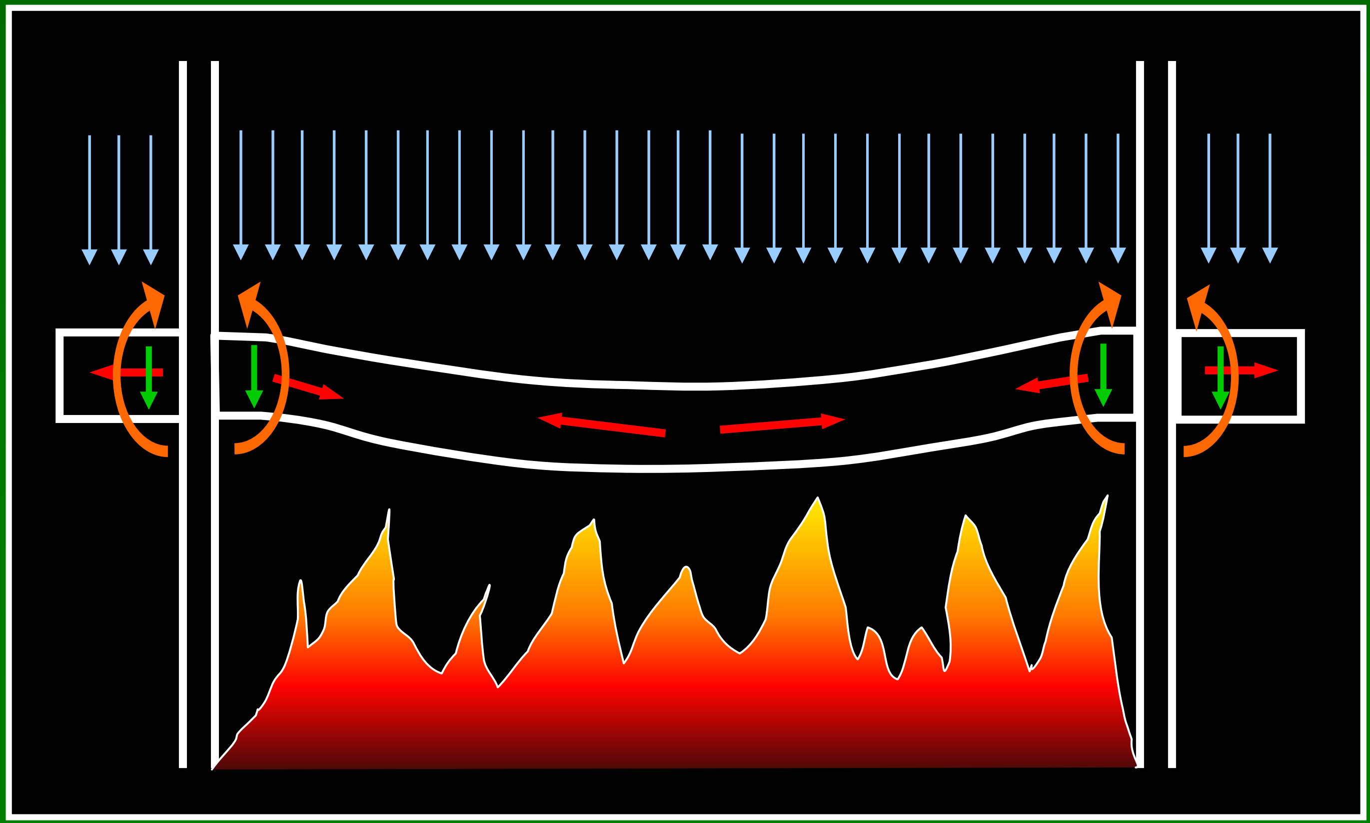
Ian W. Burgess   J. Buick Davison

Steel in Fire Forum

Rotherham, UK   September 2004

Beam and Joint Forces in Fire

Beam:	Joint:
Bending	Shear
Bending and Compression	Shear, Bending and Compression
Tension	Shear, Bending and Tension



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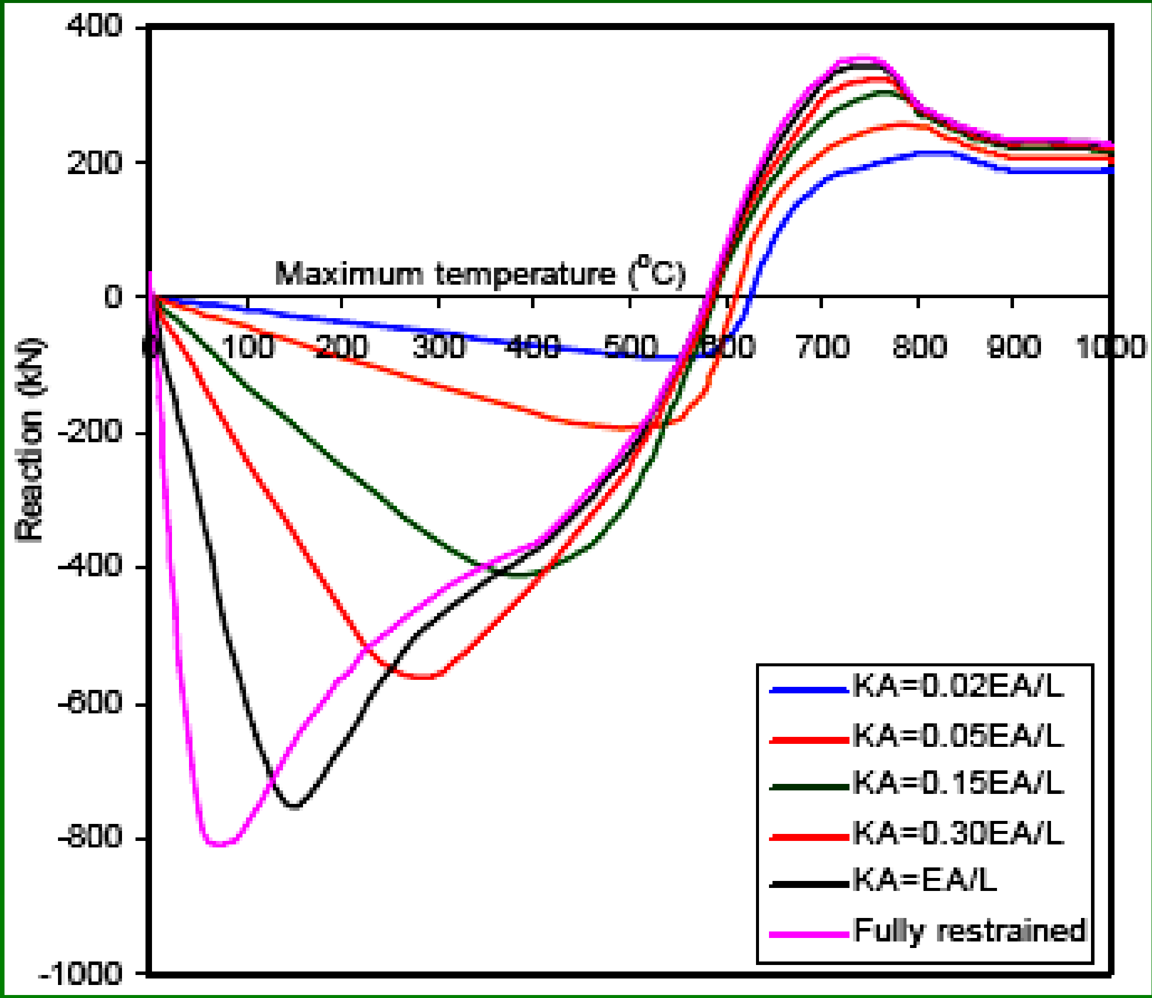
Axial Beam Forces in Fire

Axial beam forces depend on the axial joint stiffness.



by Y.Z. Yin, Manchester Centre for Civil and Construction Eng.

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Cardington Beam-Column Joint after Fire Test # 7

Beam shear buckling   Beam flange buckling

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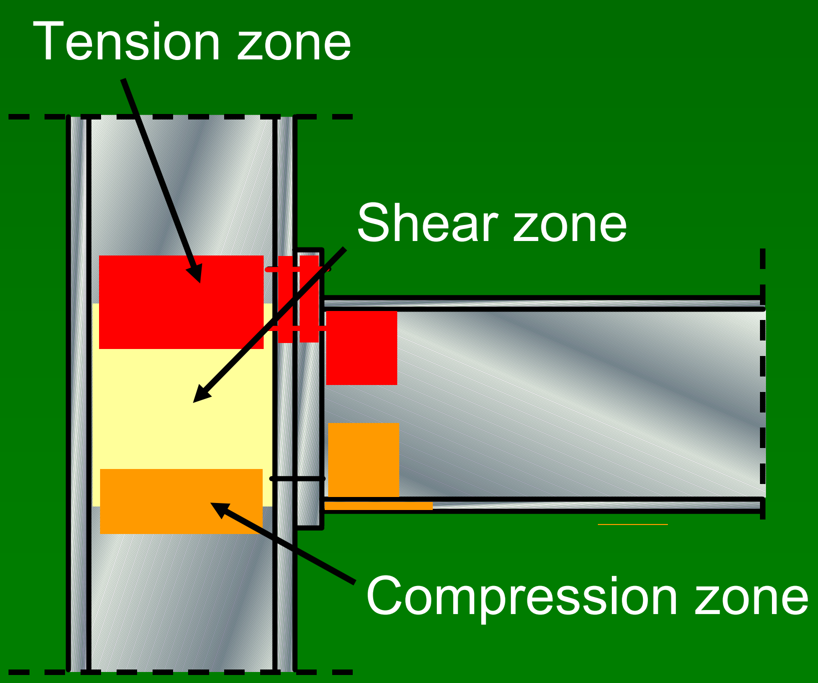
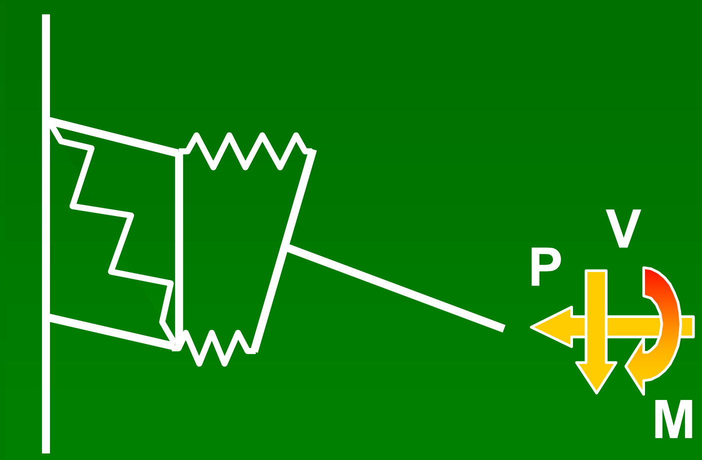
The Component Method

- A flexible approach based on modelling the zones of fundamental behaviour (“components”) within a joint.
- Reassembling a model of the joint with springs.





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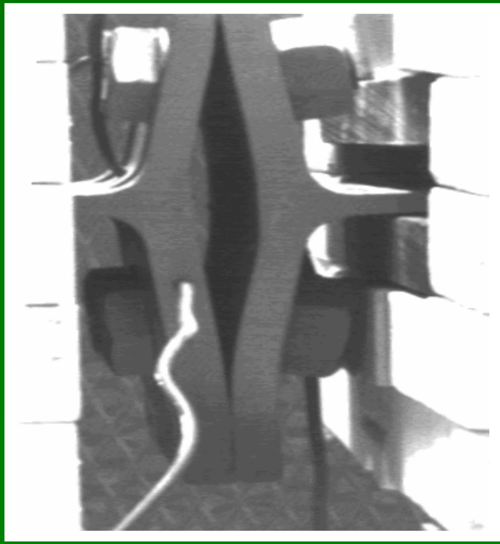
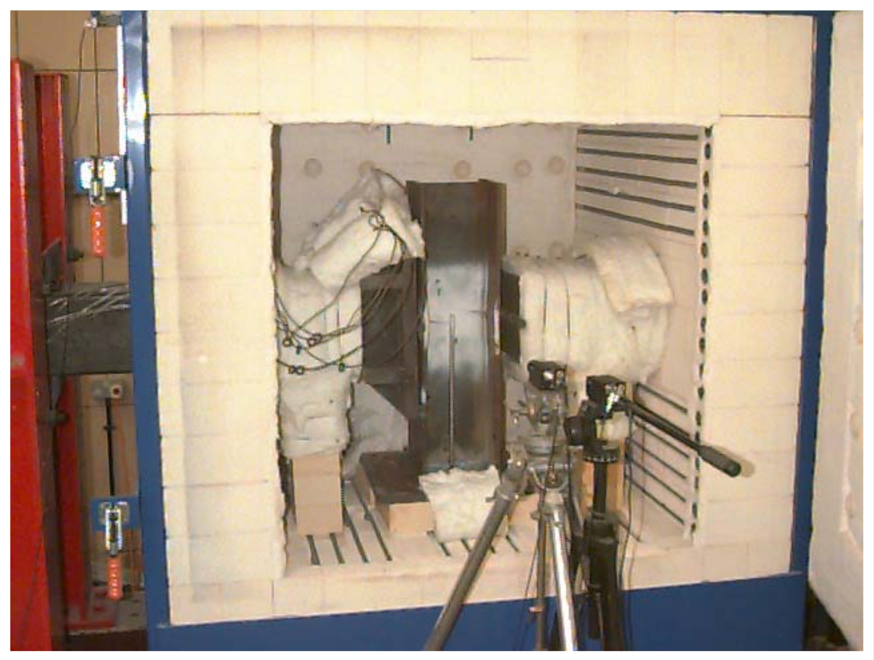
What has been done before?

Experimental test program and analytical / semi-empirical models by S. Spyrou (1998 – 2001) at the University of Sheffield:

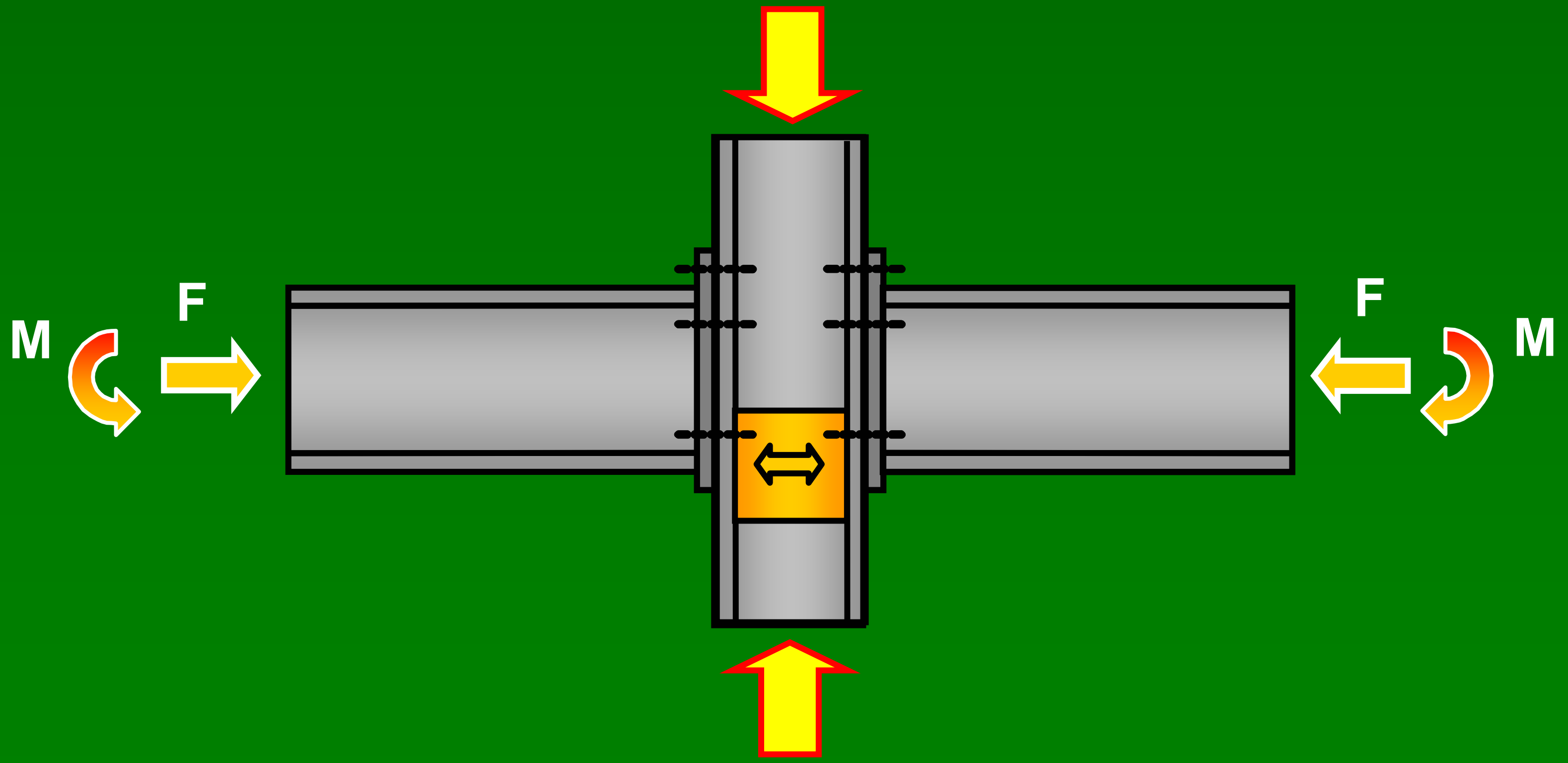
- Tension zone of endplate joints as T-Stub
- Compression zone in the column web





Compression Zone: Column Web

- Can become critical at a relatively early stage of fire due to thermal expansion of the beams.
- Can cause column buckling by forming a plastic hinge in the column and increasing the buckling length.



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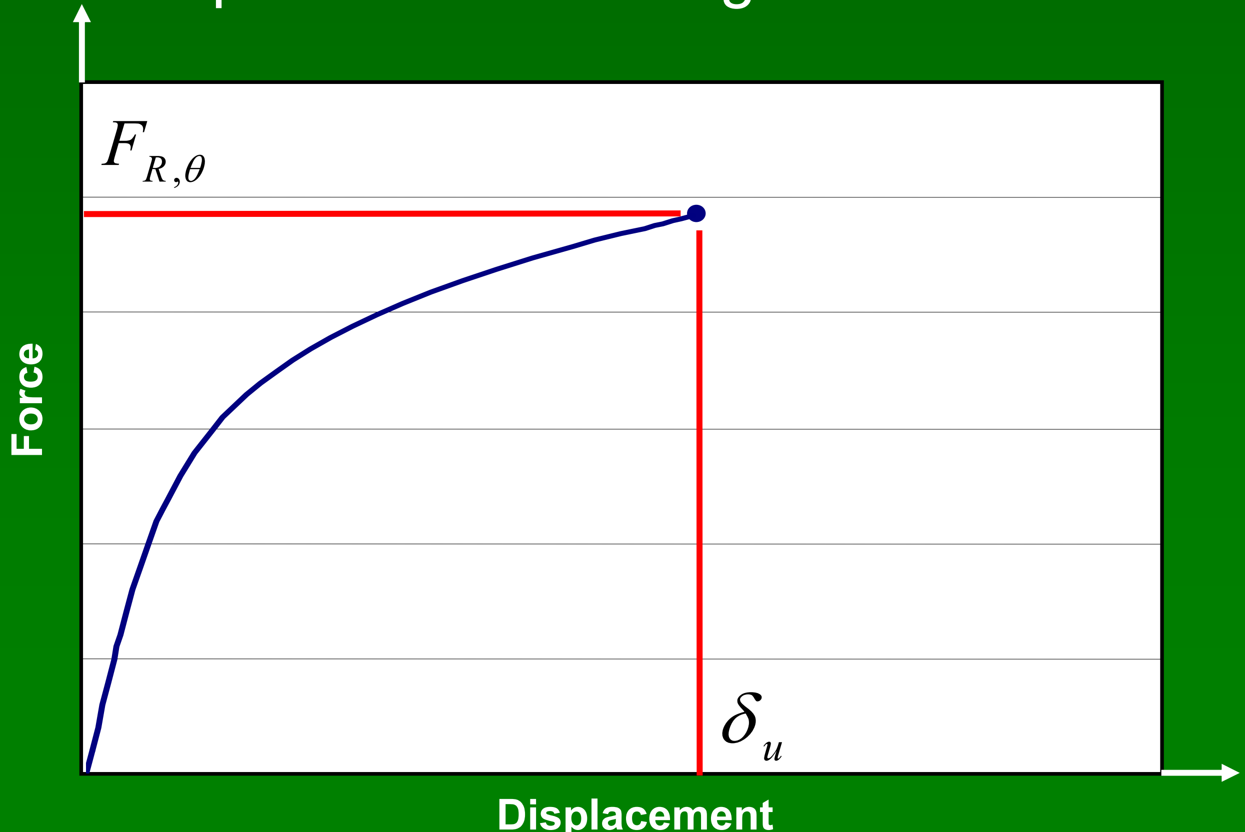
Force – Displacement Model…

Force – Displacement Model for the Compression Zone

1. Ultimate strength
2. Displacement at ultimate strength
3. Curve up to ultimate strength



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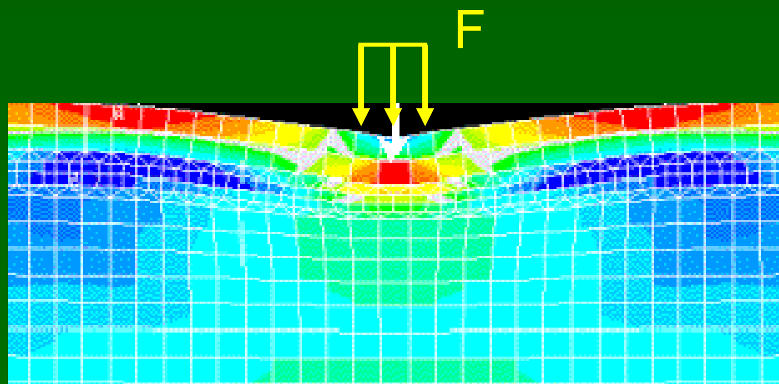
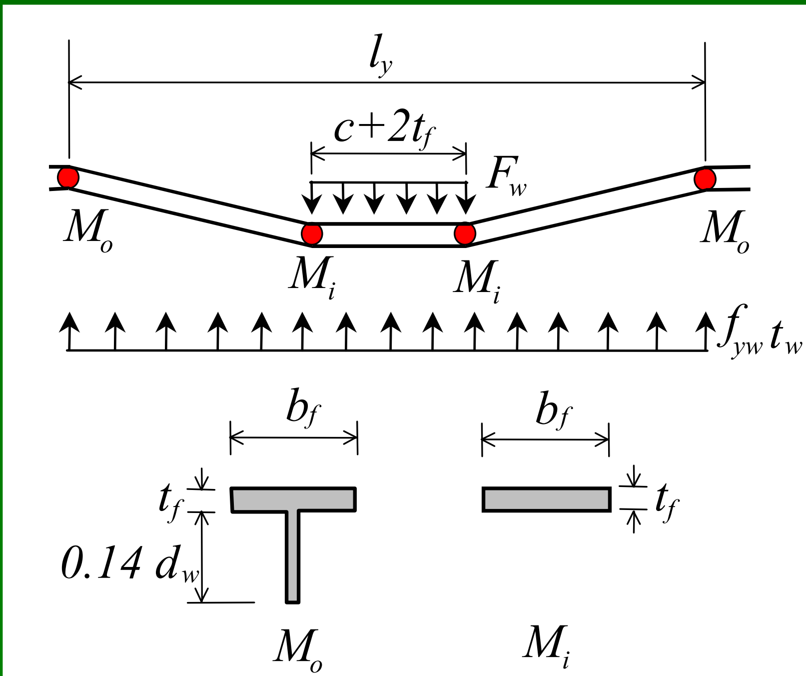
1. Lagerqvist – Equation for the Ultimate Strength





$$F_{R,\theta} = k_{y,\theta} f_{yw} L_{eff} t_w$$

$$L_{eff} = \chi_F l_y$$

$$\chi_F = \frac{0.5}{\lambda_F} \leq 1.0$$

$$\lambda_F = \sqrt{\frac{l_y t_w k_{y,\theta} f_{yw}}{F_{cr}}}$$

$$F_{cr} = k_F \frac{\pi^2 k_{E,\theta} E}{12\left(1-\upsilon^2\right)} \frac{t_w^3}{d_w}$$

with $k_F = 3.5$

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2. Numerical Study of the Peak Displacement

A 3D ANSYS Finite Element Model was used to perform a parametric study of the displacement at ultimate strength.

Parameters studied:

Web thickness	t_w	=	4 - 11 mm
Web depth	d_w	=	95 - 271 mm
Yield stress	f_y	=	235 - 460 N/mm^2
Flange thickness	t_f	=	4 - 15 mm
Load introduction width	c	=	12 - 96 mm

2. & 3. Displacement of the Compression Zone

Equation for the displacement at ultimate strength as found in the parametric study:

$$\delta_{u,pl} = 0.25\,\frac{l_y t_w^2}{b_f t_f}\sqrt{\frac{t_w}{t_f}\frac{d_w}{c}}$$

Modified Ramberg-Osgood equation including the initial stiffness of EC3 Part 1.8 for the compression zone:

$$\delta_i = \frac{F_i d_w}{0.7 k_{E,\theta} E l_y t_w} + \delta_{u,pl}\left(\frac{F_i}{F_{R,\theta}}\right)^5$$

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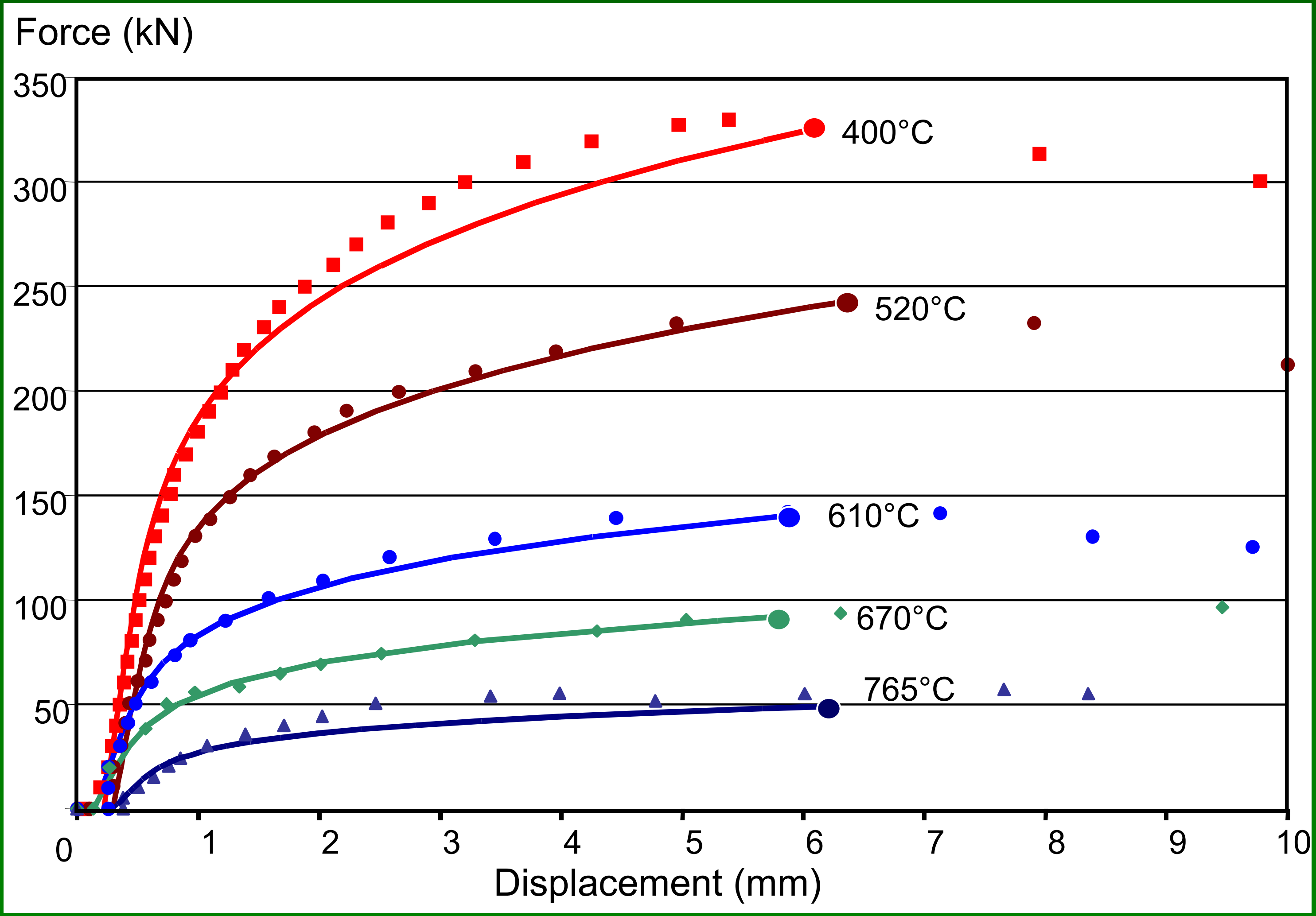
Comparison of the Analytical Model with Test results



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Influence of Axial Load…

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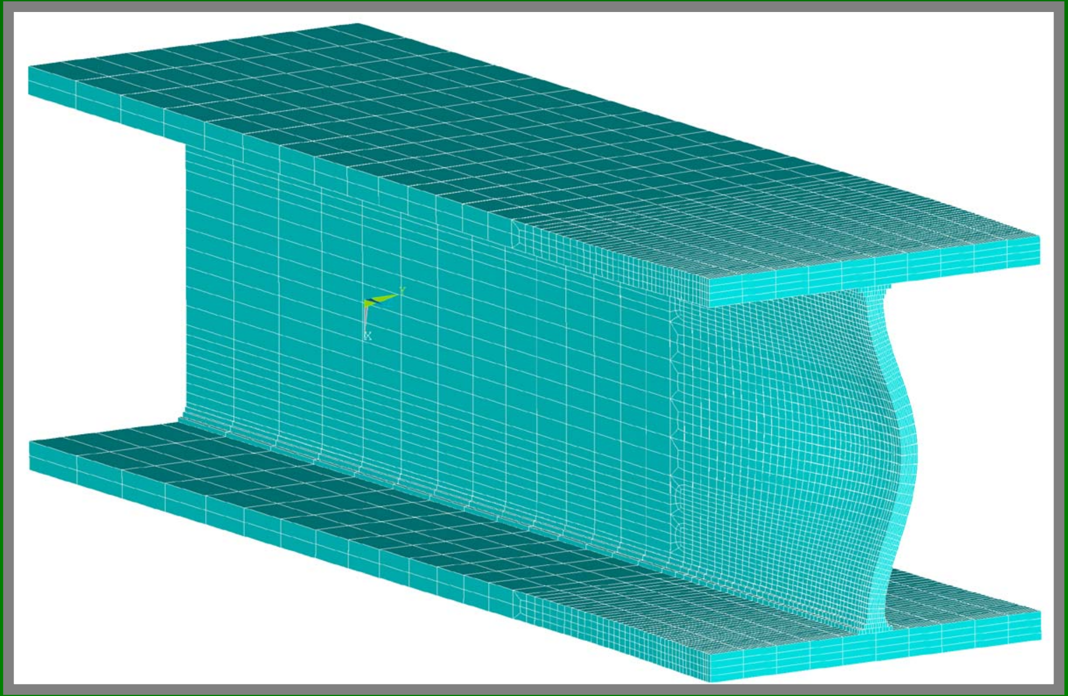
Influence of Axial Load in the Column

- Tests at 20°C have shown that axial load in the column reduces the resistance and the deformation capacity.
- All existing reduction factors are based on ambient temperature experiments.
- A FEM Study has been conducted and an experimental programme at high temperatures is in progress.

FEM Model

- ANSYS Layered Thin-Shell-Elements
- 3 British column sections with d_w / t_w between 10.4 and 22.3
- Uniform temperatures up to 650°C
- Material properties from EC3 Part 1.2
- Axial loads up to 80% of the effective yield load



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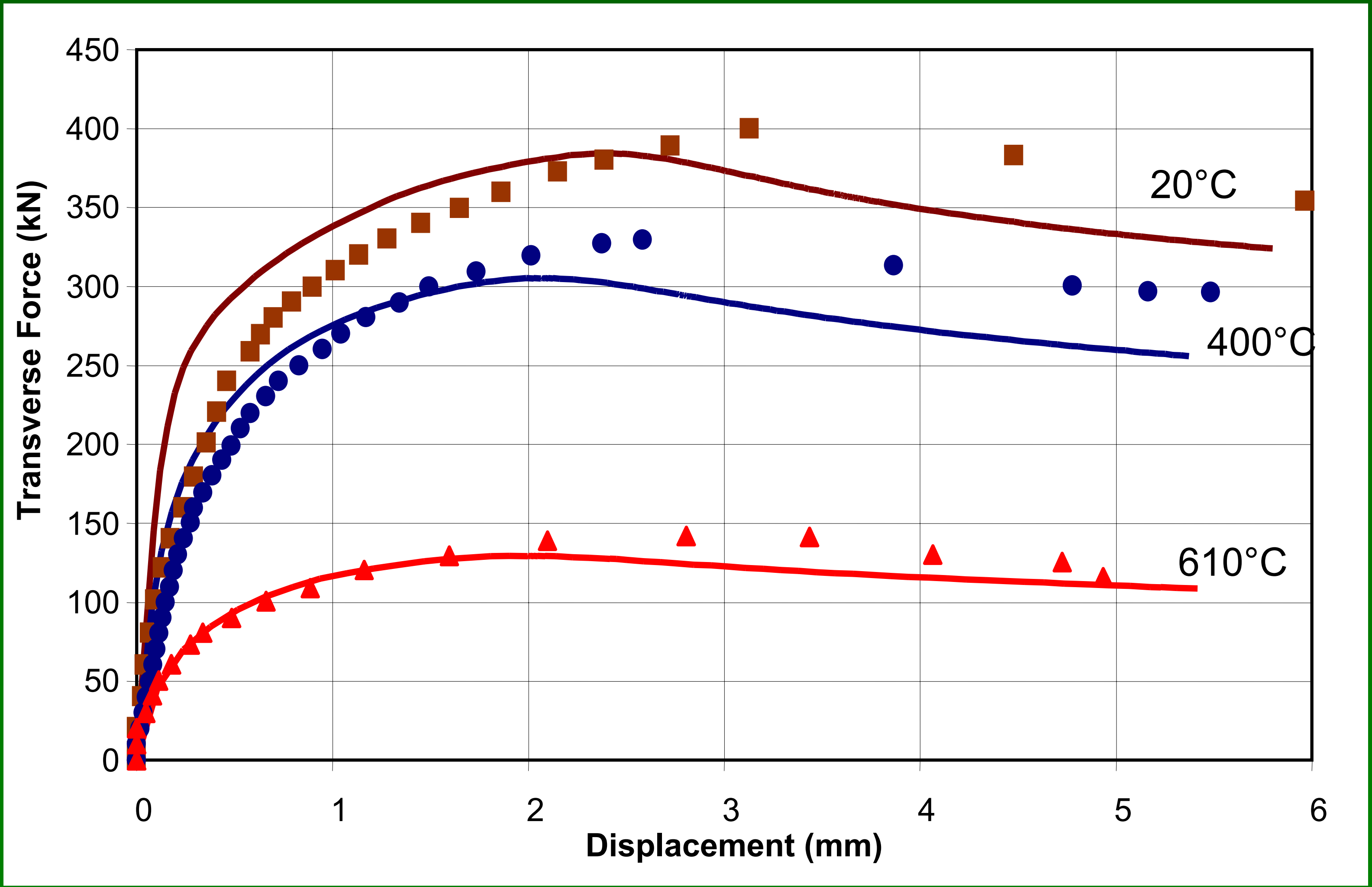
Comparison between the FEM Model and Test Results



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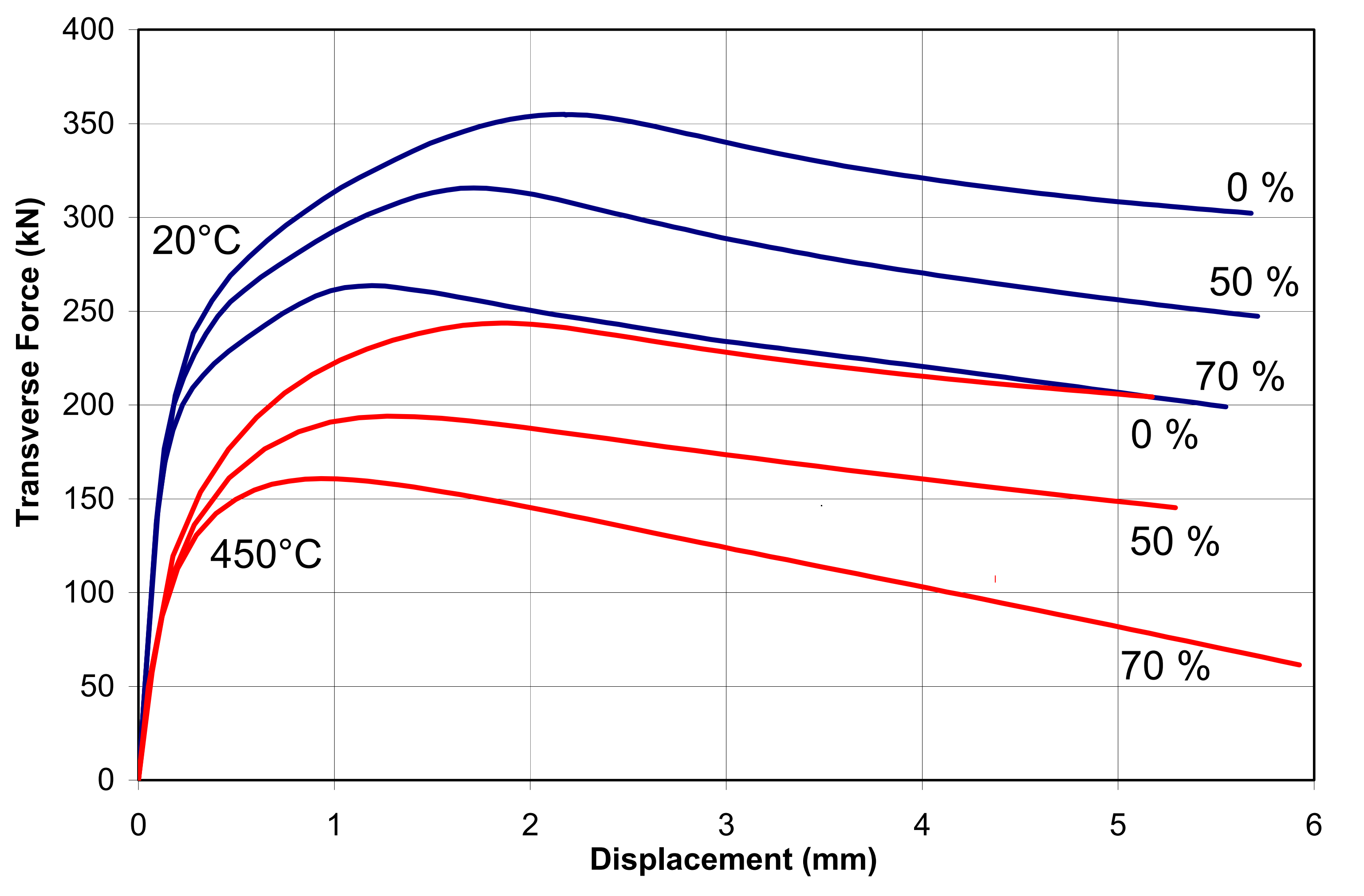
Influence of the Axial Load



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Reduction of the Ultimate Strength

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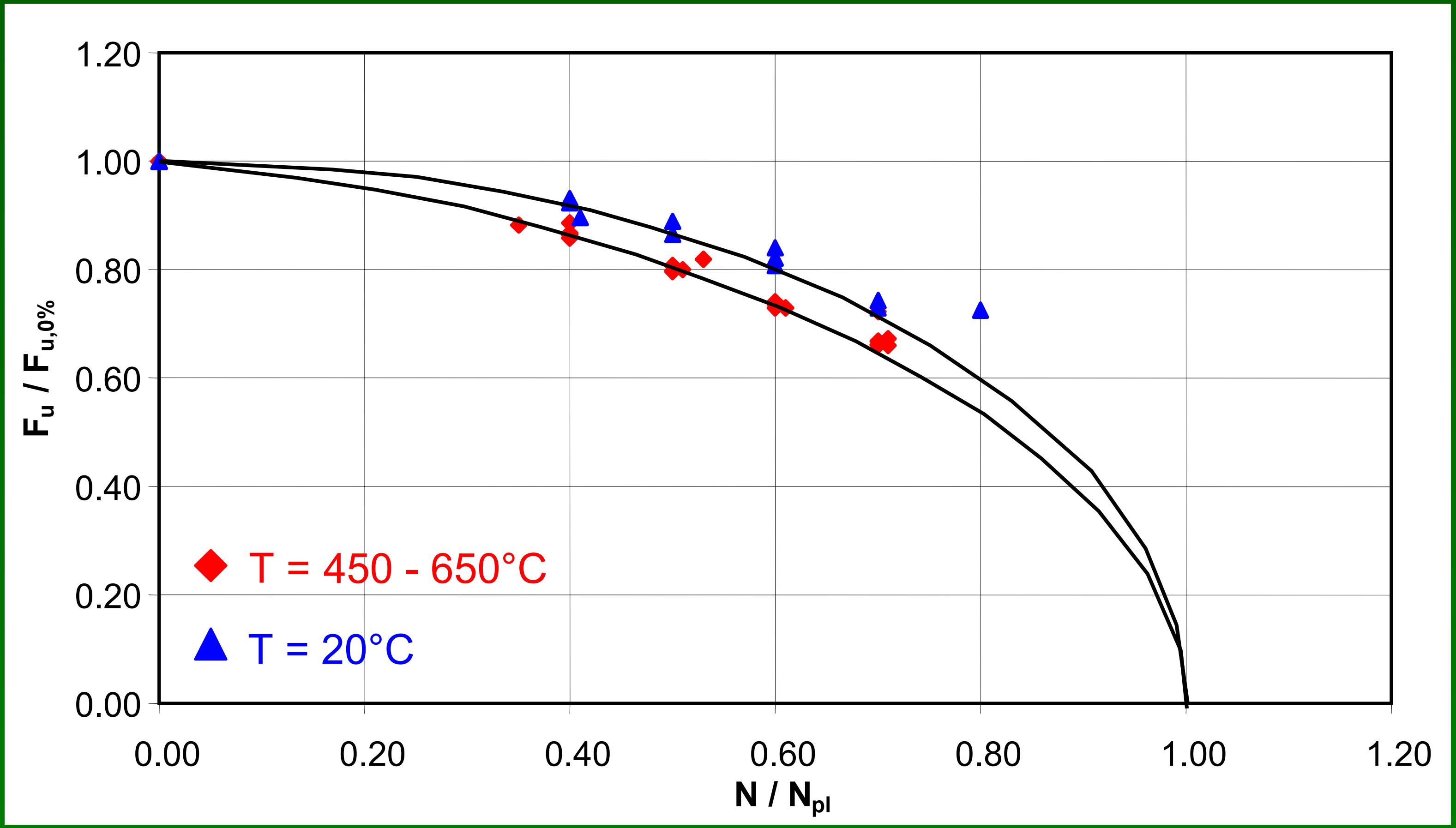

$$k_{N,20^\circ C} = \sqrt{1 - \left(\frac{\sigma_N}{f_{y,w}}\right)^2}$$

$$k_{N,\geq 400^\circ C} = \sqrt{1 - \left(\frac{\sigma_N}{k_{y,\theta} f_{y,w}}\right)^{1.55}}$$

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Reduction of the Displacement

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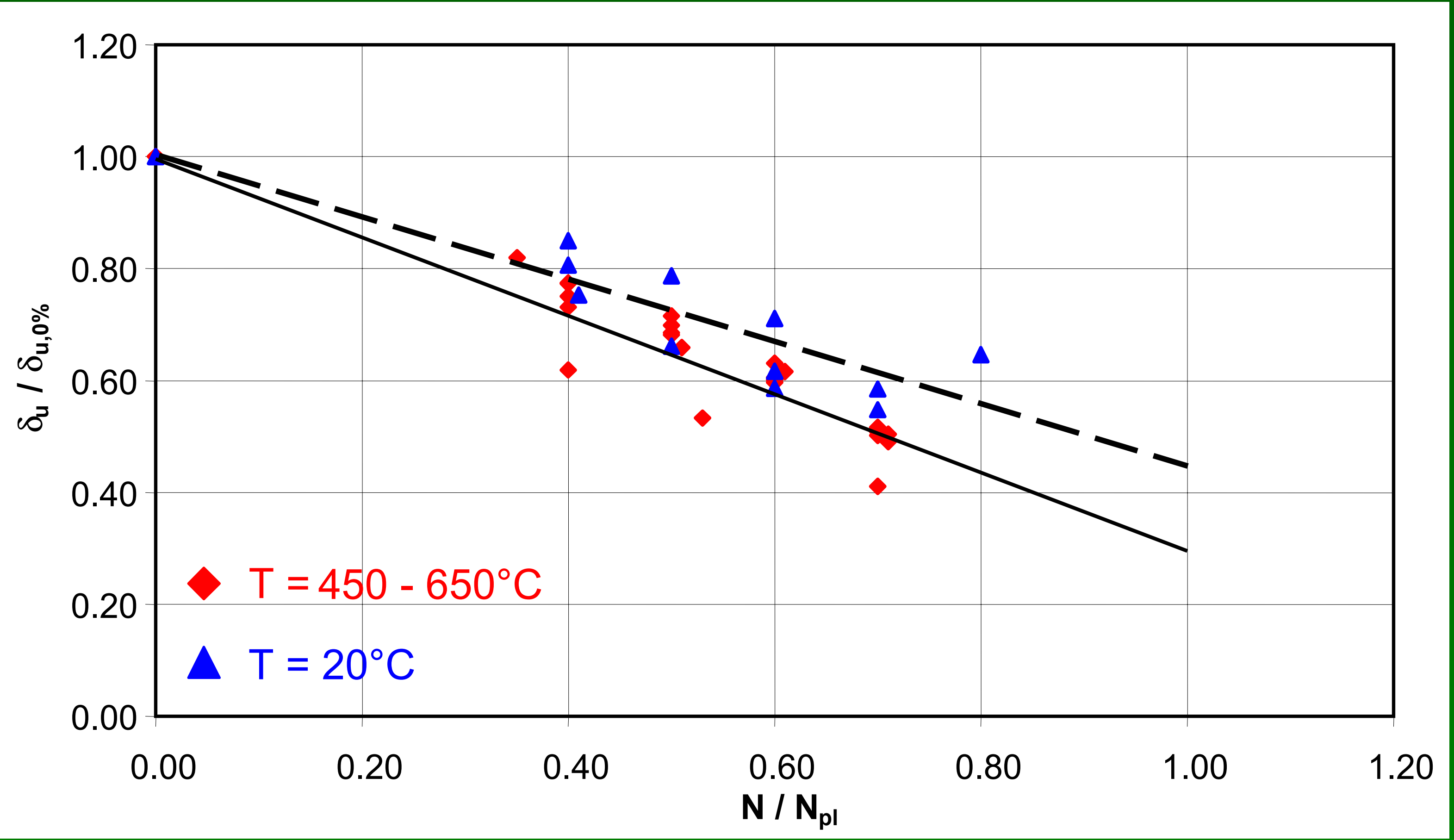

$$k_{N,\delta,20^o C} = -0.55\frac{\sigma_N}{f_{y,w}} + 1$$

$$k_{N,\delta,\geq 400^o C} = -0.70\frac{\sigma_N}{k_{y,\theta} f_{y,w}} + 1$$

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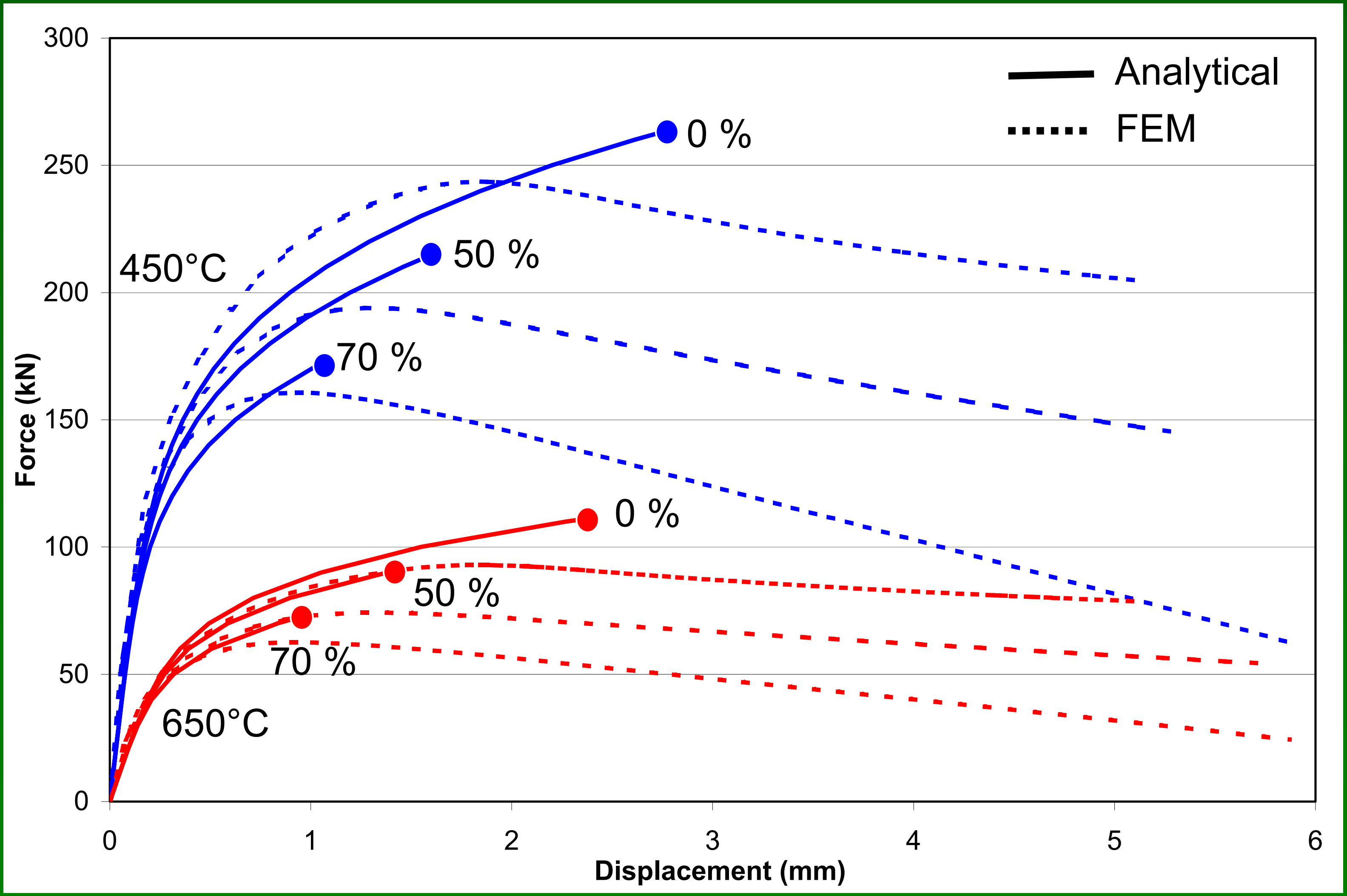
Analytical Model with Reduction Factors compared with FEM Model



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Experimental Work…

Experimental Objectives

- The influence of the axial load on the compression zone is based on numerical calculations only.
- Not a full experimental study - only for validation of numerical analysis.
- 12 tests at 4 different temperatures and 3 different axial load ratios.
- Isothermal / steady-state tests
- Specimen: UC 152x152x37 Grade S275

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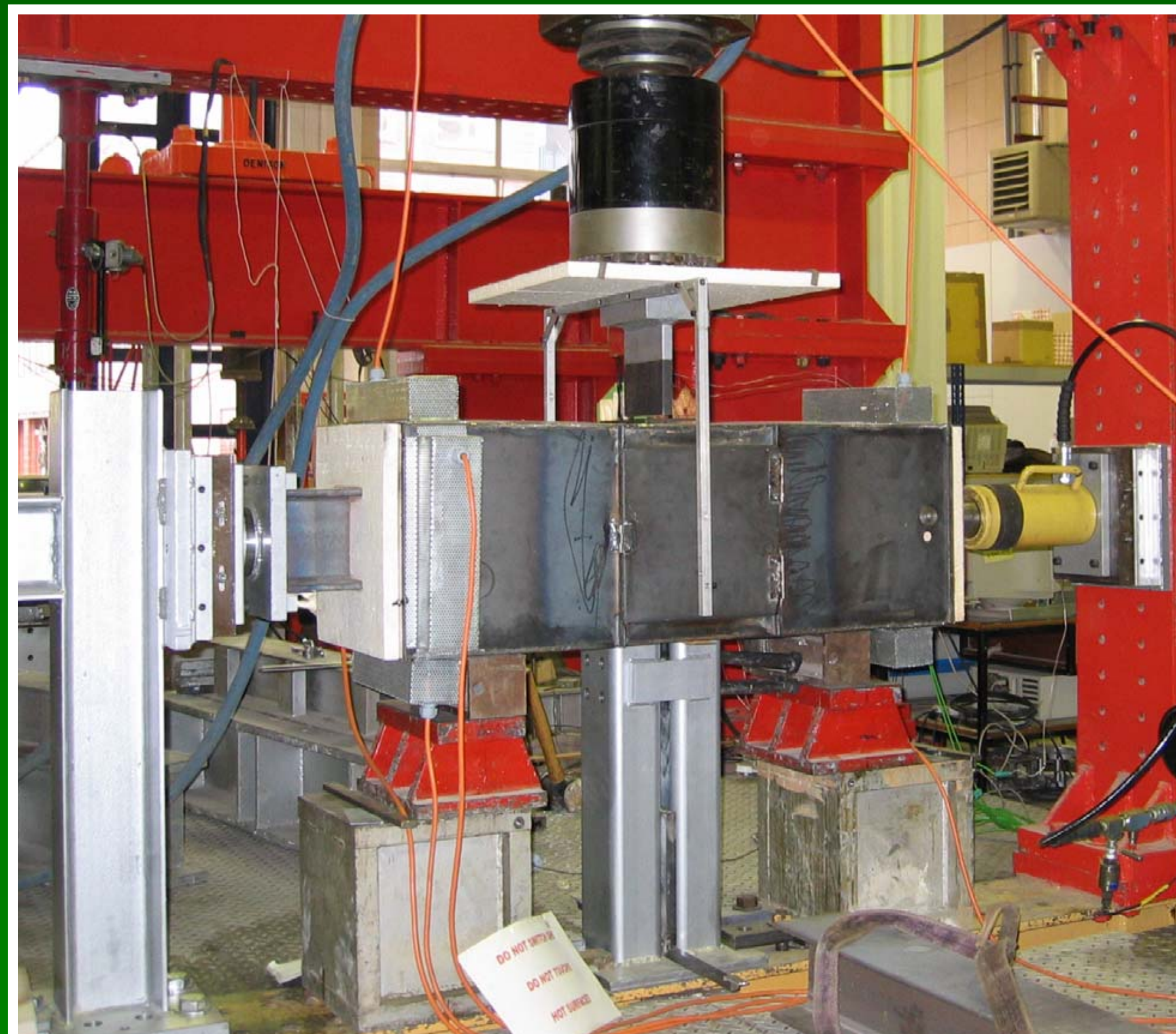
Overview of the Experimental Setup



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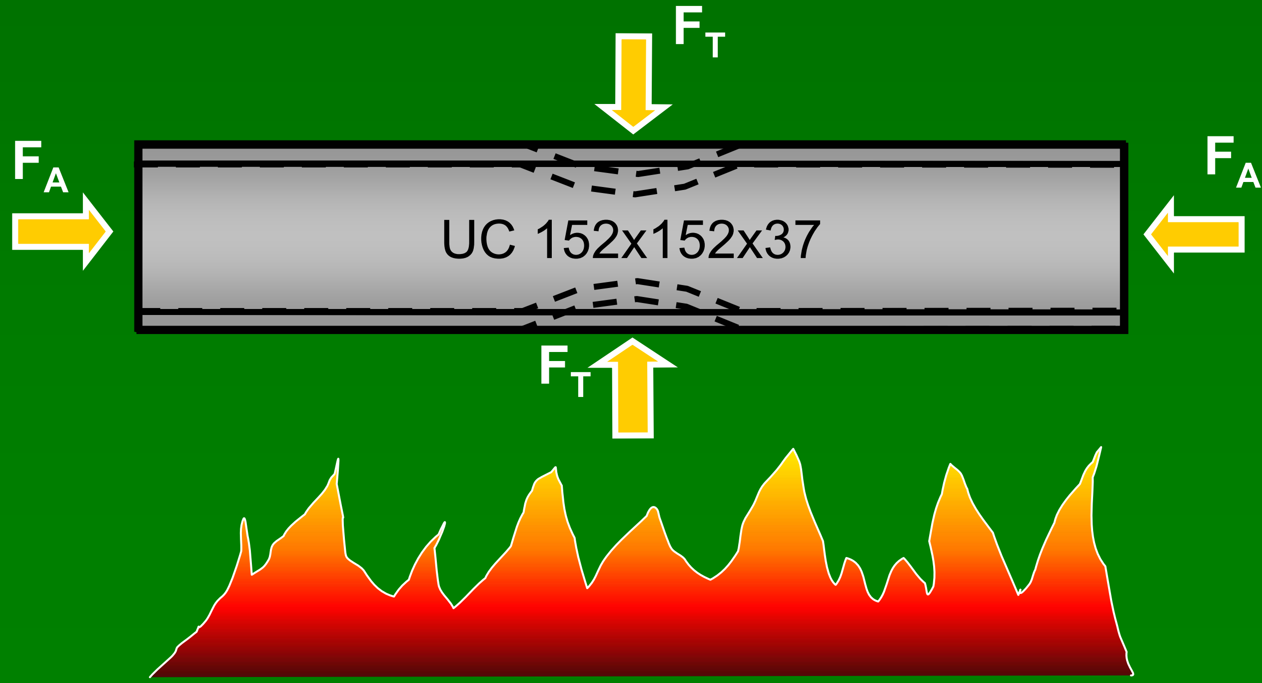
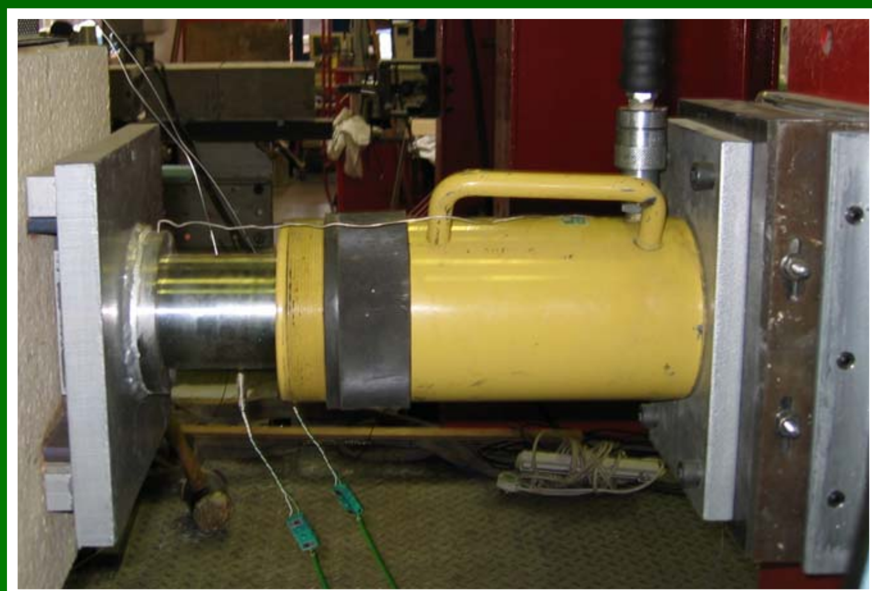
Test Procedure

1. Axial loading of the specimen to simulate the super-load in the column.
2. Heating of the specimen up to test temperature.
3. Transverse loading of the specimen until failure of the compression zone.



Axial Loading Device

- 500kN hydraulic jack to apply axial load
- Powered by pressure controlled pump to ensure a constant axial load during the heating phase.



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Electric Furnace

- Heated by 6 heating elements with a total of 8 kW
- Insulated with 50mm Fibreboard
- Each side is controlled separately to ensure uniform heating of the specimens.

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Transverse Loading & Load Introduction

- 500 kN displacement controlled actuator
- Load is introduced via 20mm thick blades to simulate the beam flanges.

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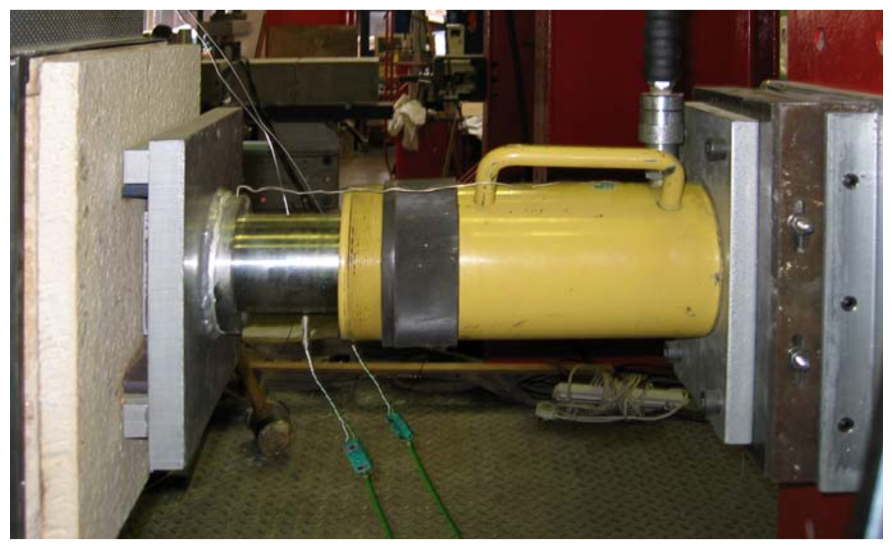
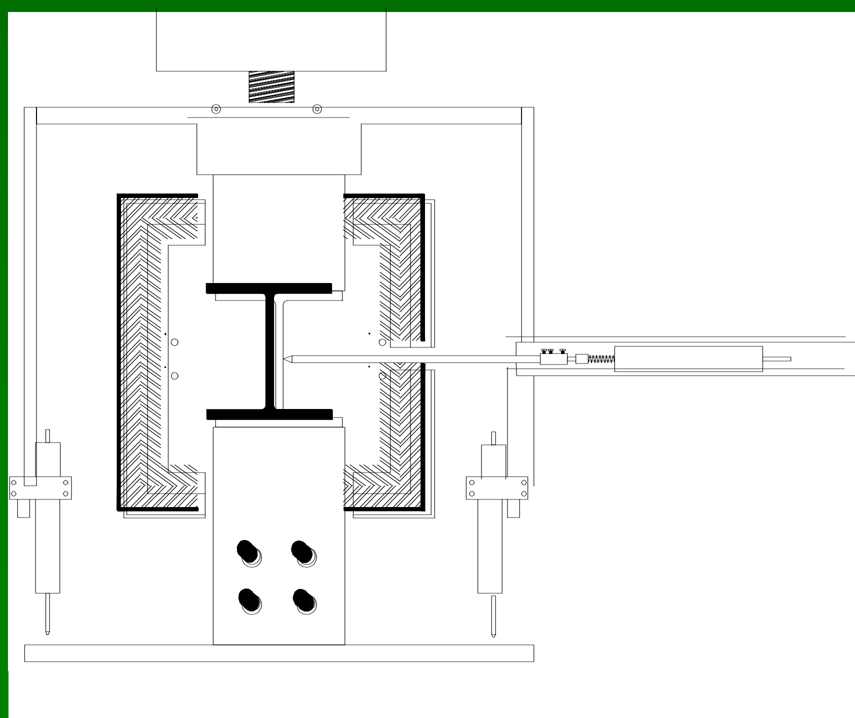
Roller Blocks

- To ensure that all transverse load is reacted by the bottom support and not by the ends, roller blocks are mounted at the ends of the specimen.



Instrumentation

- Steel temperatures are measured by 12 thermocouples.
- 2 LVDTs measure transverse displacement outside the furnace.
- A LVDT fixed to a ceramic rod measures out-of plane deflection of the web.



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Planned and Conducted Tests

Temp \ Axial LR	0.0	0.2	0.3
20 °C			✓
450 °C	✓	✓	✓
550 °C	✓	✓	✓
600 °C		✓	

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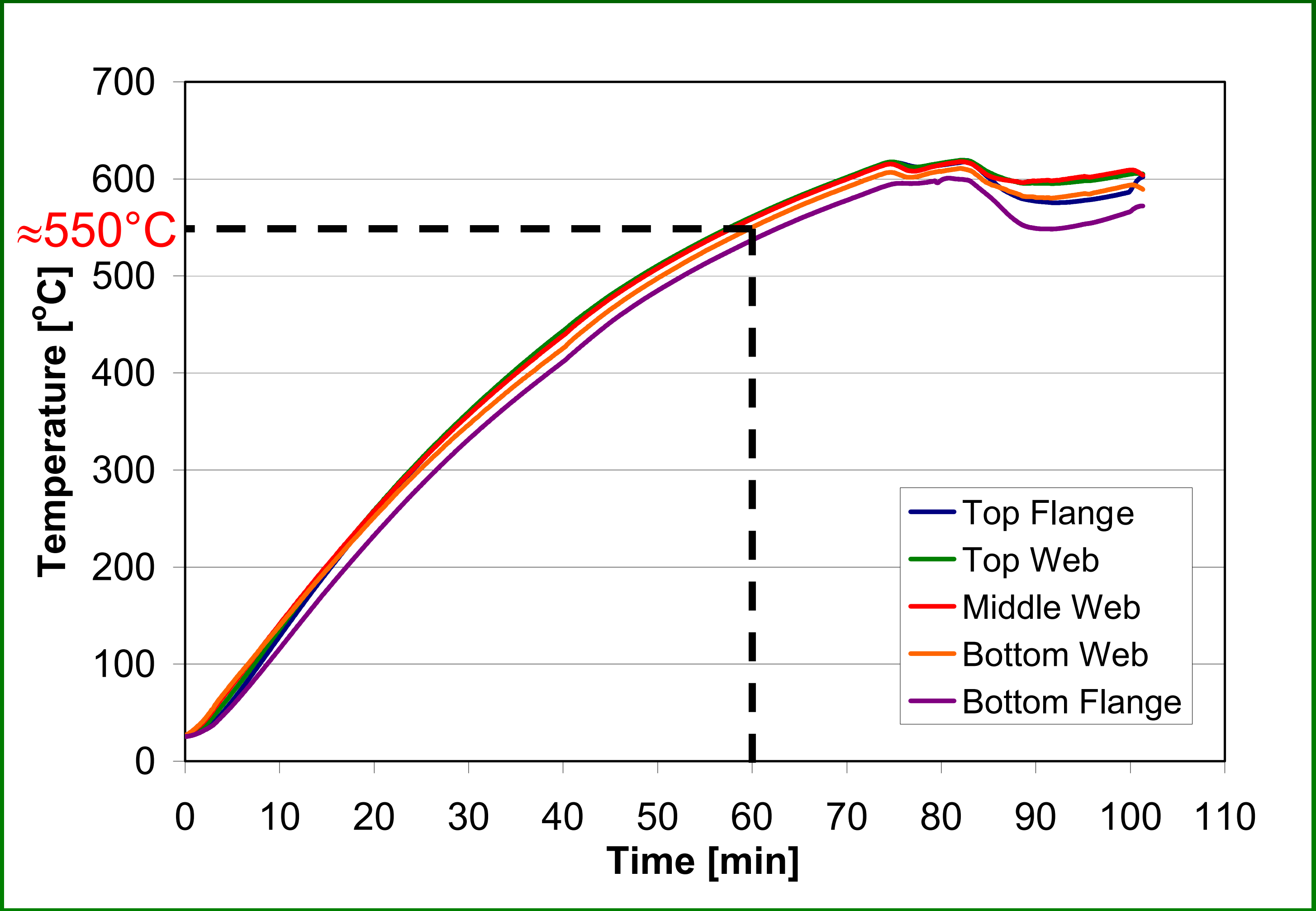
Typical Time-Temperature curves



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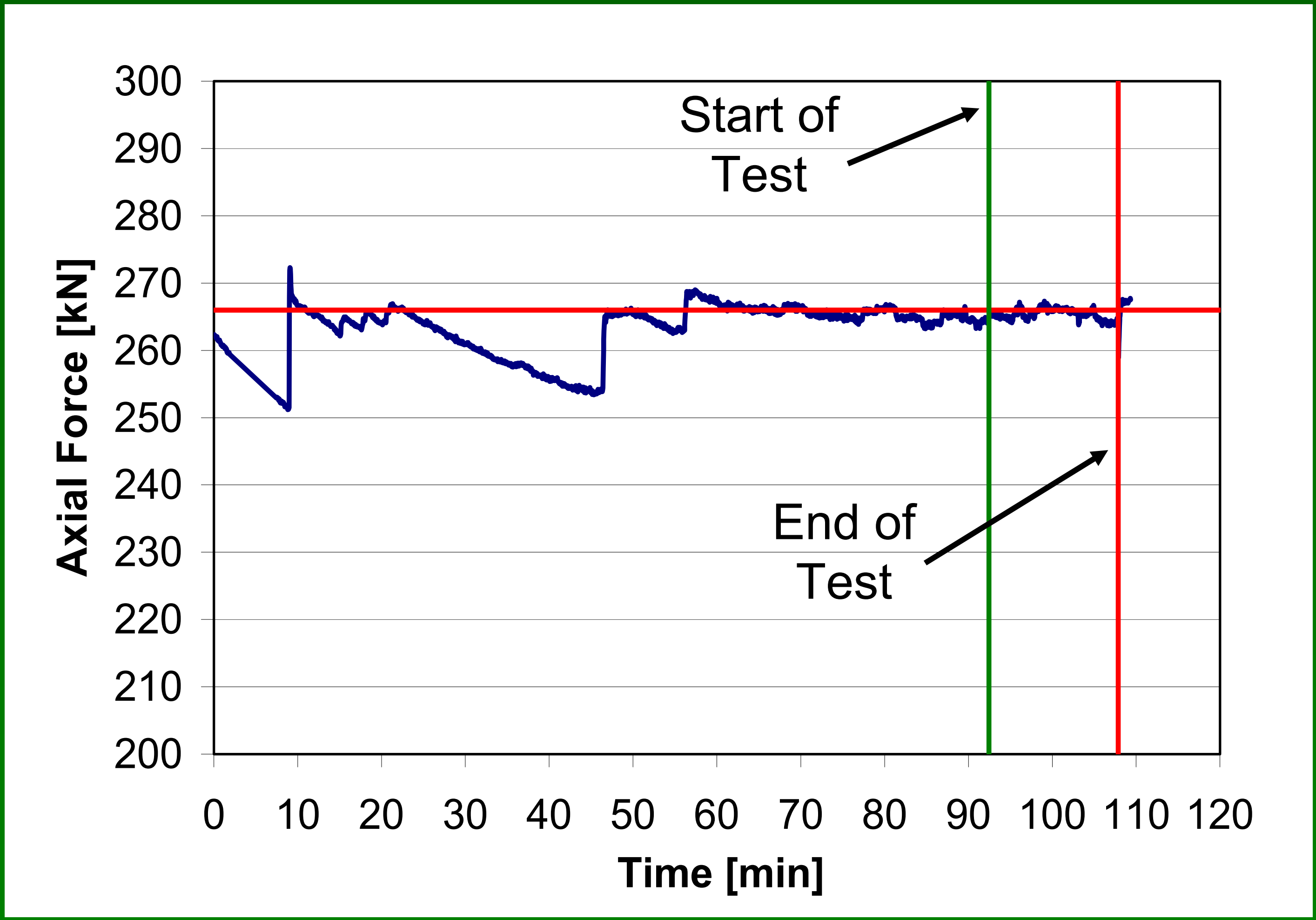
Axial Load in the Specimen



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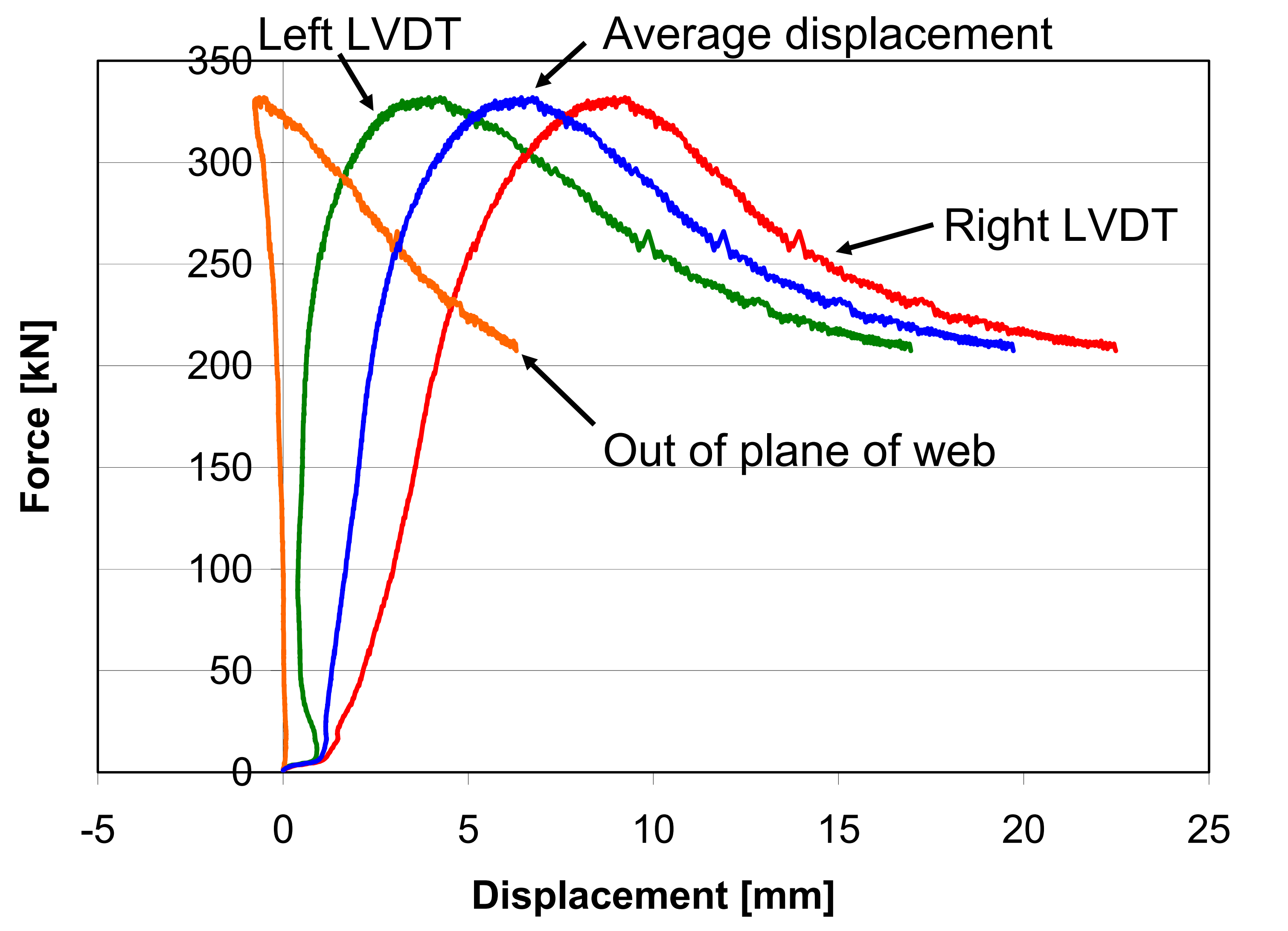
Typical Transverse Displacement



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Summary of the Conducted Tests

Test #	Web temp.	Flange temp.	Axial load N	Axial load ratio $N/N_{pl,1.0\%}$	F_u	d_u
	[°C]	[°C]	[kN]	[-]	[kN]	[mm]
3	20	20	394	0.3	413.7	6.4
6	20	20	398	0.31	423.4	7.5
4	450	424	3	0.00	331.7	5.0
1	453	440	266	0.23	331.0	5.9
7	458	429	403	0.36	331.4	5.4
2	515	482	390	0.40	280.0	4.6
5	531	516	268	0.29	246.4	6.8
8	549	513	2	0.00	257.4	6.0
9	591	562	266	0.39	175.1	6.4

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Comparison between Experiments and FEM-Model…

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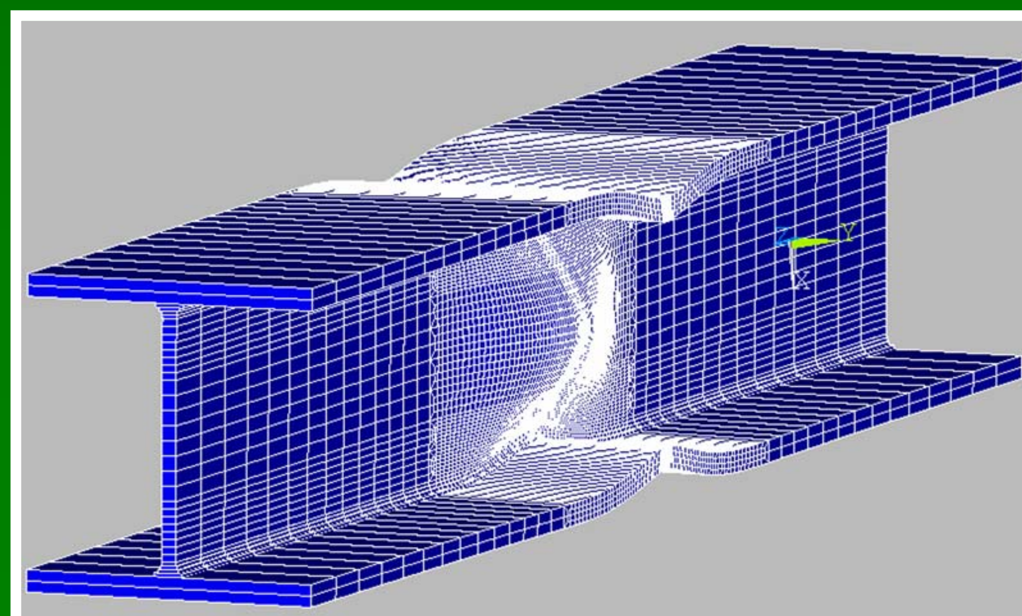
Deformed Shapes of Tests vs. FEM



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Material Curves for Steady-State Tests

- The high temperature material model in EC 3 Part 1.2 is based on the transient tensile tests.
- Thermal creep effects are included, which are marginal in steady-state experiments.
- No strain-hardening above 400°C is considered.
- To model steady-state experiments realistically the EC3 material model can not be used.

A new material model has been developed based on the steady-state tensile tests by Kirby and Preston.

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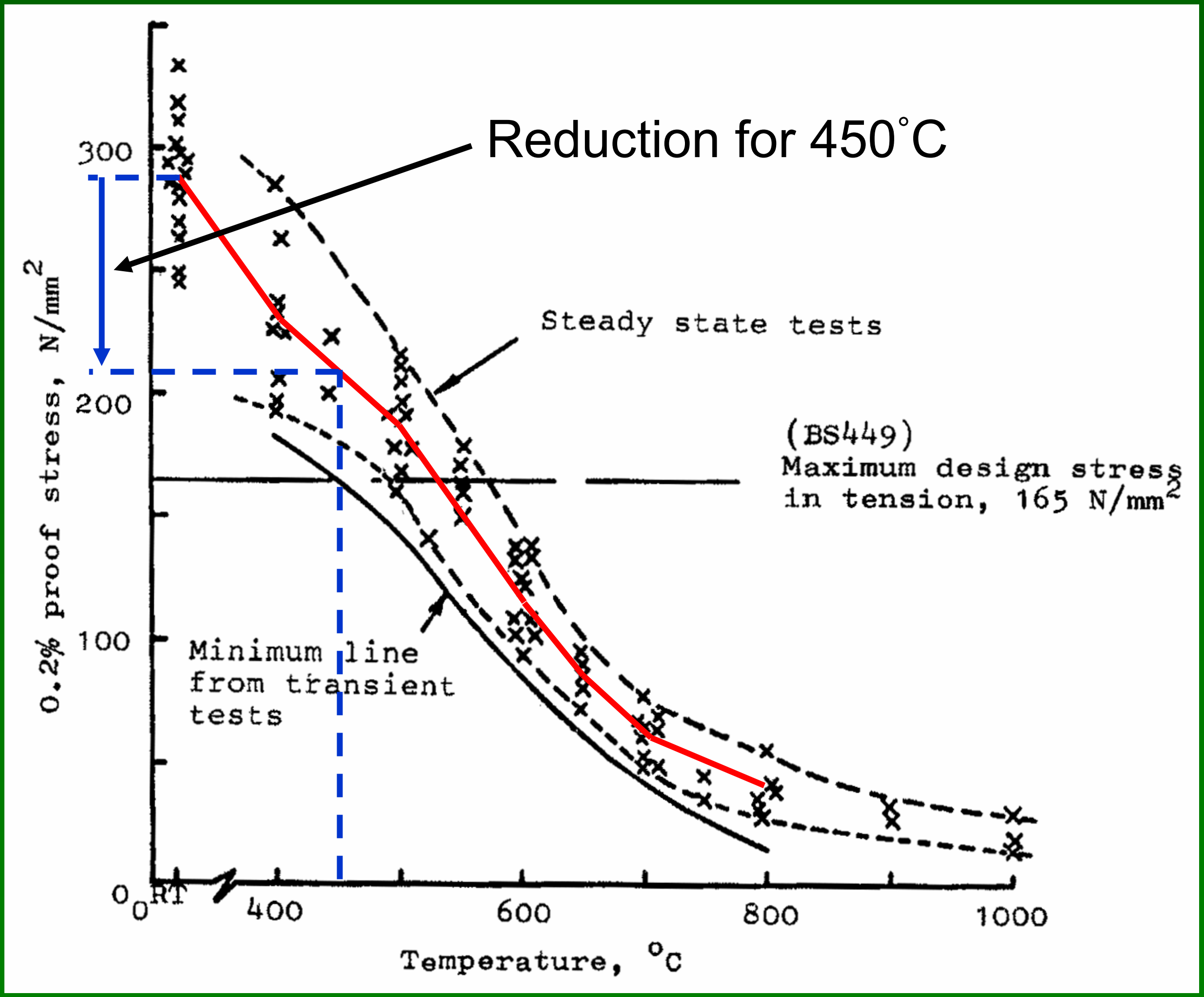
Reduction of the Stress at 0.2% Strain



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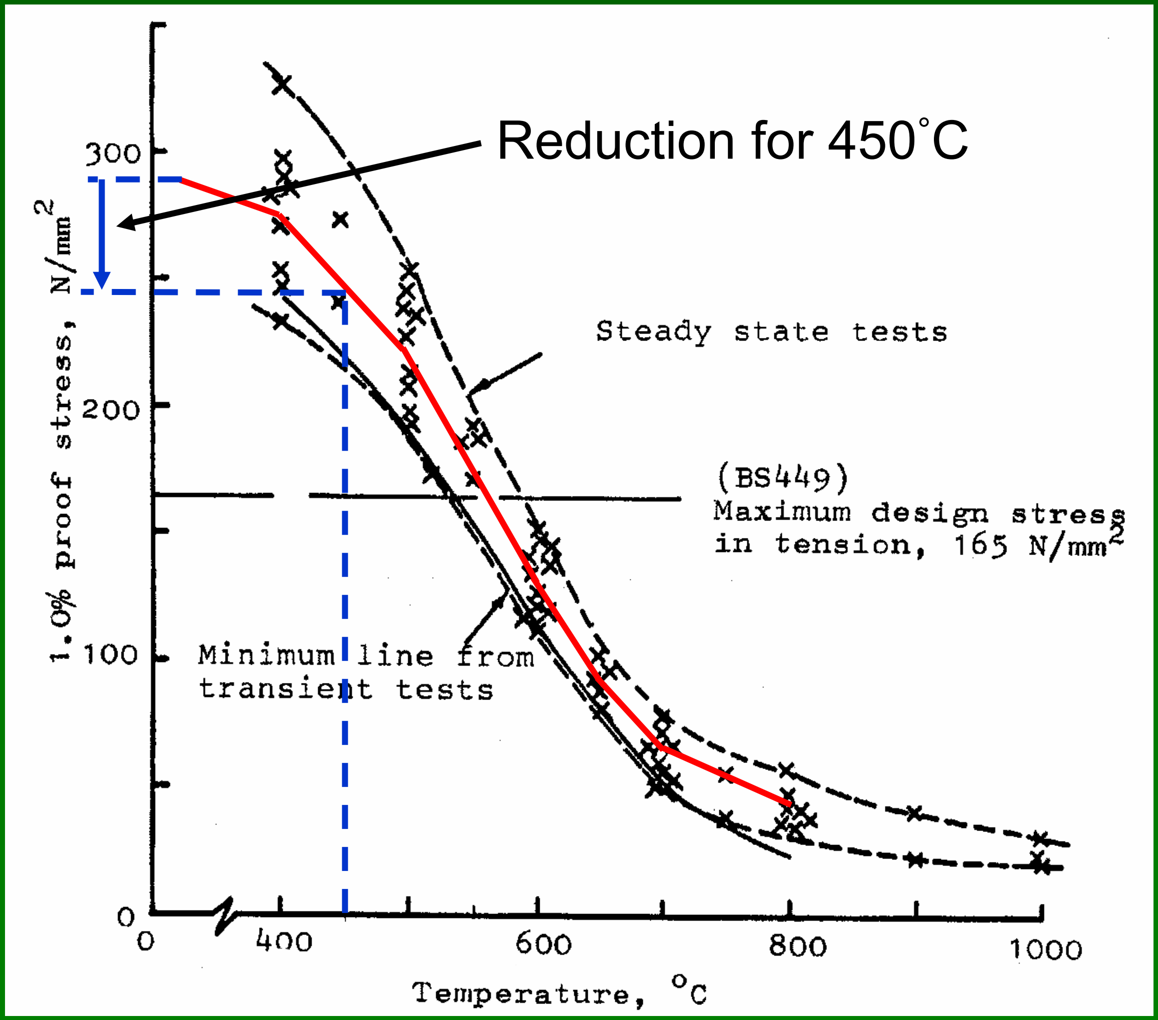
Reduction of the Stress at 1.0% Strain



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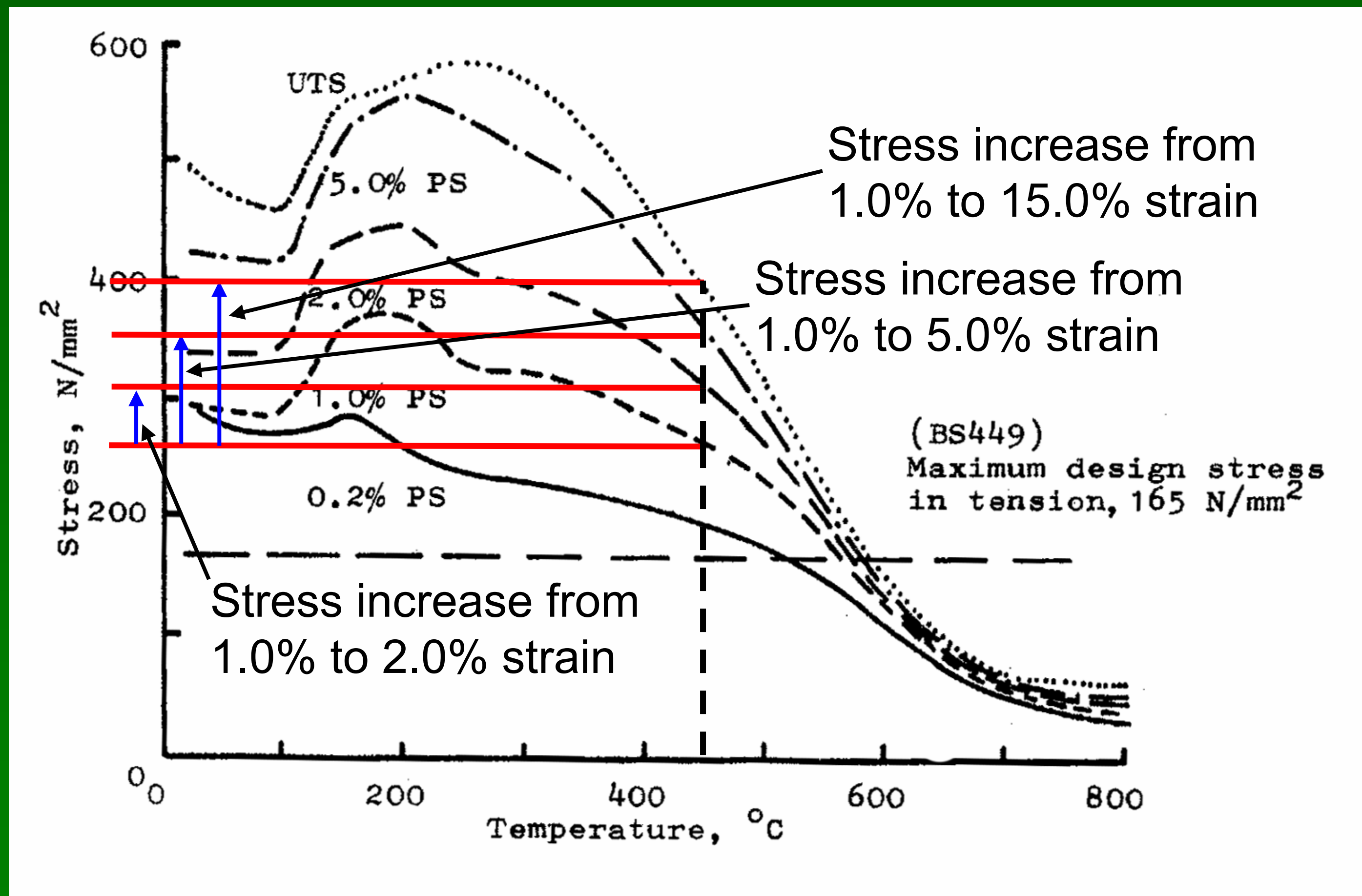
Reduction of the Strain Hardening



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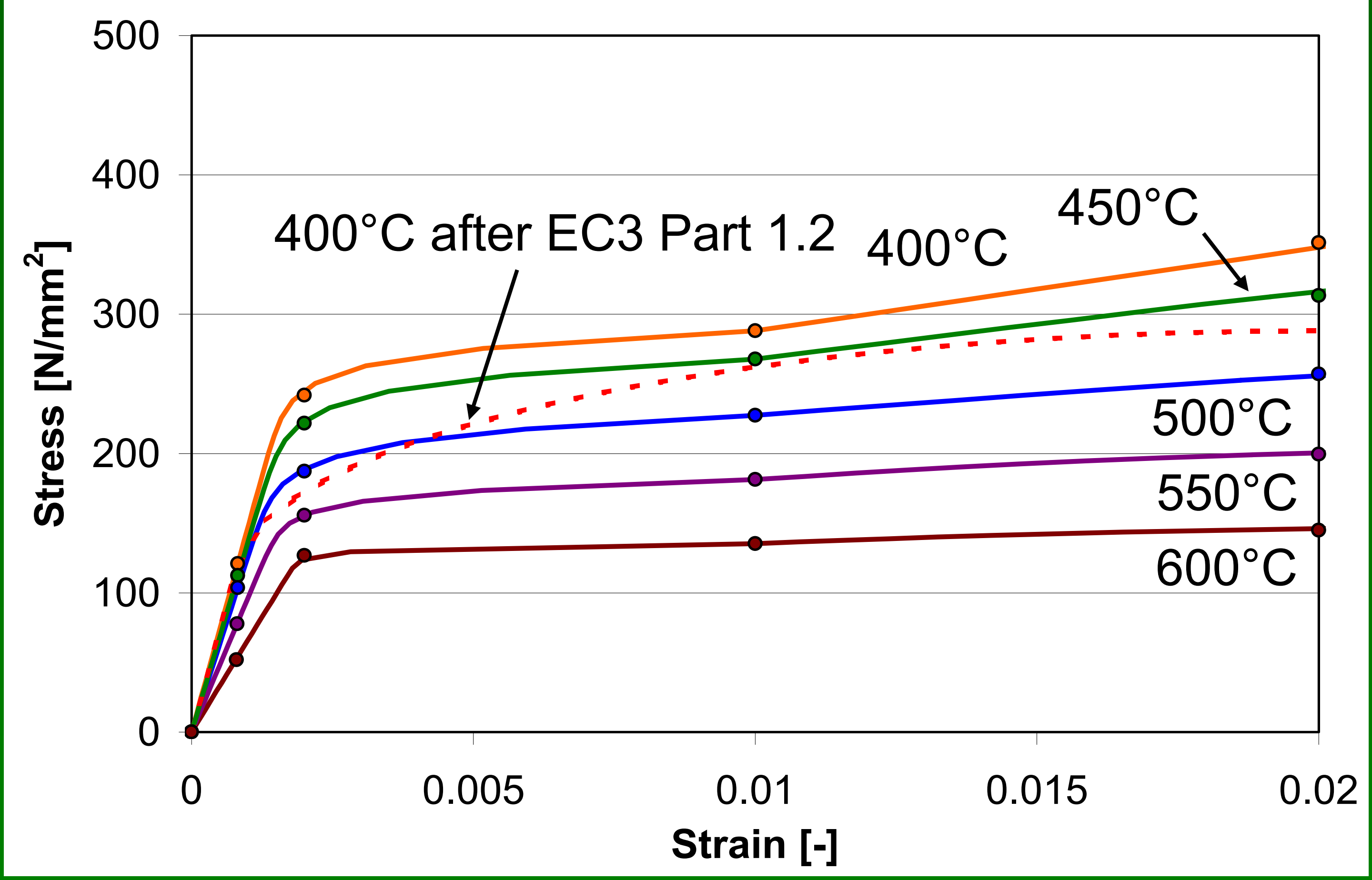
Material Curves for Steady-State Tests



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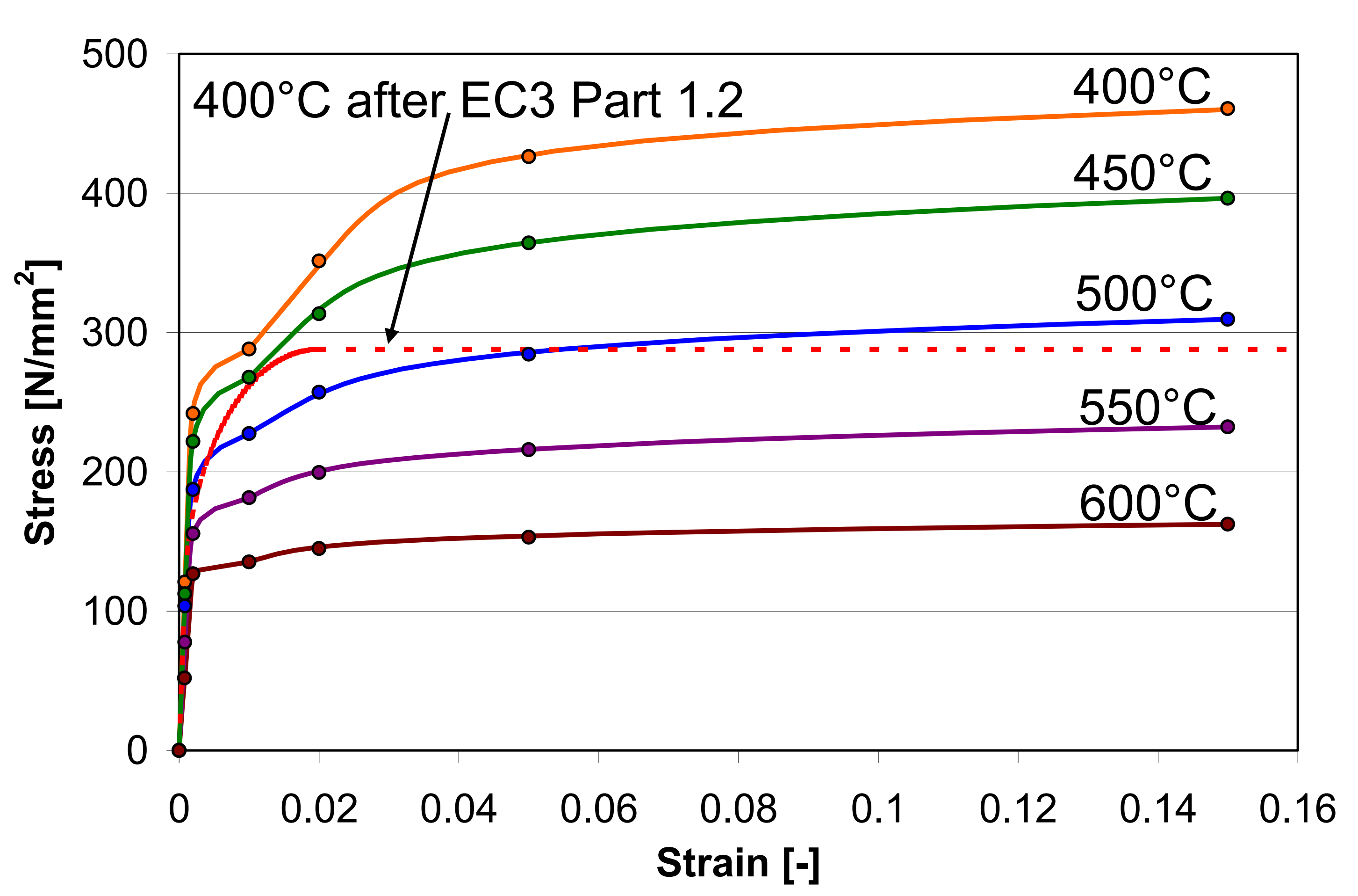
Material Curves for Steady-State Tests



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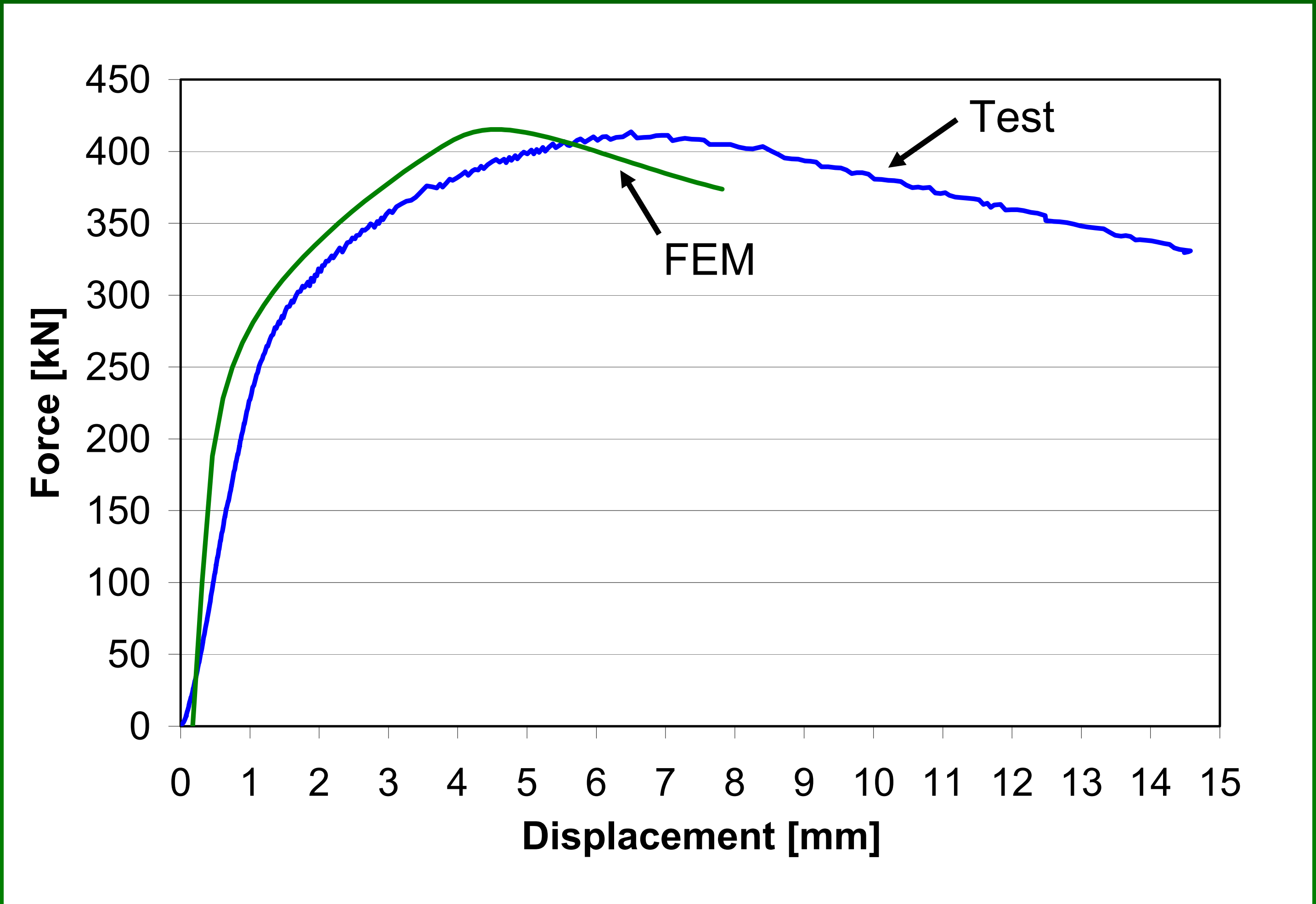
Comparison Test – FEM

Test #: 3 – Temp.: 20°C – Axial load: 394kN



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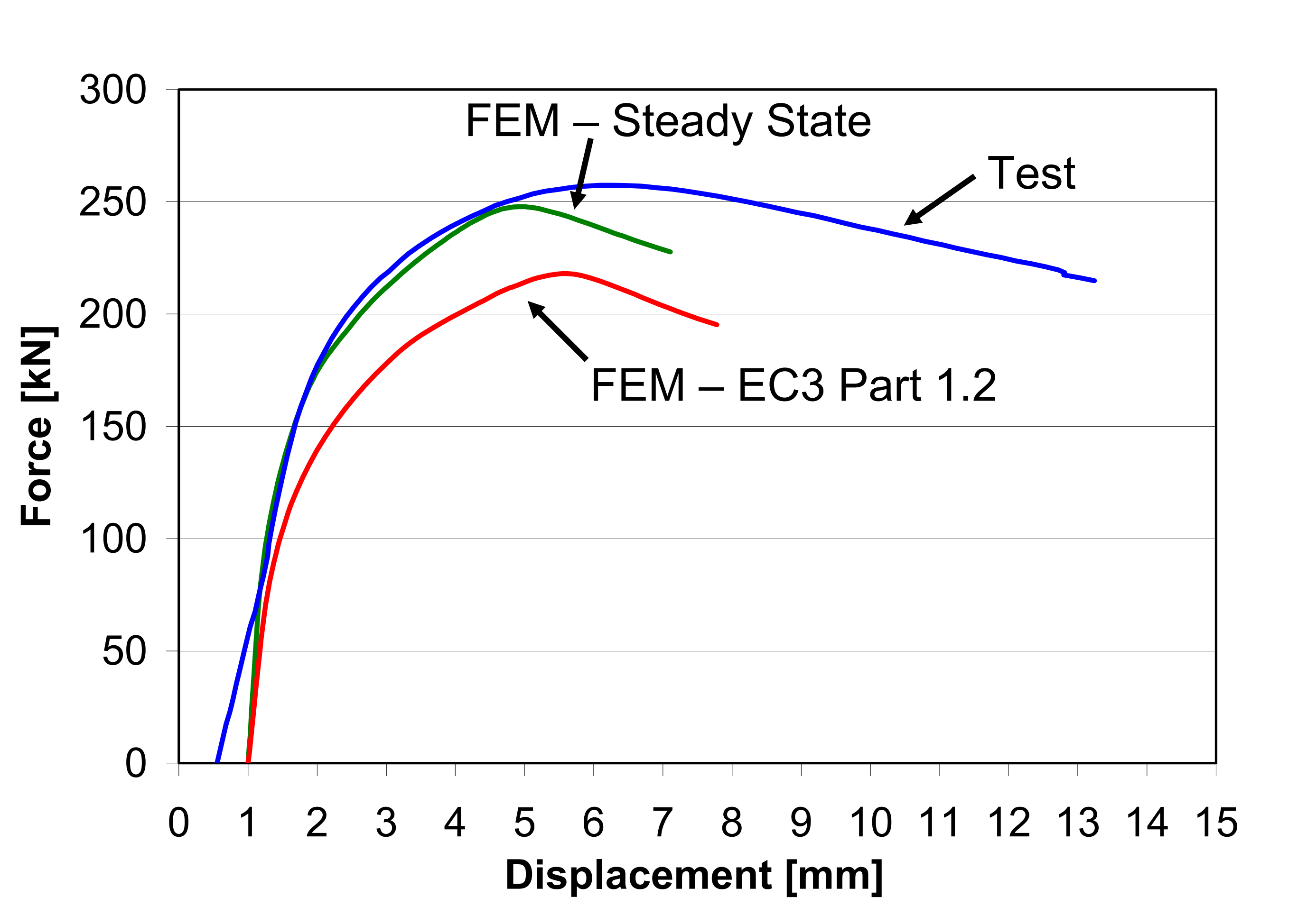
Comparison Test – FEM

Test #: 8 – Temp.: 549°C – Axial load: 2kN



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Comparison Test – FEM

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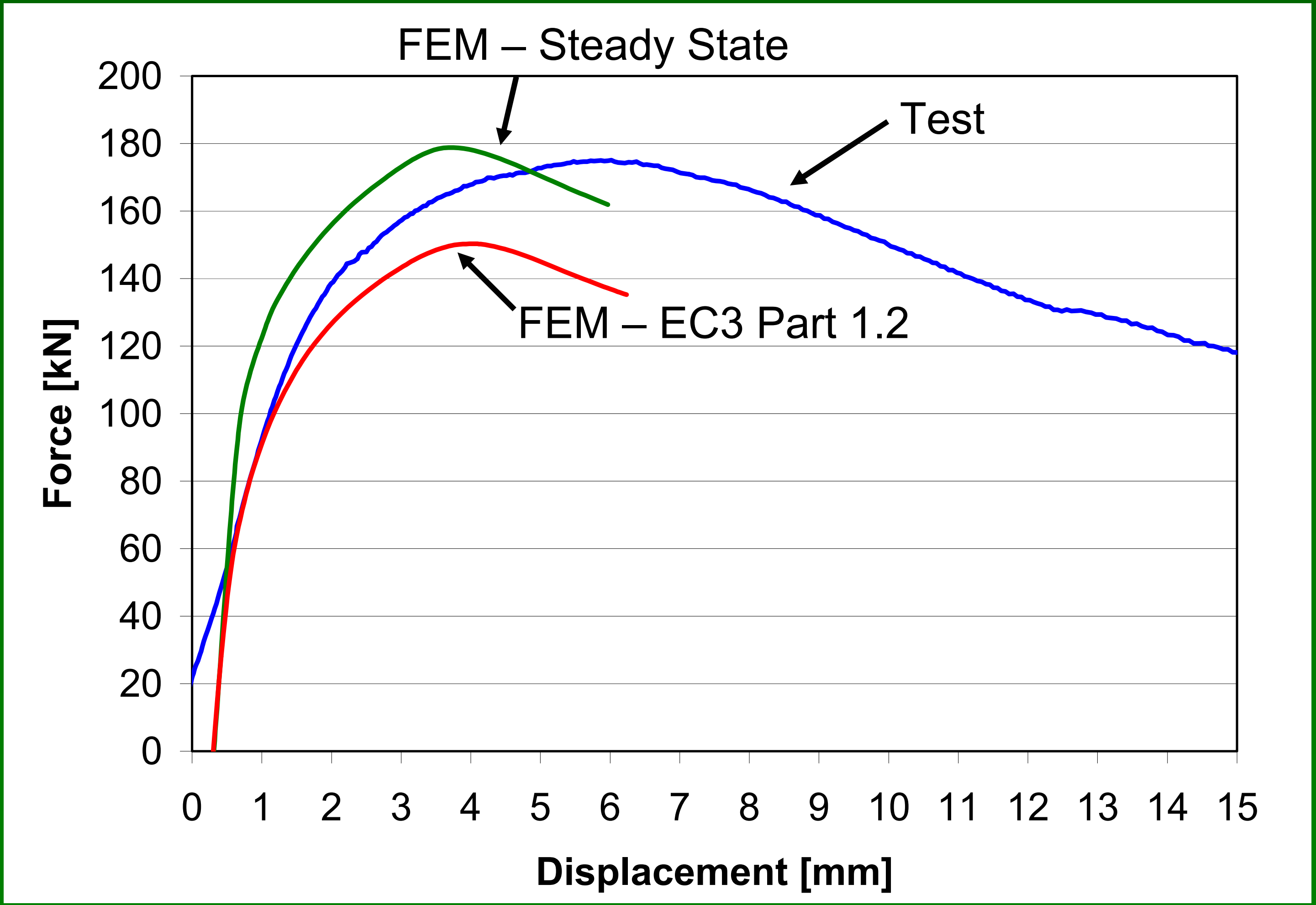
Test #: 9 – Temp.: 591°C – Axial load: 266kN



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Practical Application…

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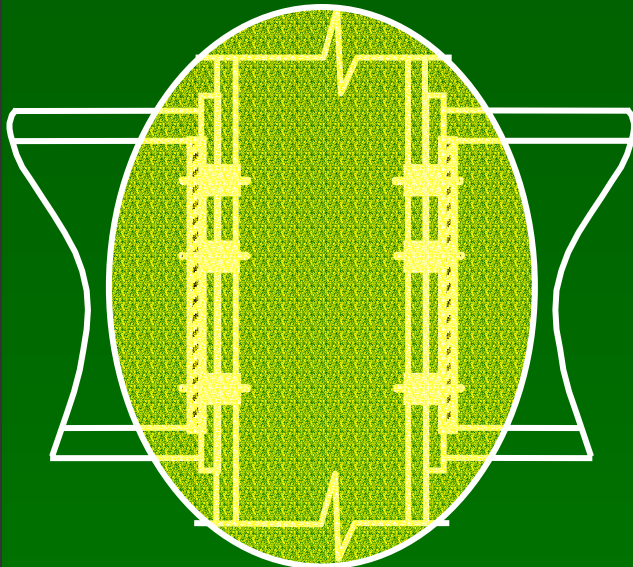
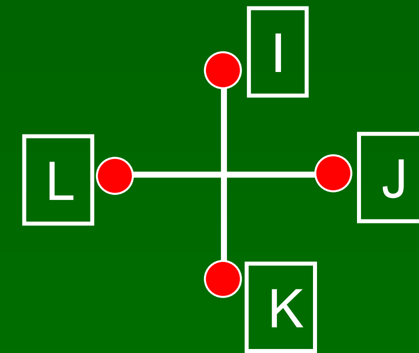
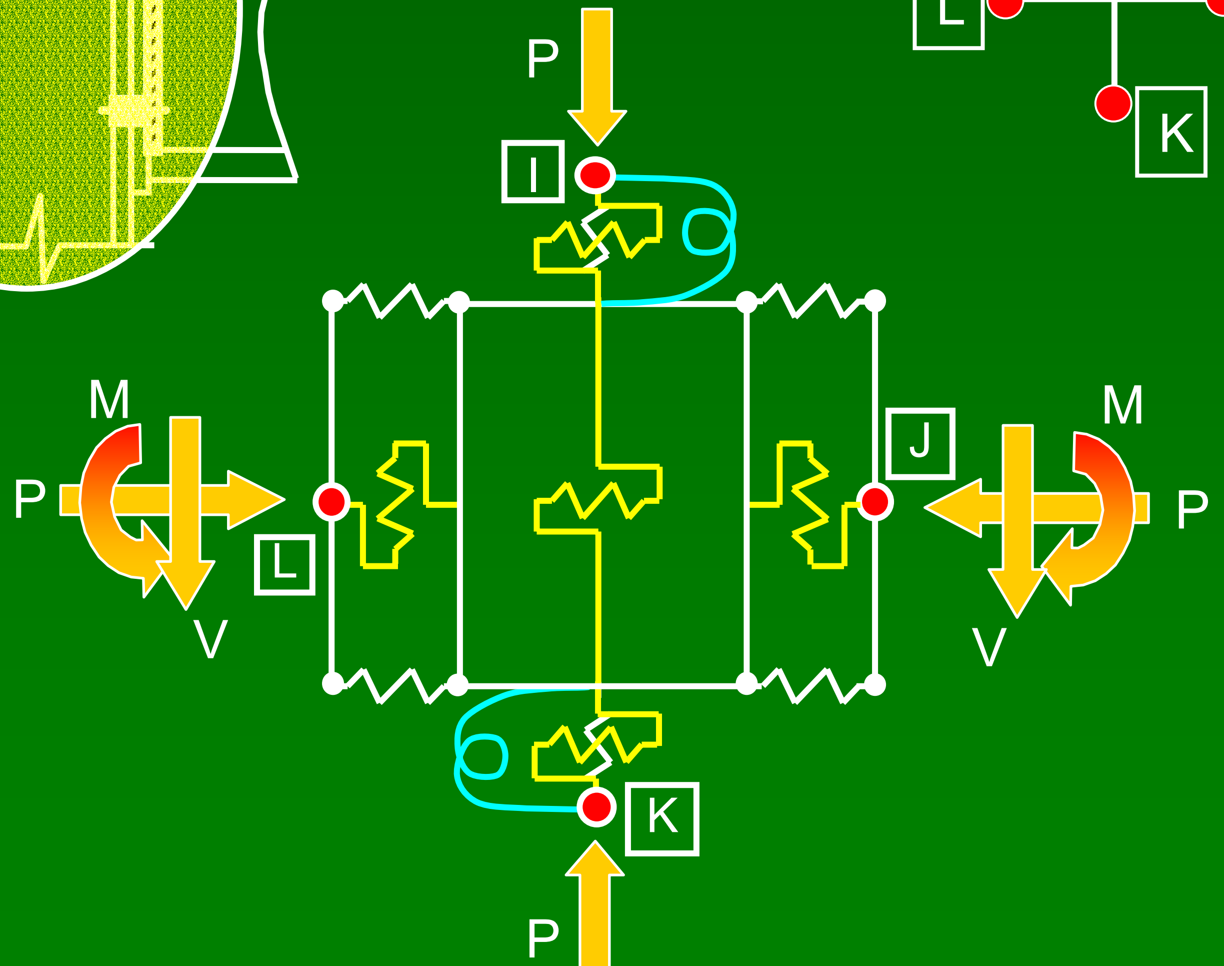
High-temperature component-based joint finite element







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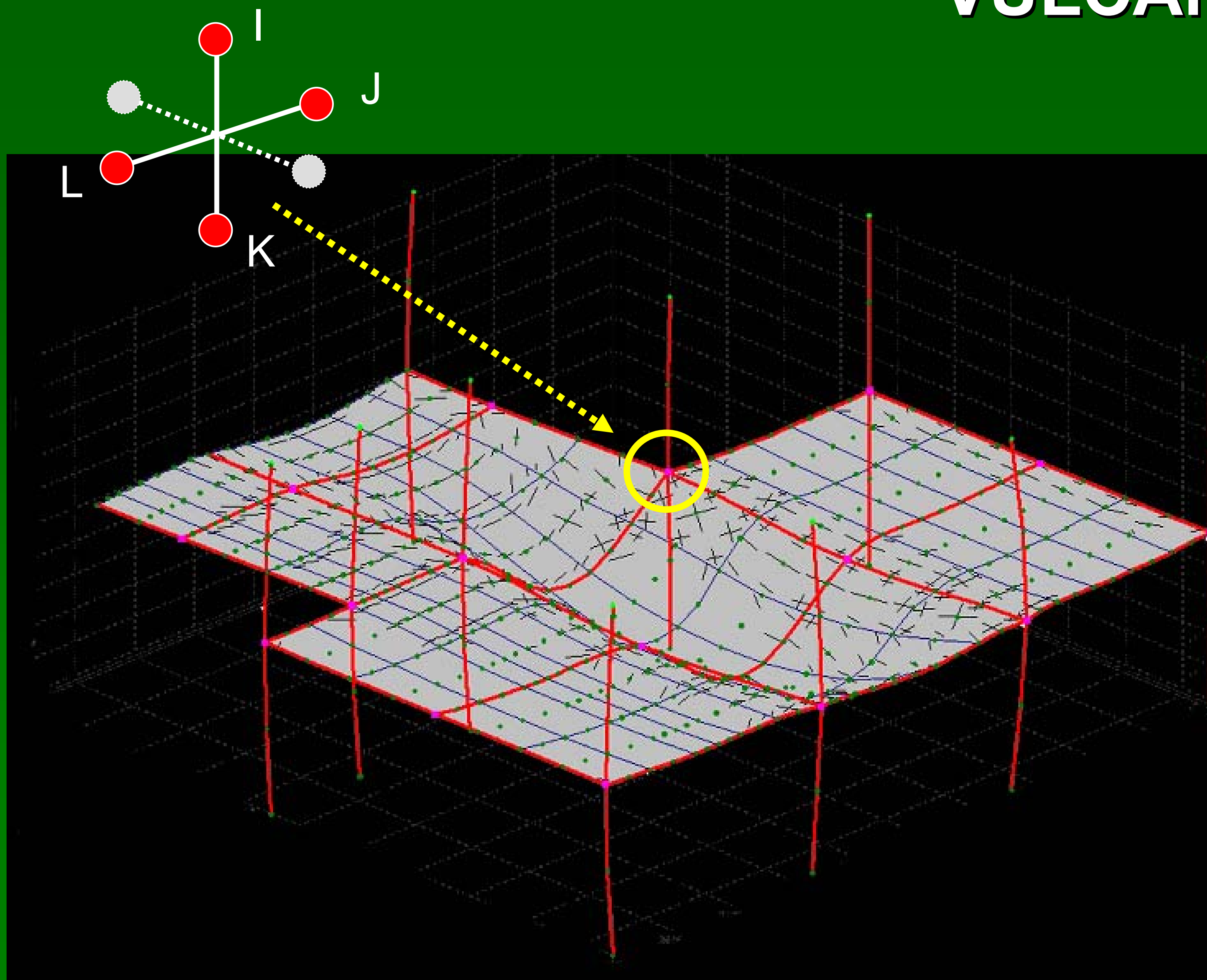
Implementation of the element in VULCAN



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Conclusion

- To predict the behaviour of joints in fire a flexible approach like the component method is required.
- Each component needs to be analysed at elevated temperatures.
- For the compression zone a workable approach for elevated temperatures has been developed.
- Material curves to model steady-state experiments have been derived.
- The Component Method together with VULCAN gives a feasible way to include realistic joint behaviour in the global analysis of structures in fire.

What is next?

- Finish the experimental study.
- Do more FEM-modeling for a wider understanding of the compression zone.
- Revise the simplified model and the reduction factors.
- Assemble component based joint element.
- Run whole composite frame analysis with VULCAN.

Joint Component Behaviour in Fire

Questions ..?

Florian M. Block

Steel in Fire Forum

Rotherham, UK September 2004