An integrated computational environment for simulating structures in real fires

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BRE CENTRE *for* FIRE SAFETY ENGINEERING

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Introduction

Background | Review | Motivation

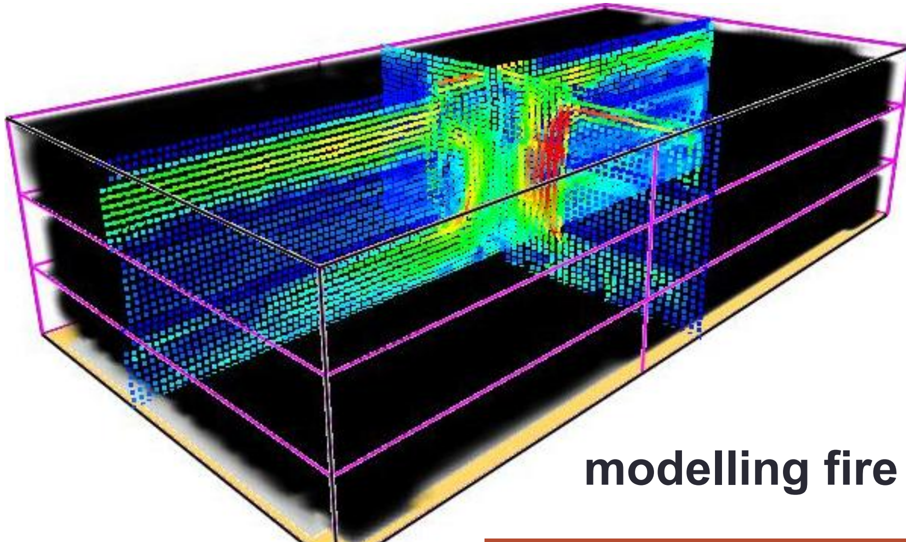

2001-09-11|WTC COLLAPSE

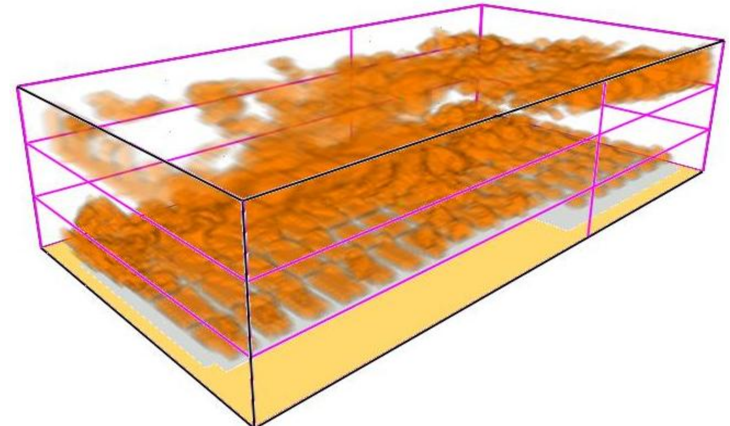
Why some structures collapse and others don’t in large fires ?

Do we have nice numerical tools for simulating structures in fires?

Key components of simulating structures in fire

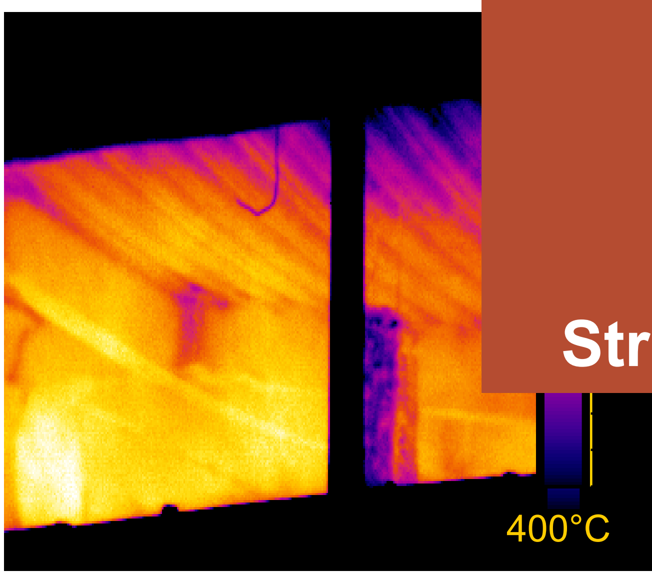
1.





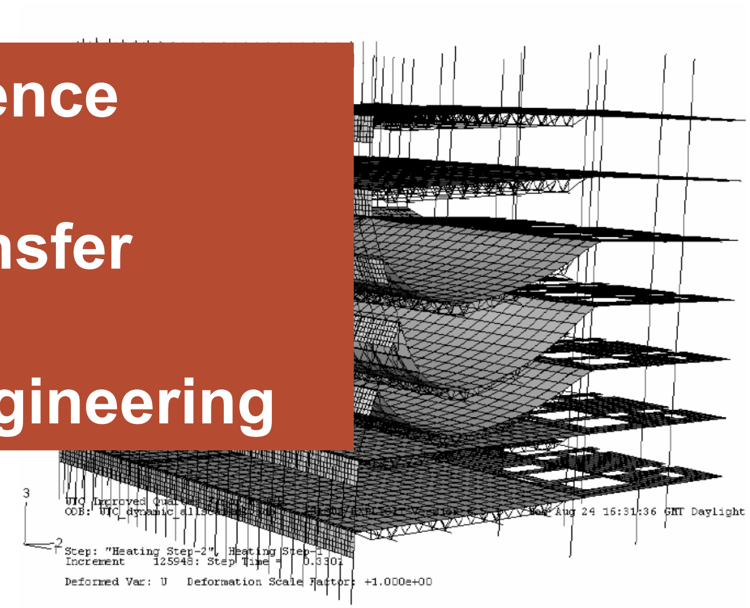
modelling fire and smoke

2.



modelling structural member temperature evolution

Fire science
+
Heat transfer
+
Structural engineering



modelling structural response to the point of collapse

The “spectrum” of modelling

The “spectrum” of modelling | computational

When does MODELLING become SIMULATION ?

The “spectrum” of modelling | multi-hazard

Is deterministic analysis satisfactory in this context?

The “spectrum” of modelling | multi-hazard probabilistic

How to deal with uncertainty ?

Monte Carlo Method

Identity random parameters and their pdfs
(sensitivity analysis may be necessary)

⇩

Set pass/fail criteria

⇩

Determine the acceptable level of “confidence”

⇩

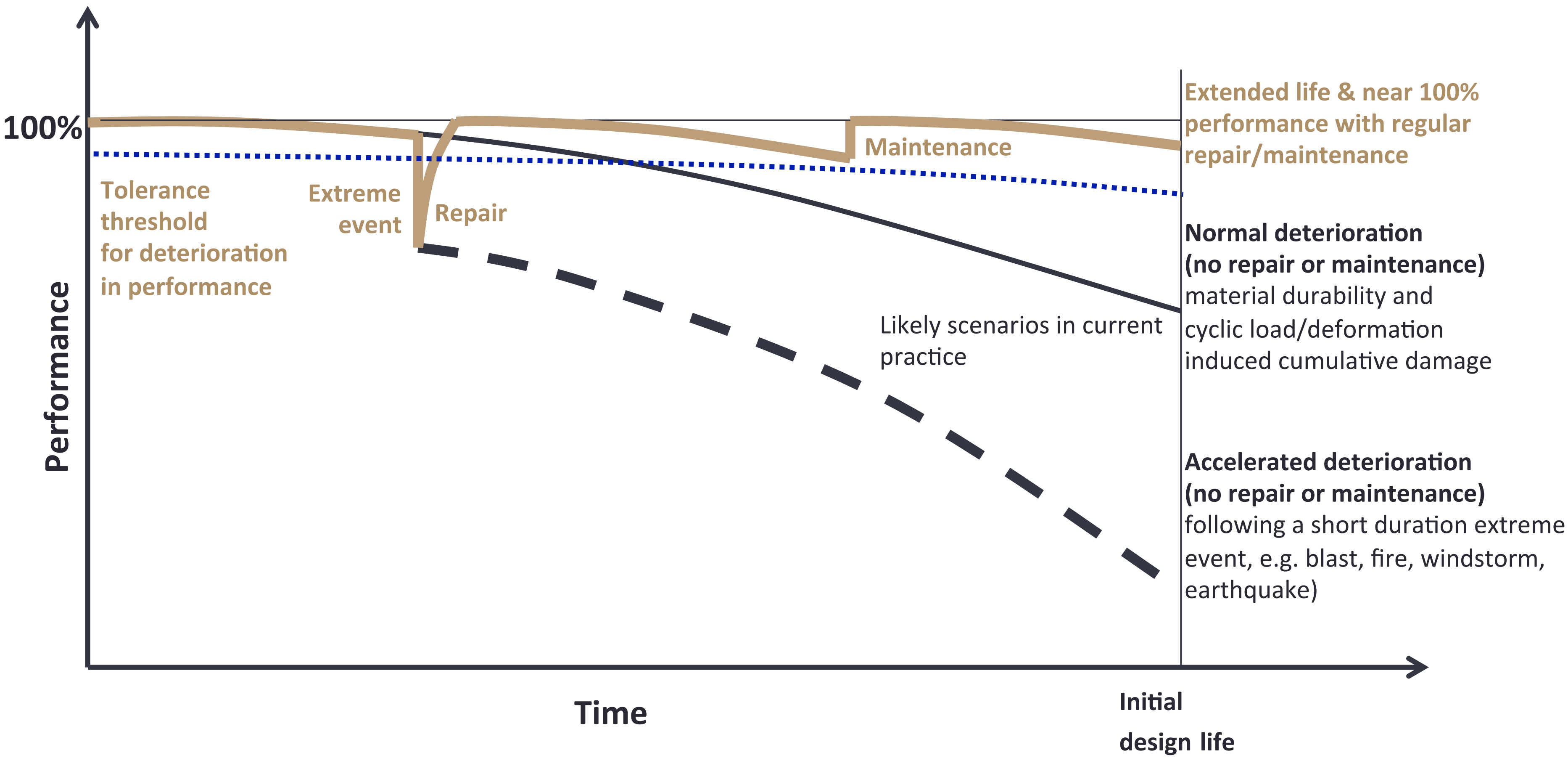
Run “n” number of deterministic analyses by randomly selecting values of random parameters
(reduce “n” using a variance reduction technique)

⇩

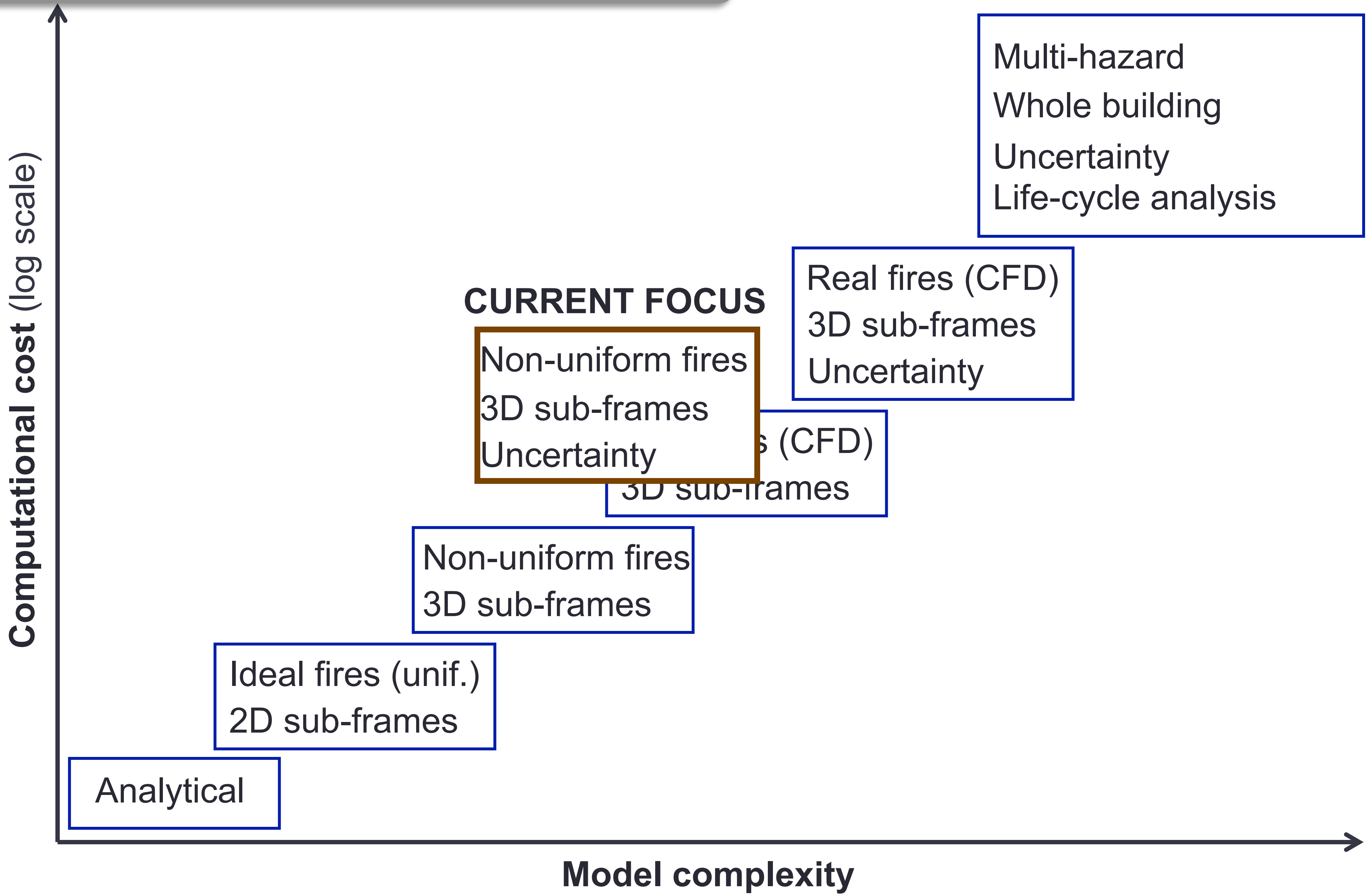
⇩

Determine the probability of failure

Life-cycle analysis



The "spectrum" of modelling



Integrated computational environment for structures in fire

This is only part of the big picture

Fire models
Standard
Natural/parametric (short hot/long cool)
Localised
Travelling
CFD (FDS, OpenFOAM, ANSYS-CFX)

fire – heat transfer middleware

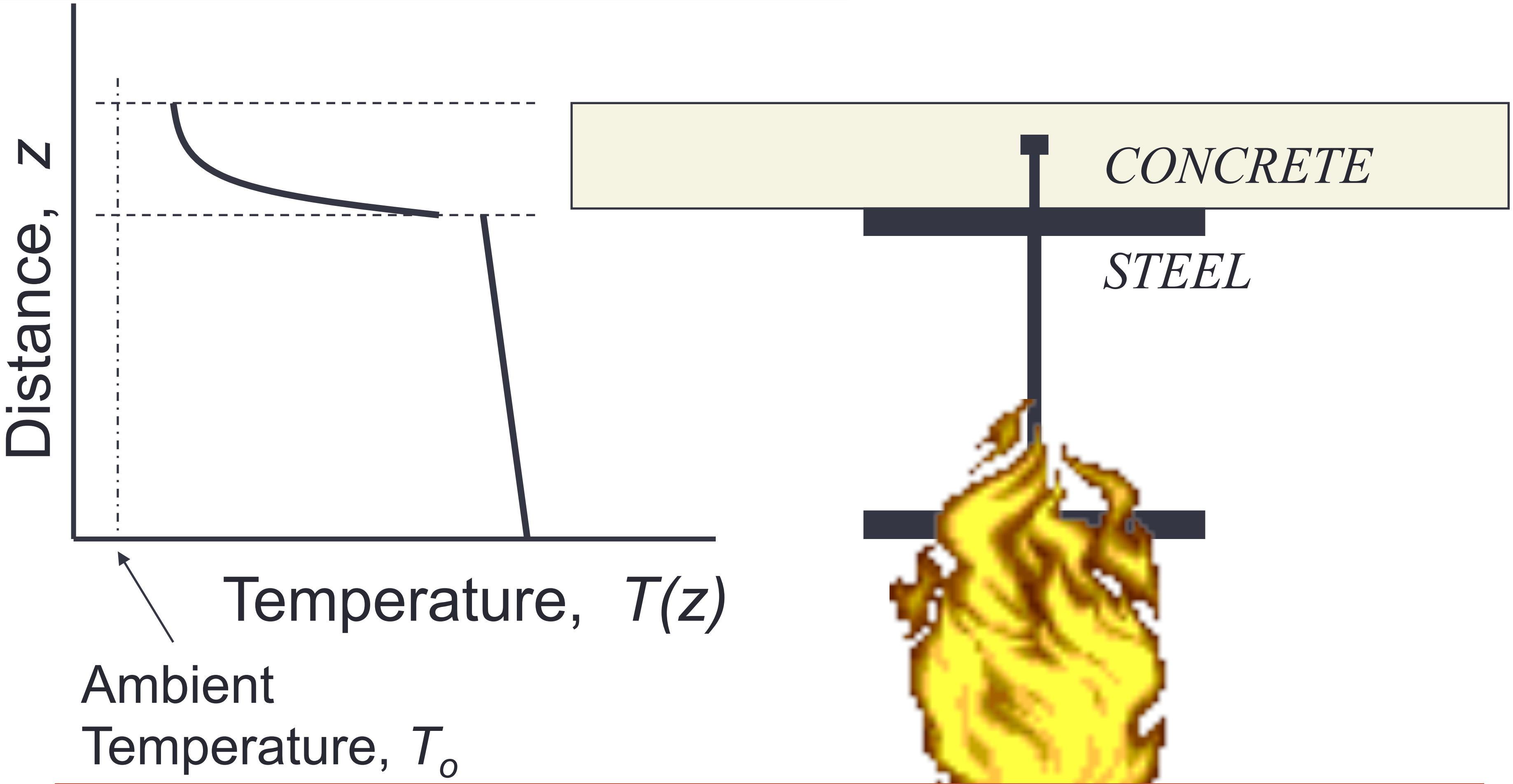
Heat transfer
OpenSees, ABAQUS, ANSYS

heat transfer - thermomechanics middleware

Structural response
OpenSees, ABAQUS, ANSYS (general)
SAFIR, VULCAN (special purpose)

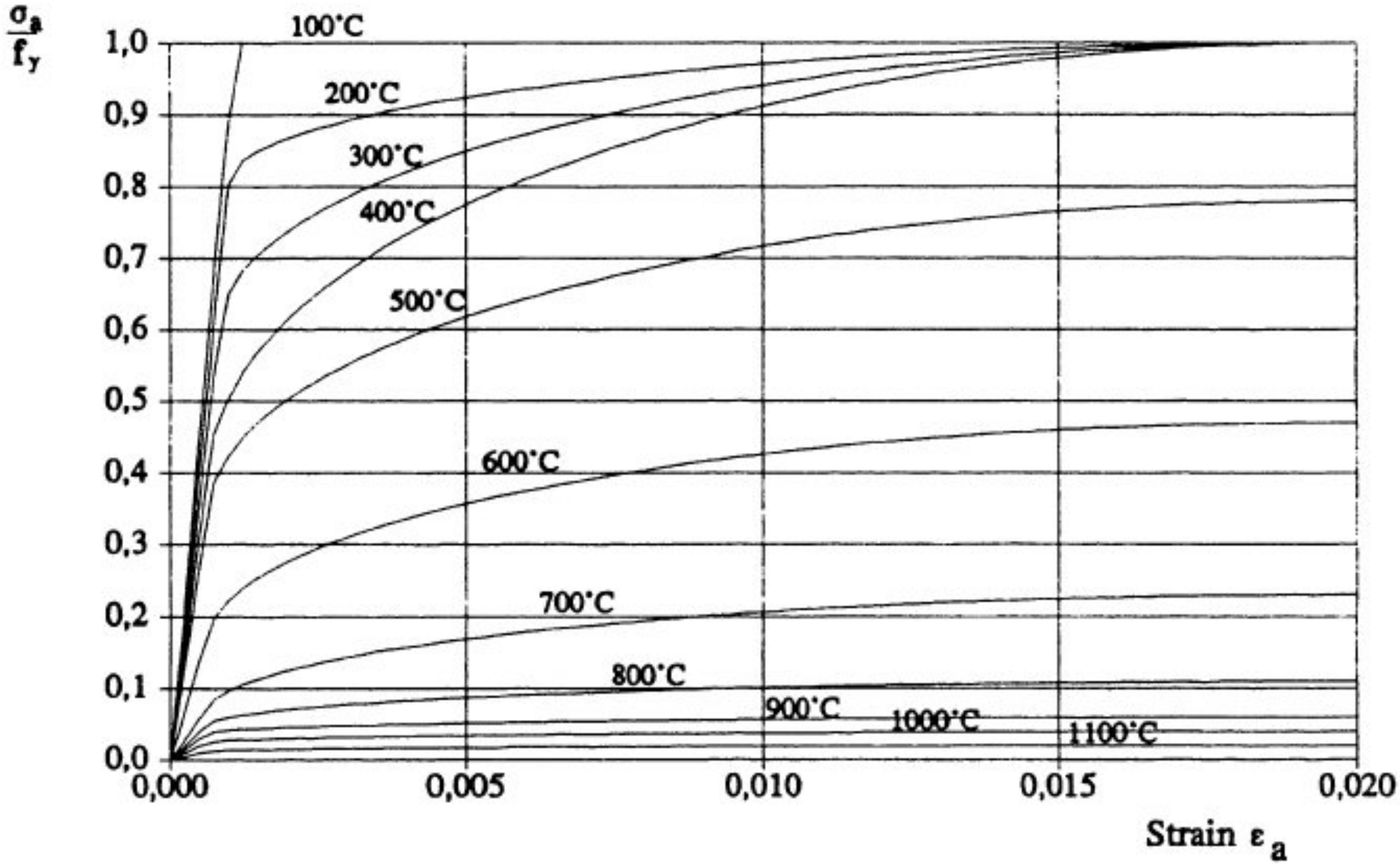
Structures in fires

Effect of fire on structures



1. Materials of construction are exposed to high temperatures
2. Thermally induced deformation
3. Restraint effects
4. Effect of fire history

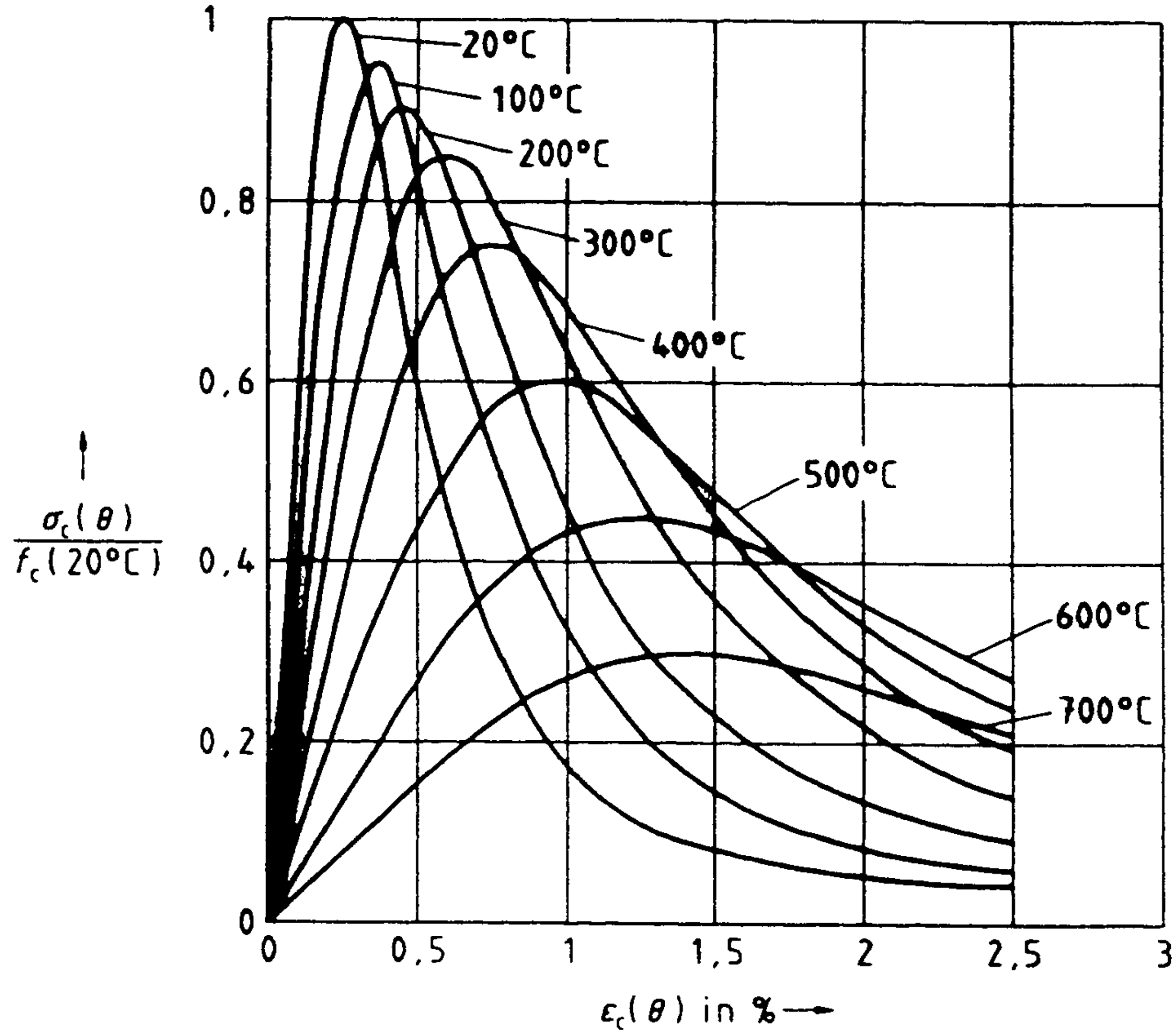
Material | Structural steel stress-strain behaviour



Source: ENV 1993-1-2:1995

(S235 steel)

Material | Siliceous concrete stress-strain behaviour



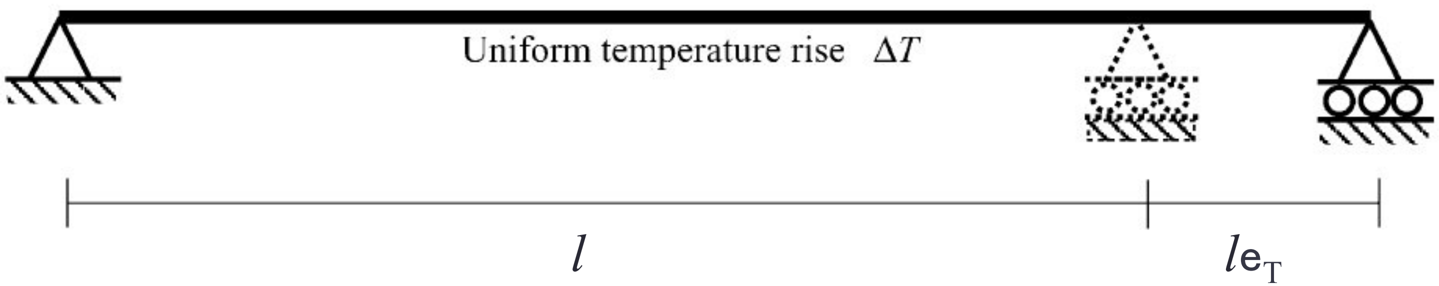
Source: ENV 1992-1-2:1995

Thermally induced deformation | Thermal expansion

- Uniform temperature rise ΔT;
- Unrestrained;
- Thermal expansion:

$$\varepsilon_T = \alpha \Delta T$$

Thermal expansion coefficient of steel
[?] ≈1.2e-5



$$\varepsilon_{total} = \varepsilon_t = \varepsilon_T = \alpha \Delta T$$

$$\varepsilon_{mechanical} = \varepsilon_m = 0$$

Thermally induced deformation | Thermal bowing

❖ Simply supported beam subjected to a uniform thermal gradient:

1. Thermal gradient ($T_{,y}$) over the depth,

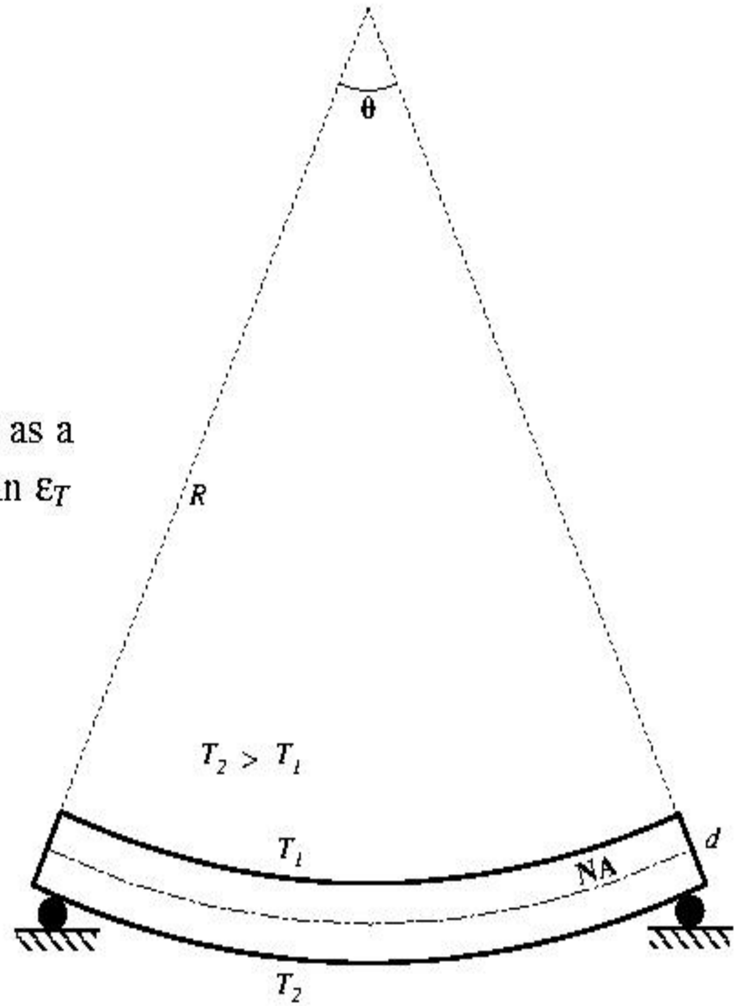
$$T_{,y} = \frac{T_2 - T_1}{d}$$

2. A uniform curvature (ϕ) is induced along the length,

$$\phi = \alpha T_{,y}$$

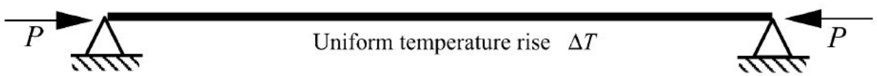
3. Curvature reduces the distance between the ends. Interpreted as a contraction strain ε_ϕ (analogous to the thermal expansion strain ε_T earlier),

$$\varepsilon_\phi = 1 - \frac{\sin \frac{l\phi}{2}}{\frac{l\phi}{2}}$$



Restraint effects

- Thermal expansion with ends restrained against translation



$$\varepsilon_t = \varepsilon_T + \varepsilon_m = 0$$

$$\varepsilon_T = -\varepsilon_m$$

$$P = EA\varepsilon_m = -EA\varepsilon_T = -EA\alpha\Delta T$$

- Thermal bowing with ends restrained against rotation

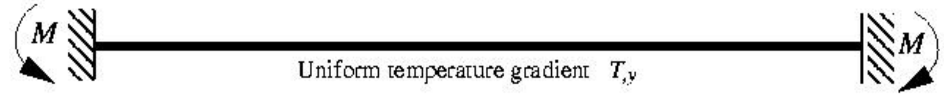


Figure 13: Fixed end beam subjected to a uniform thermal gradient

Uniform moment over the length,

Yield strength :300 Mpa
Elastic Modulus:2e5Mpa
Thermal expansion coefficient: 1.2e-5
Yield temperature increment :125 oC

- **Stocky beam (Yielding):**

The *yield temperature increment* ΔT_y

$$\Delta T_y = \frac{\sigma}{E\alpha}$$

Figure 14: Beam with finite rotational restraint with a uniform thermal gradient

- **Slender beam (Buckling):**

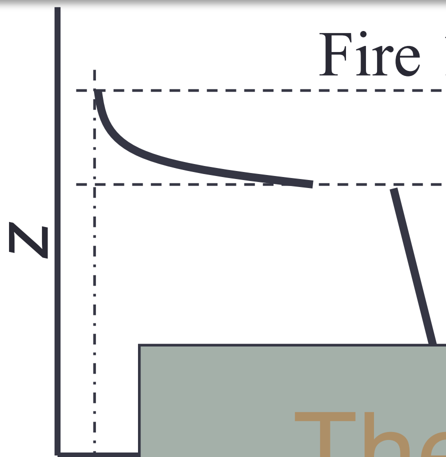
$$\Delta T_{cr} = \frac{\pi^2}{\alpha\lambda^2}$$

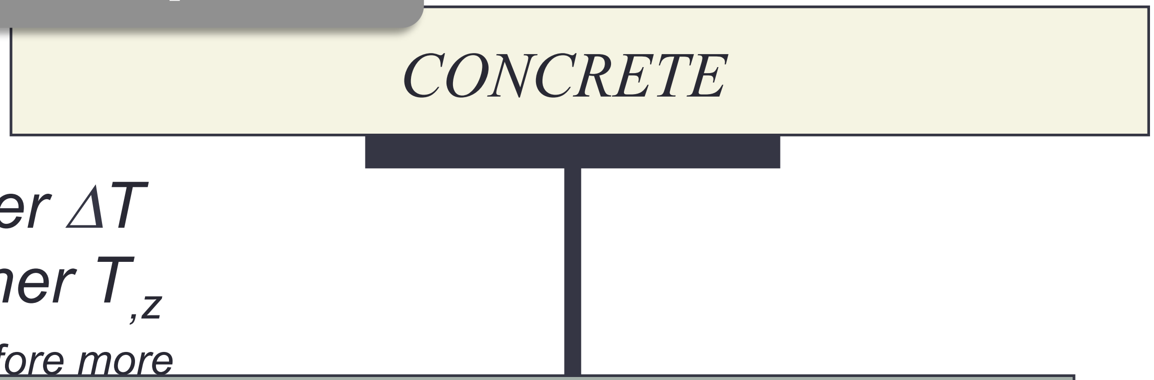
r is the radius of gyration
λ is the slenderness ratio $(\frac{l}{r})$
l is interpreted as the *effective length*

Restraining moment in the rotational springs

$$M_k = \frac{EI\alpha T_{,y}}{\left(1 + \frac{2EI}{k_r l}\right)}$$

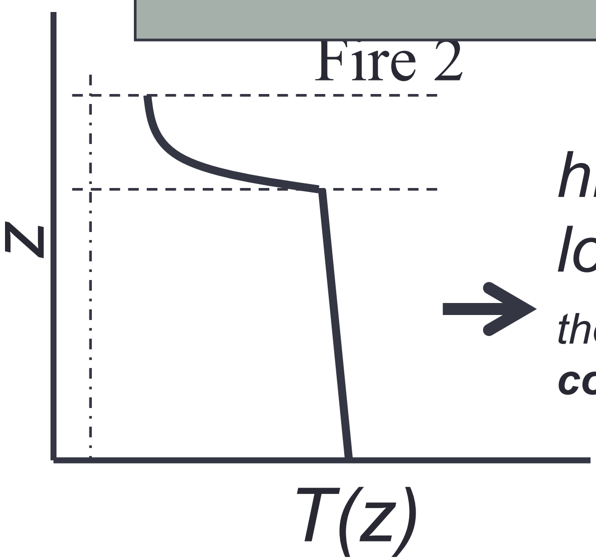
Effect of fire history on response



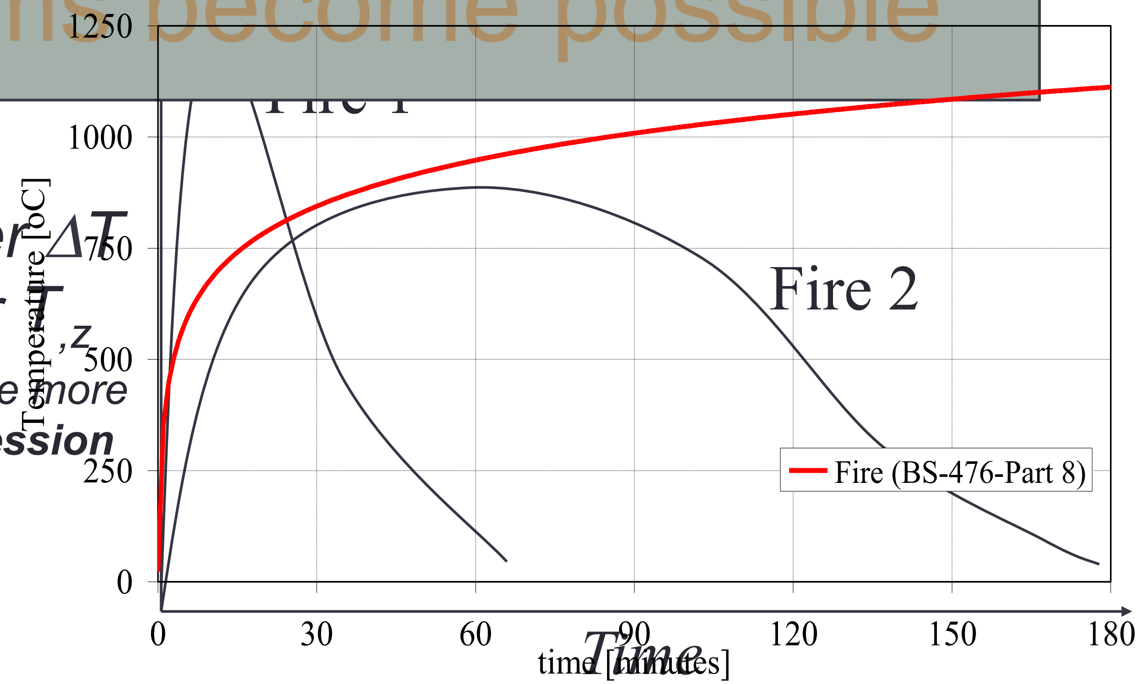


lower ΔT
higher $T_{,z}$
therefore more

Therefore different collapse Mechanisms become possible

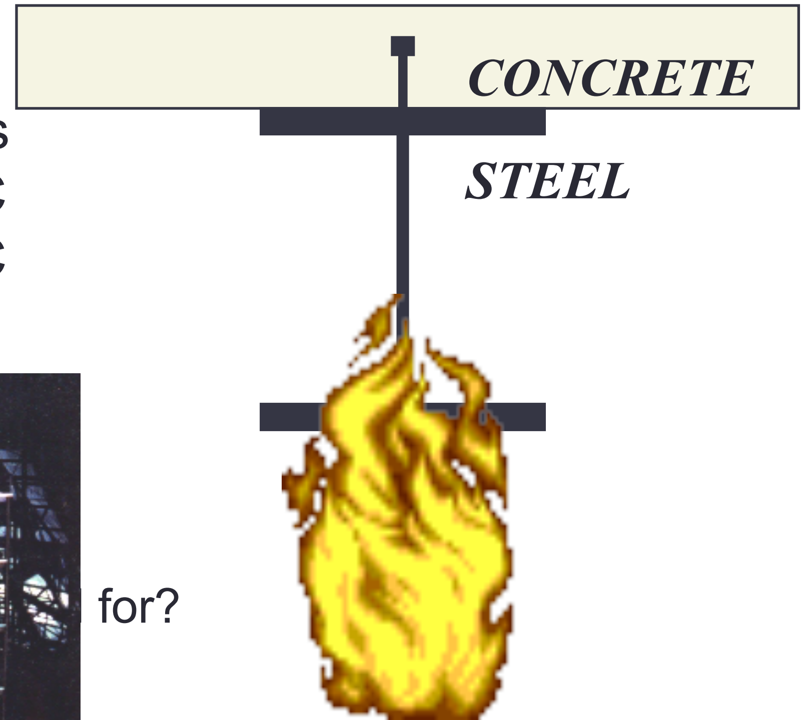


higher ΔT
lower $T_{,z}$
therefore more ***compression***



"Performance" in the context of structural fire resistance

Observation
Fire heats steel, steel loses stiffness & begins to lose strength at temperatures above 400°C with only half the strength remaining at 550°C

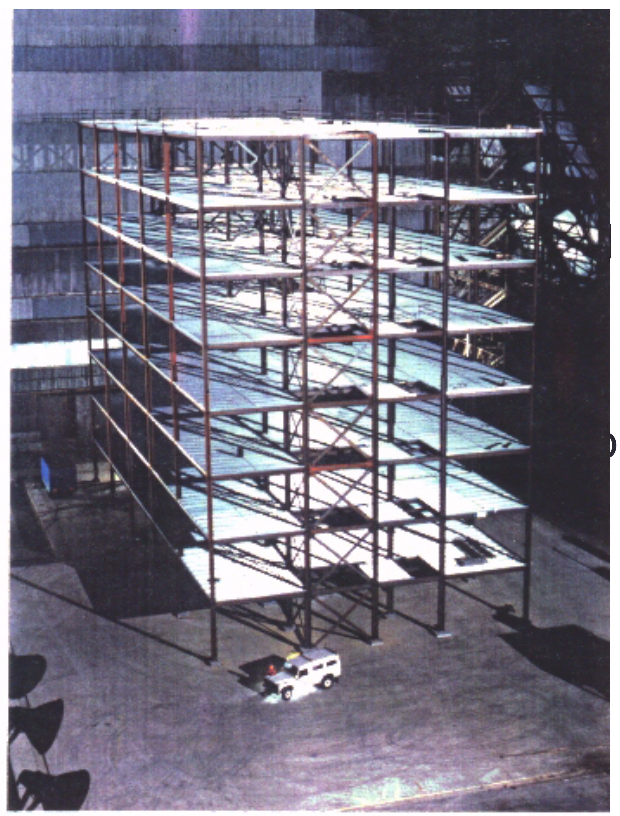


Solution
Protect all steel for a *lo*

Issues
1. How long should a str for?

2. Cause (heating) and e and displacements) w ble structures such as

but not for



Why do we need an "integrated computational enviroment" ?

Current widespread practice is **"prescriptive"** (standard fire + isolated member)

Built-environments are getting more complex and dense creating higher risk (consequences of disaster are increasing) => "alternative" or **performance based engineering** (PBE) approaches

Even when PBE approaches are used (on rare occasions), in general **uniform compartment fires** are assumed (a single compartment temperature at a given instant in time – no spatial variation): oversimplification at best – wrong at worst!

But even if one wanted to make a realistic estimate of the fire, there are **no tools to simulate the whole process**, (if commercial vendors make them they would be too expensive – furthermore researchers will have no control over the tools)

Yes it is very unlikely that such an environment will be used in routine engineering – but routine engineering can benefit from research to create a **better understanding of structural response in real fires** – IF ONLY we had such a tool! Currently the only way to do a fully coupled simulation is to "conduct an experiment"

Integrated computational environment for structures in fire

Fire models
Standard
Natural/parametric (short hot/long cool)
Localised
Travelling
CFD (FDS, FireFOAM, ANSYS-CFX)

Fire – heat transfer middleware

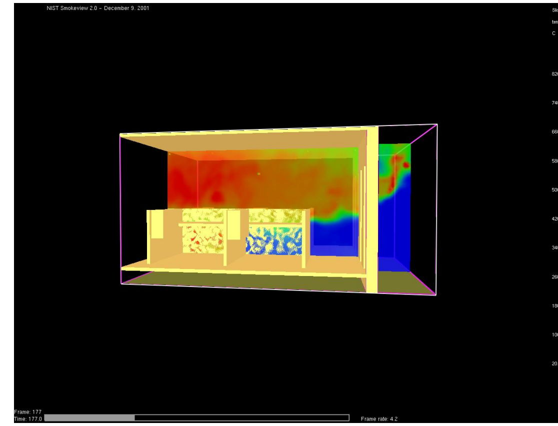
Heat transfer
OpenSees, ABAQUS, ANSYS

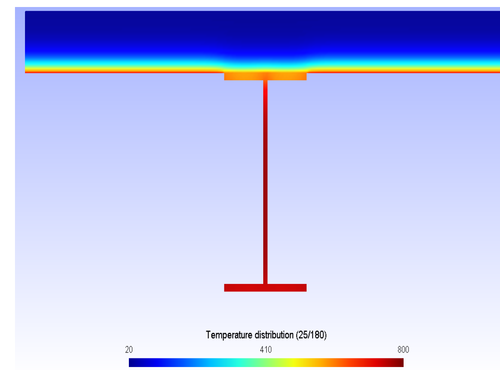
Heat transfer - thermomechanics middleware

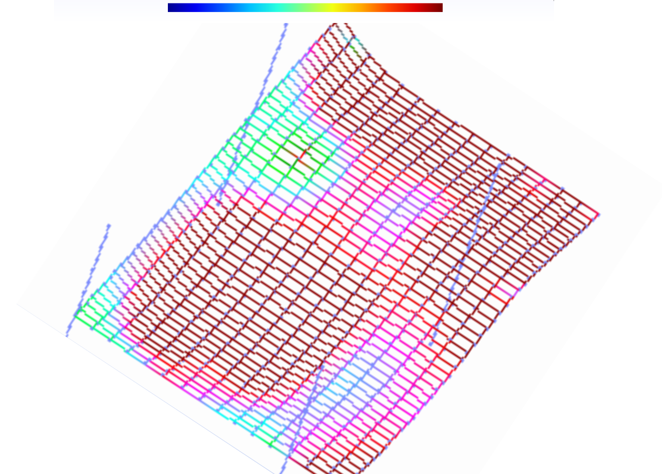
Structural response
OpenSees, ABAQUS, ANSYS (general)
SAFIR, VULCAN (special purpose)

Integrity failure

structure – fire coupling







Integrated computational environment

- Current development of OpenSees

We extend OpenSees

UoE OpenSees wikisite

https://www.wiki.ed.ac.uk/display/opensees

Pages

UoE OpenSees

3 Added by Andrew McFarlane, last edited by Liming Jiang on Apr 29, 2014 (view change)

University of Edinburgh
OpenSees
Developers Group

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OpenSees

The Open System for Earthquake Engineering Simulation, featured as an object-oriented and open source framework.

- Command manual
- Demonstration examples
- Downloading executable application
- Browsing source code

About OpenSees at UoE

The OpenSees developers group based in the School of Engineering, University of Edinburgh first started in 2009. The aim of this work is to add a structural in fire modelling capability in OpenSees.

Users

A number of wiki pages are provided to help users to carry out thermomechanical analyses with OpenSees using simple examples.

Developers

A detailed description of all the new or modified classes developed for enabling thermomehcanical analyses in OpenSees.

Publications

Links to publications by the group are provided here.

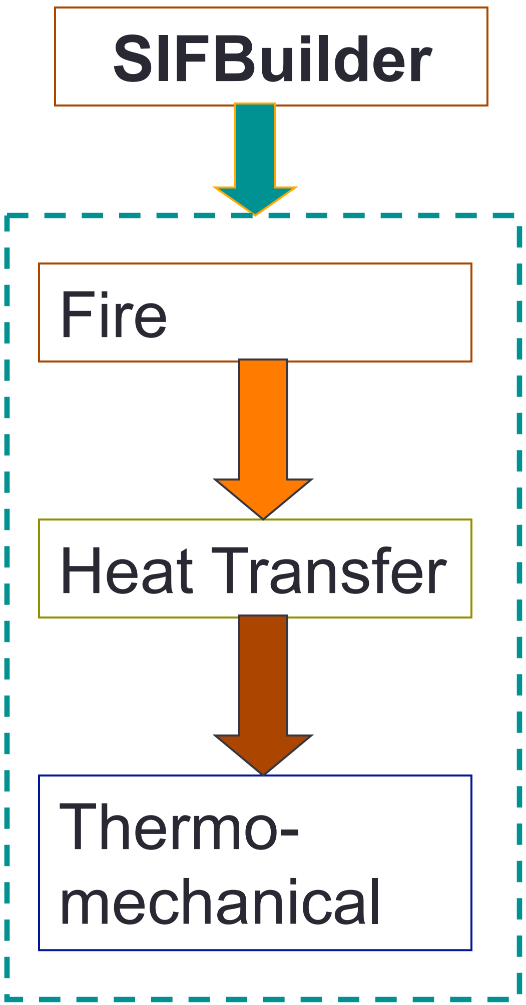
Download

An executable version of OpenSees compiled for use in Windows can be downloaded and source codes developed can be browsed or downloaded. We'll update all the bug-fixing issues on that page.

This wiki site is administered by Liming Jiang@University of Edinburgh

OpenSees development for Structure in Fire

- Scheme for Modelling Structure in fire



User-friendly interface for creating (regular) structural models and enable consideration of realistic fire action

Models of fire action (only ***idealised*** fires), i.e., Standard fire, Parametric fire, EC1 Localised fire, Travelling fire

Heat transfer to the structural members due to fire action

Structural response to the elevated temperatures

SIFBuilder

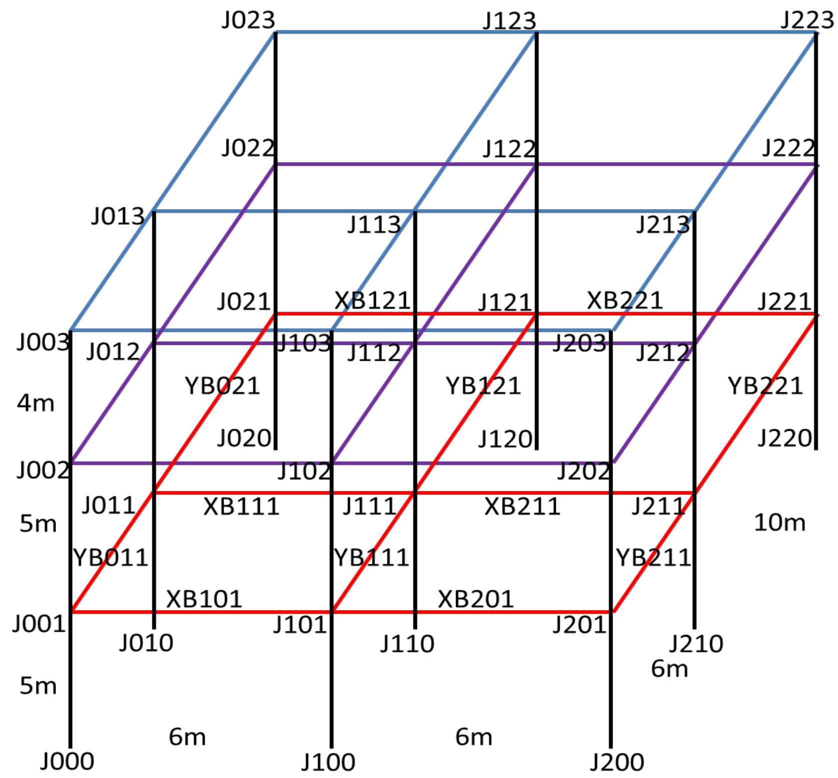
SIFBuilder

- ✓ **Developed for creating large models**
- ✓ **Driven by Tcl**
- ✓ **Minimum input required**

Geometry information
-XBays,Ybays,Storeys

Structural information
-Material, Section

Loading information
-Selfweight, Horizontal loading
-Fire action



Fire modelling

Fire modelling

- ❑ Uniform fire?
- ✓ Standard fire: ISO-834 fire curve
- ✓ Hydro-carbon fire: EC1
- ✓ Empirical Parametric fire: EC1 Parametric fire model

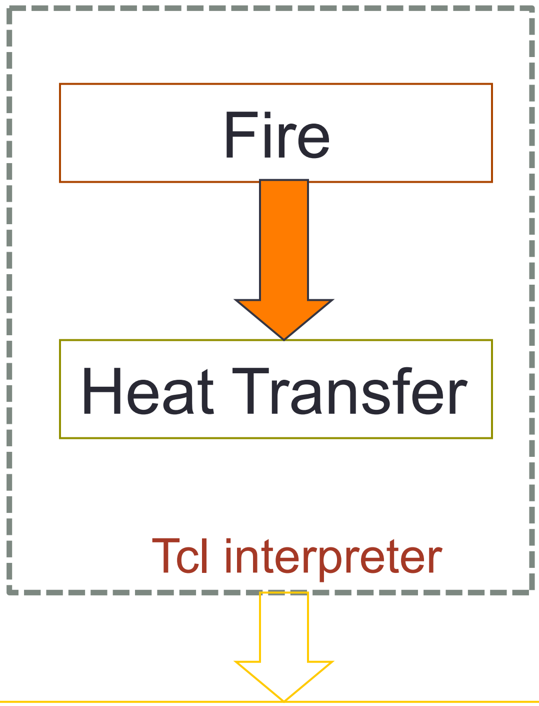
- ❑ non-uniform fire?
- ✓ EC1 Localised fire
- ✓ Alpert ceiling jet model
- ✓ Travelling fire

- ❑ Potential abilities
- ✓ Connected with FDS
- ✓ We never close the door
  -localised heat flux input

Heat transfer

Heat transfer analysis

- Heat transfer and thermo-mechanical analyses



- ✓ Still under developing
- ✓ Tcl commands available
- ✓ Easy to extend

❑ Heat flux BCs

- Convection, radiation, prescribed heat fluxes

❑ HT materials

- CarbonSteelEC3, ConcreteEC2
- Steel ASCE
- easy to extend the library,
- Entries for conductivity, specific heat

❑ HT elements

- 1D, 2D, 3D heat transfer elements

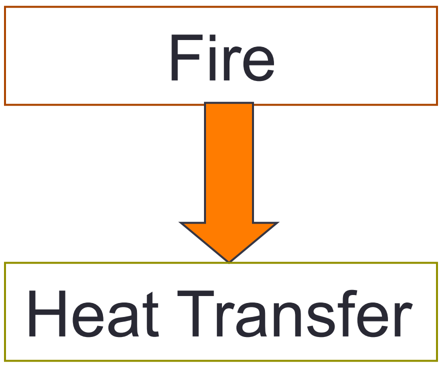
❑ HT recorders (for structural analyses)

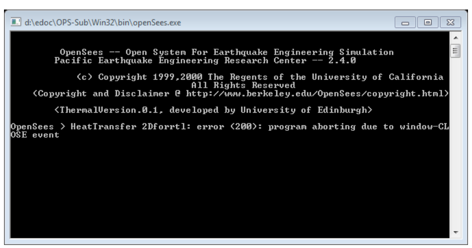
❑ Simple Mesh

- I Beam, Concrete slab, Composite beam

Heat transfer analysis

- Tcl commands for Heat transfer analysis





❑ Initialization of heat transfer module

HeatTransfer 2D<3D>;

--To activate Heat Transfer module

❑ Definition of Heat Transfer Materials

HTMaterial CarbonSteelEC3 1;.

HTMaterial ConcreteEC2 2 0.5;

❑ Definition of Section or Entity

HTEntity Block2D 1 0.25 0.05 $sb 0.10;

❑ Meshing the entity

#SimpleMesh $MeshTag $HTEntityTag $HTMaterialTag $eleCtrX $eleCtrY;

SimpleMesh 1 1 1 10 10;

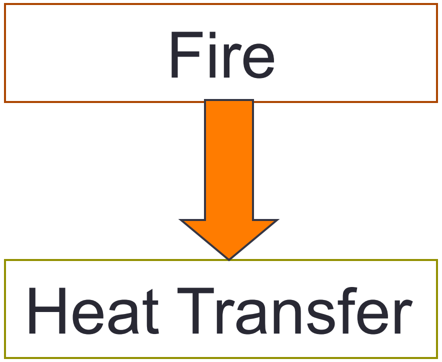
❑ Definition of fire model

FireModel Standard 1;

……..

Heat transfer analysis

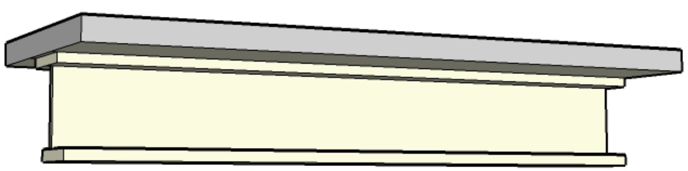
- Strategy for efficient heat transfer modelling



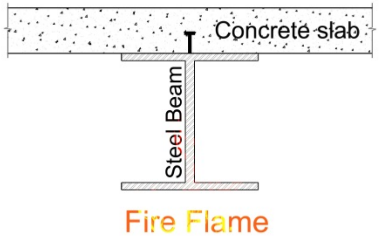
Idealised uniform fires, T(t):

Heat flux input is spatially invariant over structural member surfaces;

2D heat transfer analysis for beam section, 1D for concrete slab



3D



2D

1D

Heat transfer analysis

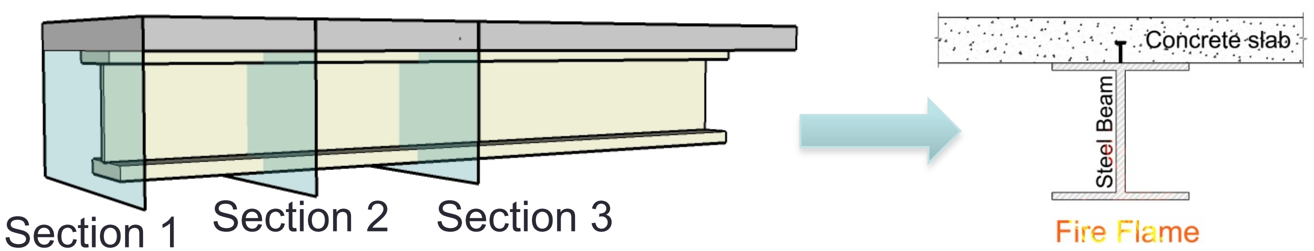
- Strategy for efficient heat transfer modelling

Idealised non-uniform fires, T(x,y,z,t):

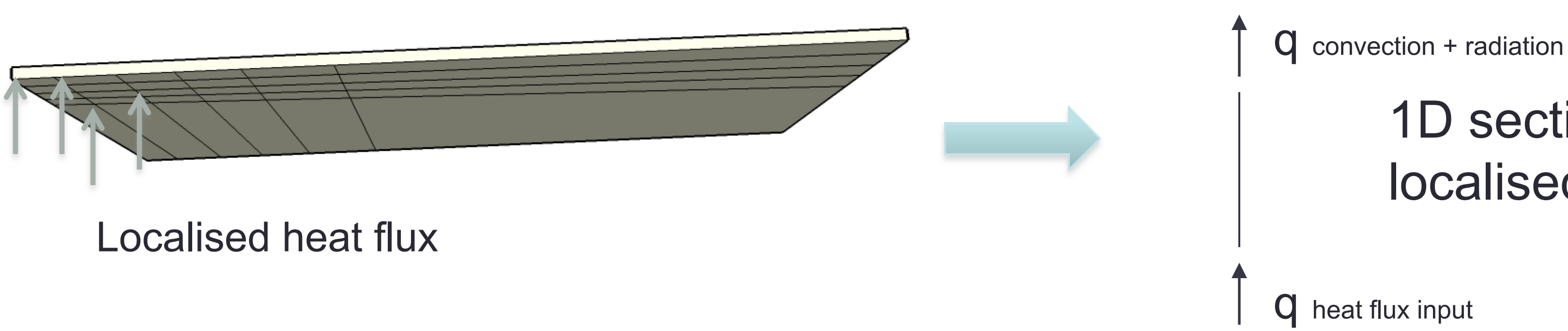
○Heat flux input varies with the location ;

○Composite beam: a series of 2D sectional analyses

○Concrete slab : using localised1D Heat Transfer analyses



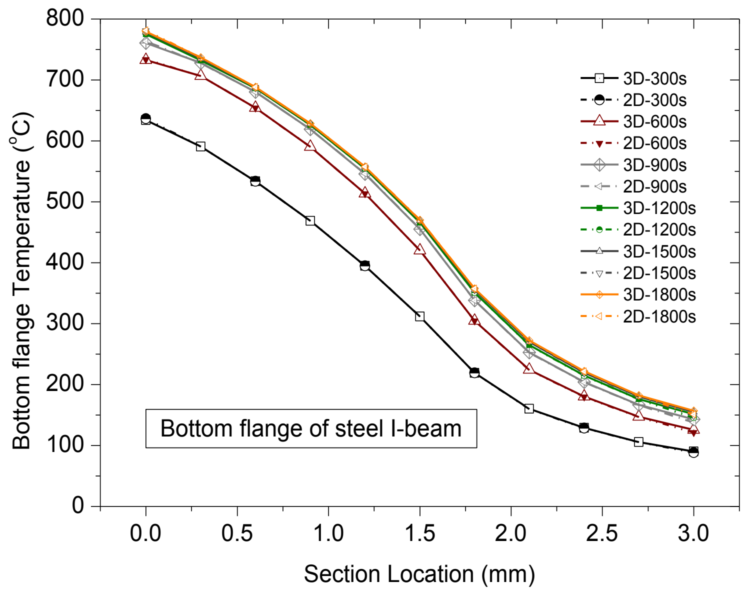
2D section with localised BC



1D section with localised BC

Heat transfer analysis

- Composite Beam- 2D approach VS.3D approach



Composite beam

Length: 3m

Steel beam: UB 356 × 171 × 51

Concrete slab: 1.771× 0.1m

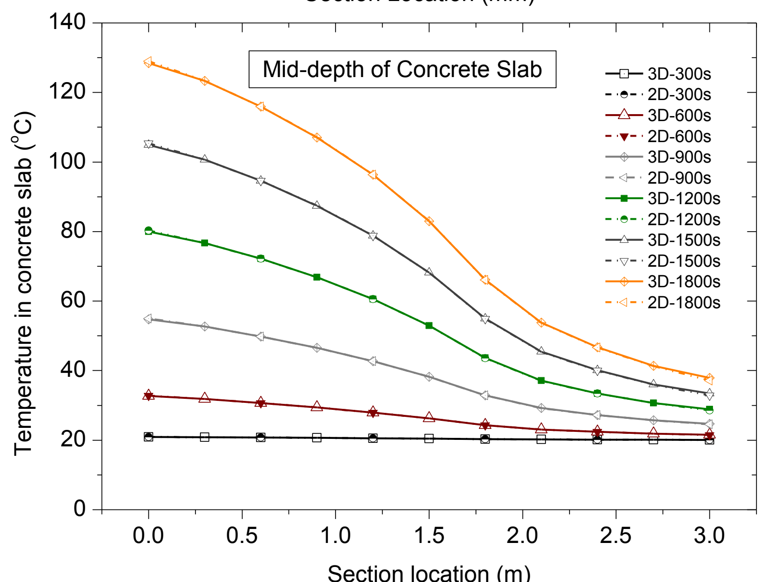
Material with Thermal properties according to EC2 and EC3

EC localised fire

Heat release rate: 3MW

Diameter: 1m, Ceiling height:3m

Fire origin: under the beam end



What we found

Exactly the same temperature profile!

Heat transfer analysis

- Concrete Slab
  - 1D approach VS.3D approach

Concrete slab:

Dimension: 5m×5m× 0.1m

Material with Thermal properties according to EC2

EC localised fire

Heat release rate: 5MW

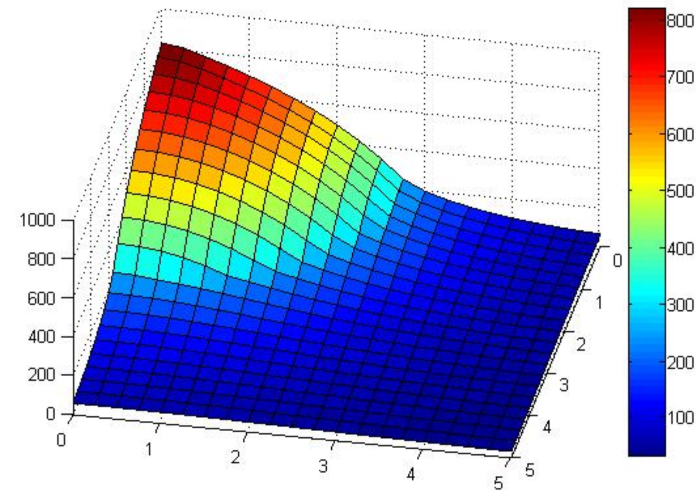
Diameter: 1m

Ceiling height:3m

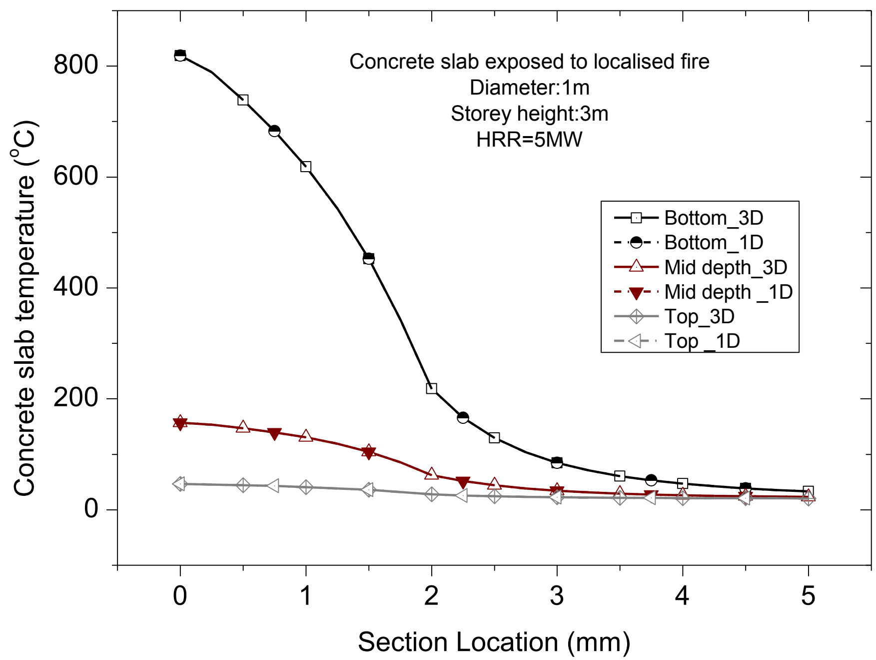
Fire origin: under the slab corner

What we found:

Localised 1D analysis produces identical temperature profile as 3D analysis



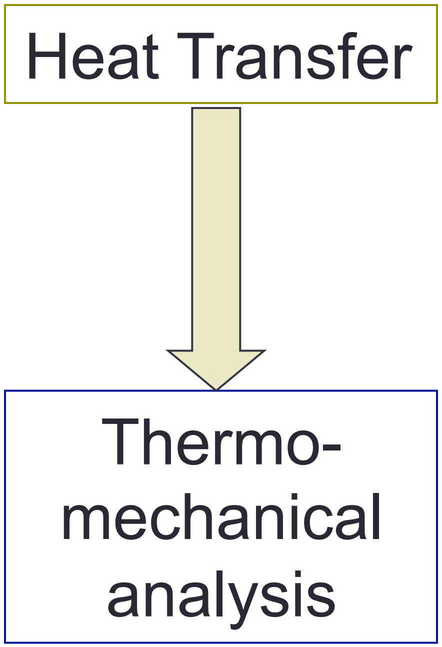
Temperature plot for slab bottom



Thermo-mechanical analysis

Thermo-mechanical analysis

- Thermo-mechanical classees



❑ HT recorders (for structural analyses)

❑ Thermomechanical materials

- With temperature dependent properties

❑ Thermomechanical sections

-Beam sections & membrane plate section

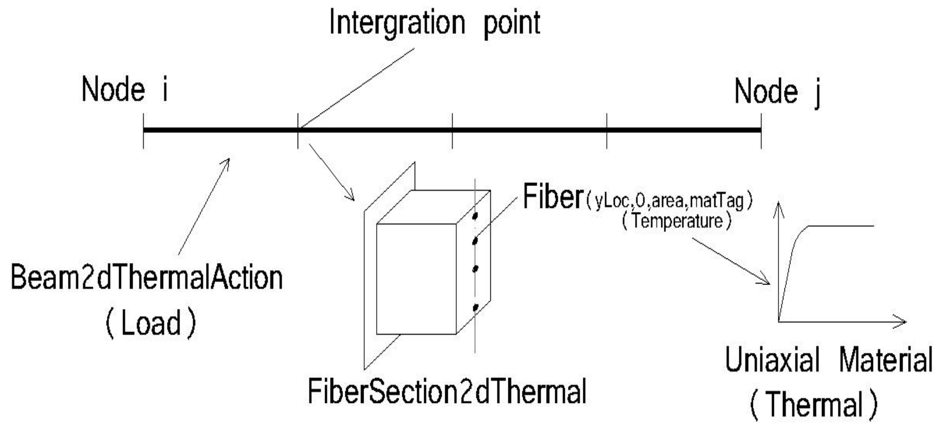
❑ Thermomechanical elements

-Disp based beam elements, MITC4 shell elements

❑ Loading:Thermal action

-2D&3D BeamThermalAction, ShellThermalAction

- NodalThermalAction



Thermo-mechanical analysis

- Tcl commands for material, section, and elements

```
uniaxialMaterial SteelECThermal $matTag <EC3> $fy $E0;
…

section FiberThermal $secTag {
Fibre..
Patch..
Layer..
}
…

element dispBeamColumnThermal $eleID $node1 $node2 $NumIntgers
$secTag $GeomTransTag;
…

block2D $nx $ny $NodeID0  $EleID0 ShellMITC4Thermal $SecTag {
….
}
```

Thermo-mechanical analysis

- Tcl commands for defining beam thermal actions

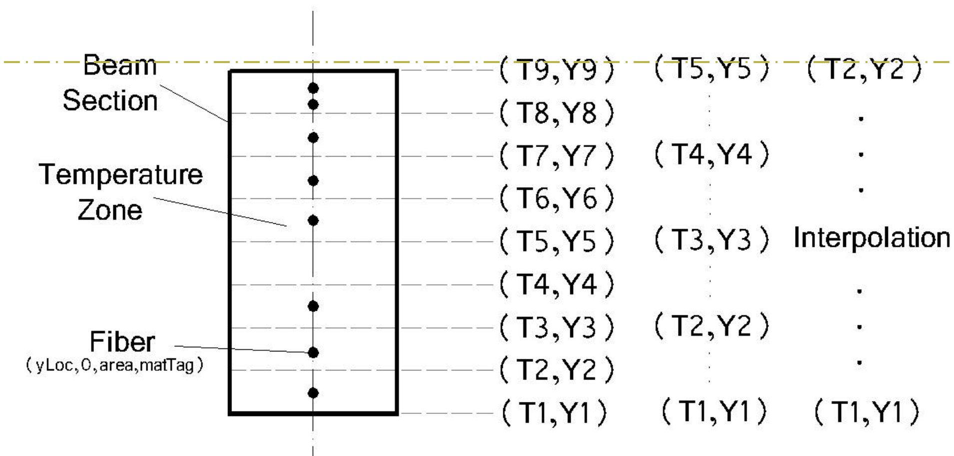
❑ Uniform along beam length, non-uniform through depth

Using Linear Load pattern

```
pattern Plain $PatternTag  Linear{
…
eleLoad –ele $eleID -type -beamThermal $T1 $y1 $T2 $y2 <$T3 $Y3 … $T9 $Y9>
…
}
```

Using Fire Load pattern for further non-uniform profile

```
pattern Fire $PatternTag $Path $Path $Path $Path $Path $Path $Path $Path $Path {
…
eleLoad –ele $eleID -type -beamThermal $T1 $y1 $T2 $y2 <$T3 $Y3 … $T9 $Y9>
…
}
```



Thermo-mechanical analysis

- Tcl commands for defining beam thermal actions

❑ Importing external temperature history file

```
pattern Plain $PatternTag  Linear {
…
eleLoad -ele $eleID -type -beamThermal -source $filePath $y1 $y2 <$y3…$y9>;
…
}
```

"BeamTA/element1.dat"

Time T1 (corresponding to y1)……………………………T9(corresponding to y9)

```
60    47.2327 46.4181  47.3834 47.5978 47.6355 47.5978  47.3834 46.4181 47.2327
120   75.5848 74.8791 76.5169  77.0164 77.1223 77.0164  76.5169 74.8791 75.5848
180   104.494 103.735 105.762  106.516 106.698 106.516  105.762 103.735 104.494
….
….
```

Thermo-mechanical analysis

- Tcl commands for defining beam thermal actions

❑ Non-uniform along beam length and depth

Apply Nodal thermal action

```
pattern Plain $PatternTag  Linear {
…
eleLoad -range $eleTag0 $eleTag1 -type -beamThermal -source -node;
load $nodeTag -nodalThermal $T1 $Y1 $T2 $Y2;
…
}
```

Source external temperature file

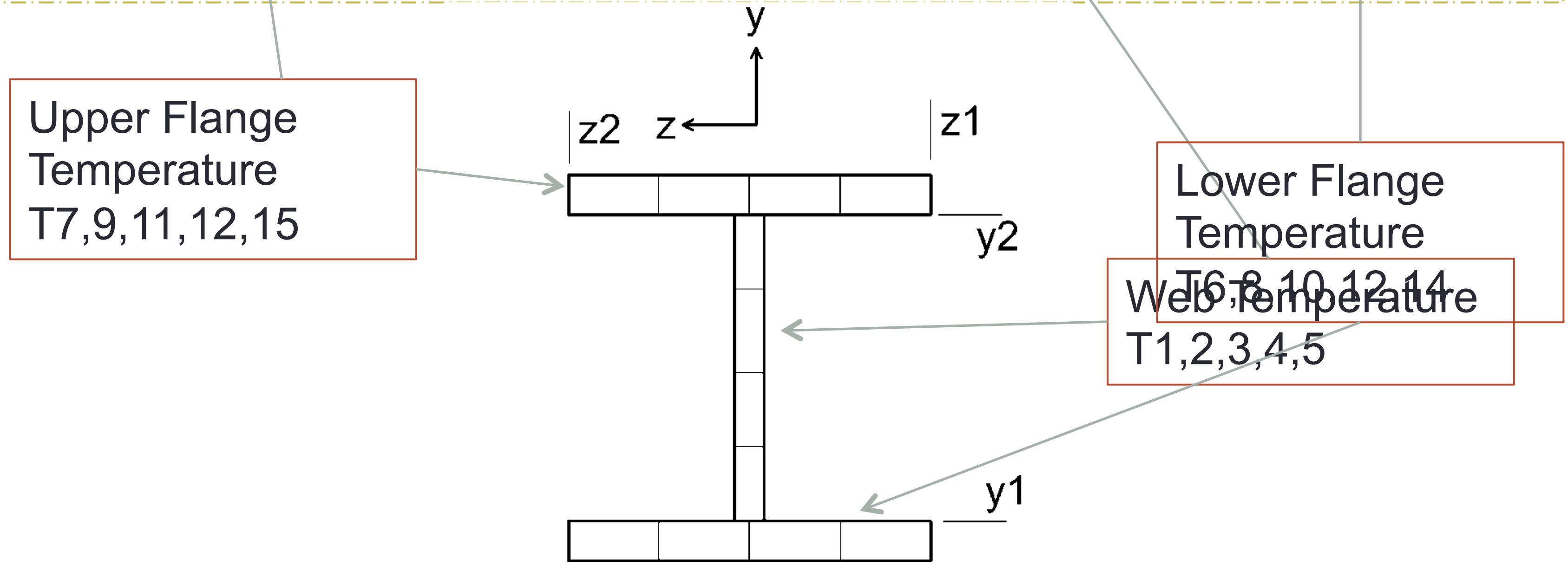
```
…
load $nodeTag -nodalThermal –source $filePath $y1 $y2;
…
```

Thermo-mechanical analysis

- Tcl commands for defining beam thermal actions

  - ThermalAction for 3D I section beams

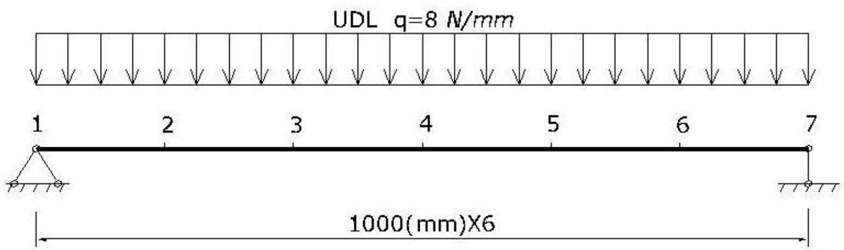
```
…
eleLoad –ele $eleID -type -beamThermal $T1 $y1 …T5 $Y5< $T6 $T7 $Z1 $T8 $T9
$Z2  … $T14 $T15 $Z5>
…
```



Examples [Available@UoE Wiki]

Examples-Simply supported beam

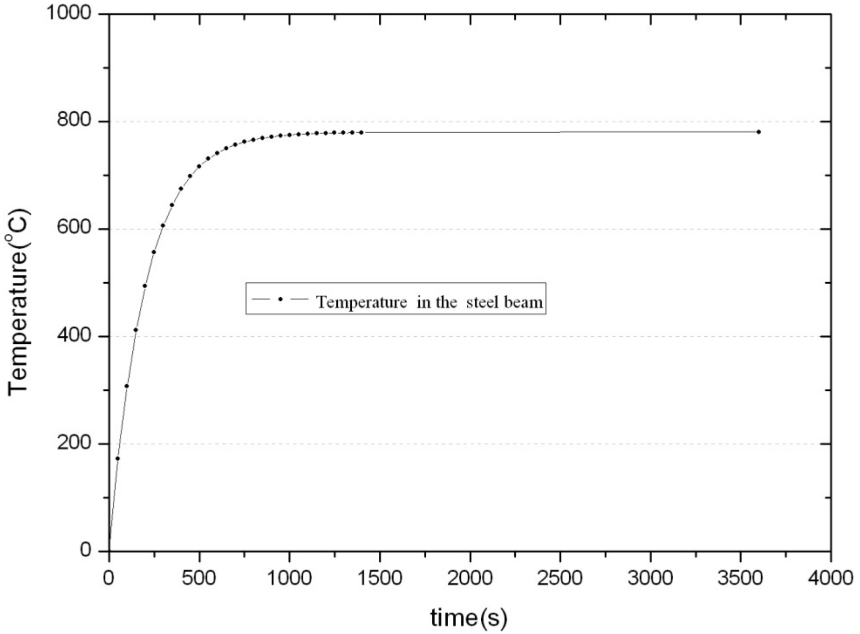
- A simply supported steel beam;
- Uniform distribution load *q*= 8N/mm
- Uniform temperature rise ΔT;
- Using FireLoadPattern



Tcl script

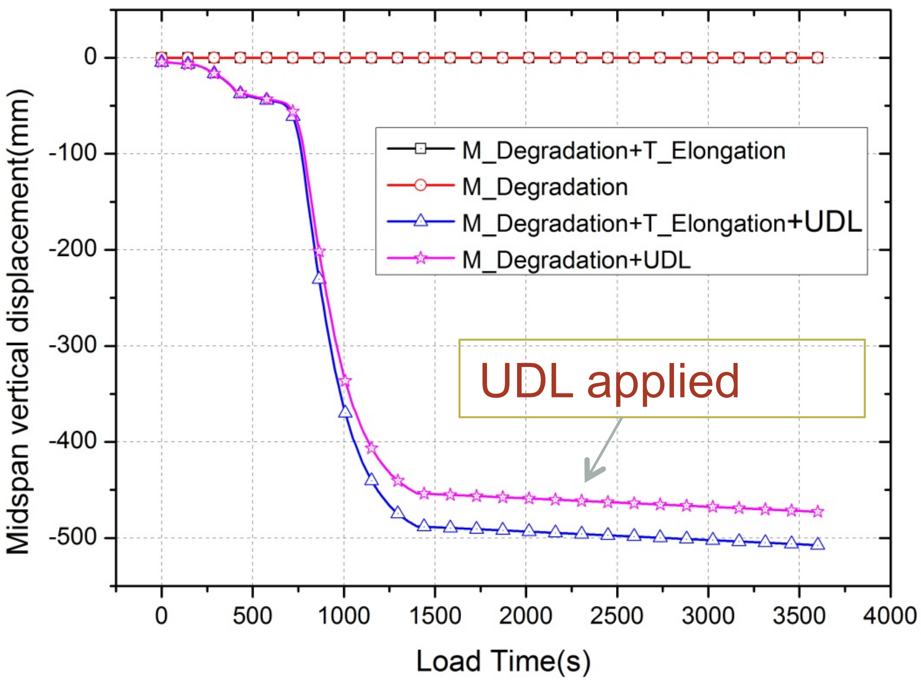
```
uniaxialMaterial Steel01Thermal 1
308 2.1e5 0.01;
```

```
element dispBeamColumnThermal
1 1 2 5 $section 1;
```



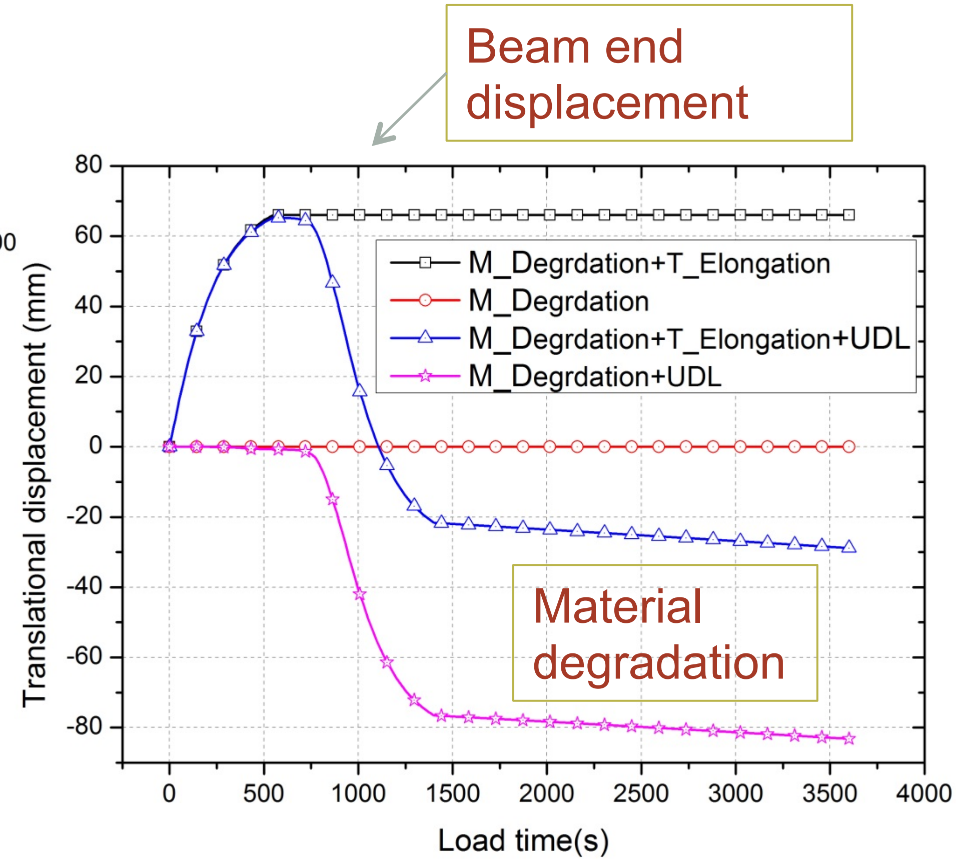
❖ Temperature-time curve defined by FireLoadPattern:

Examples-Simply supported beam



1) without thermal elongation?

2) UDL removed?



❖ Deformation shape (without UDL)

❖ Deformation shape (with UDL)

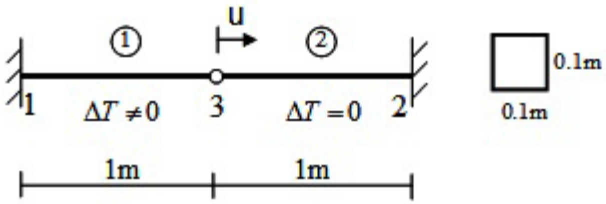
Examples-Restrained Beam under thermal expansion

- 2D elements, Fixed ends;
- Element 1 with ΔT ≠0 , only one free DOF at Node 3

- The effects of Thermal expansion;

-stiffness degradation, strength loss;

-and restraint effects;




```
set secTag 1;
  section FiberThermal $secTag {
        fiber -25 0 5000 1;
        fiber 25 0 5000 1;
  };
…


pattern Plain 1 Linear {
eleLoad -ele 1 -type -beamThermal
1000 -50 1000 50
};
```

2D beam element

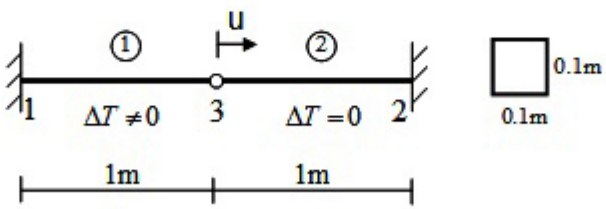
```
set secTag 1;
section FiberThermal $secTag {
        fiber -25 -25 2500 1;
        fiber -25 25 2500 1;
        fiber 25 -25 2500 1;
        fiber 25 25 2500 1;
 };
…
pattern Plain 1 Linear {
eleLoad -ele 1 -type -beamThermal 1000
-50 1000 50
};
```

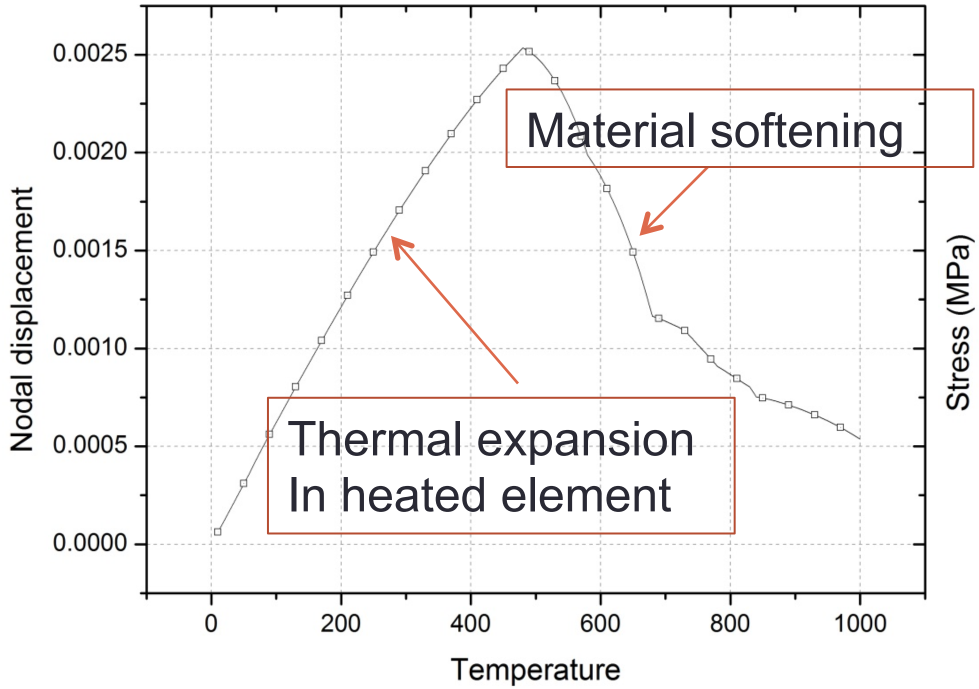
3D beam element

Examples-Restrained Beam under thermal expansion

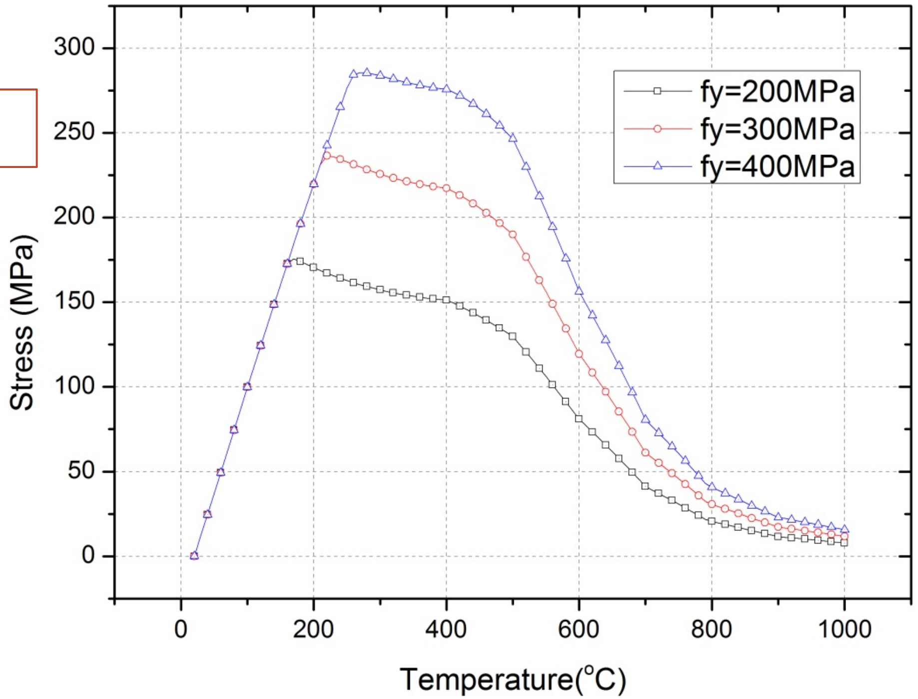
- 2D elements, Fixed ends;
- Element 1 with ΔT ≠0 , only one free DOF at Node 3

\- The effects of Thermal expansion;
-stiffness degradation, strength loss;
-and restraint effects;





❖ No strength loss in heated part (stiffness loss considered)



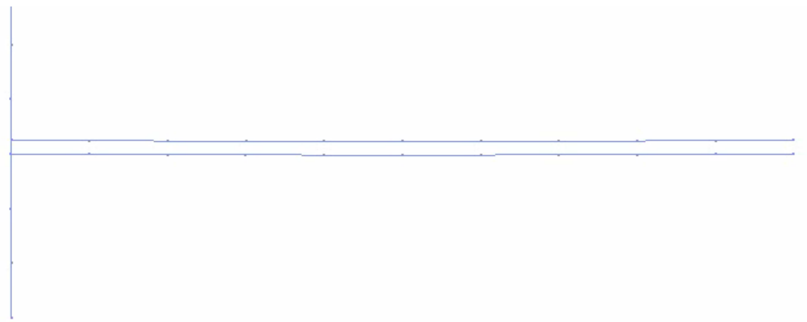
❖ Considering strength loss

Examples-Composite Beam

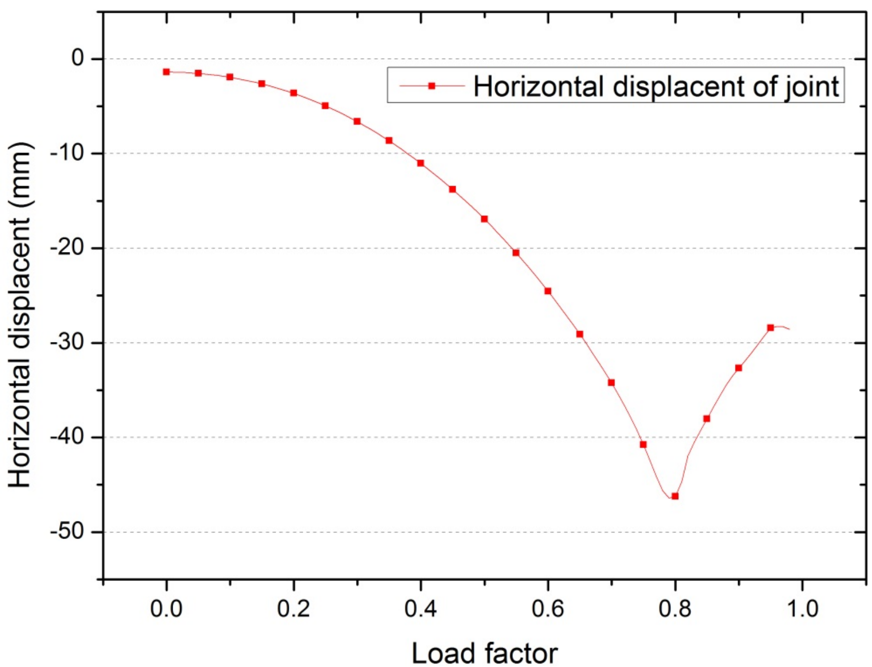
❑Composite beams with column connected

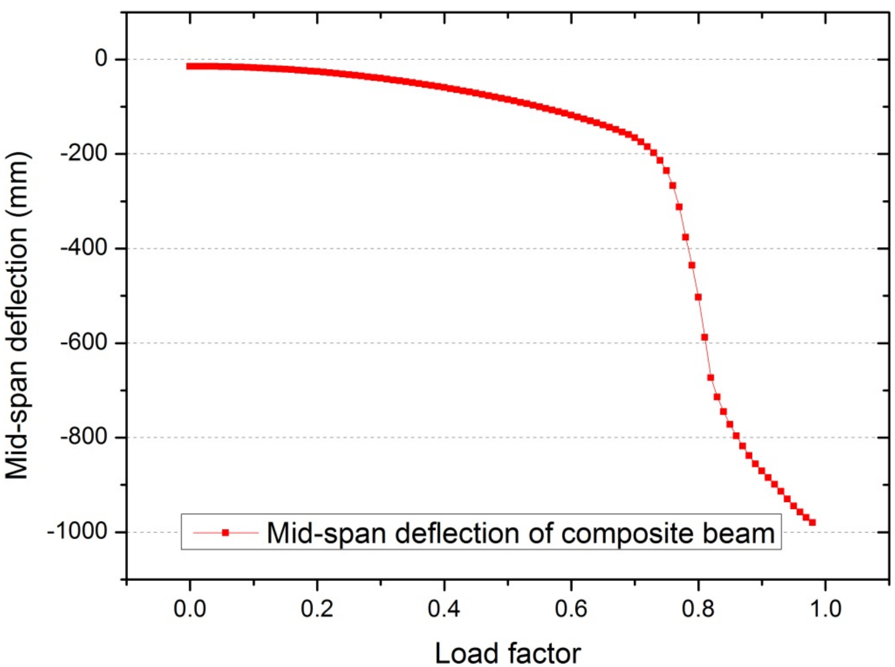
1) Column was pushed out by thermal expansion;

3) Being pulled back by Catenary action



❖ Deformation shape





Thank you ! Questions?

AN INTEGRATED COMPUTATIONAL ENVIRONMENT FOR SIMULATING STRUCTURES IN REAL FIRES

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23 JUNE 2014