Modelling of structures in fire using OpenSees

Asif Usmani, Liming Jiang

BRE Centre for Fire Safety Engineering
Institute for Infrastructure and Environment
School of Engineering
The University of Edinburgh

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

Outline

- Background
- Features of structural behaviour at elevated temperature
- OpenSees implementation
- Examples
- Planned work

Broadgate Phase 8 fire, London (23 June'90)

14 storey building under-construction

Fire duration 4.5 hrs
Temp > 1000°C for 2 hrs
Fire protection incomplete, steel temperatures estimated to be under 600°C

13.5m span/1m deep trusses and floors had over 500mm permanent deflections and buckled members and unprotected columns had shortened by upto 100mm, but there was no overall collapse

Total losses ~ £25 M,
struct. repair ~ £2 m (1500 m^2)
completed in 30 days



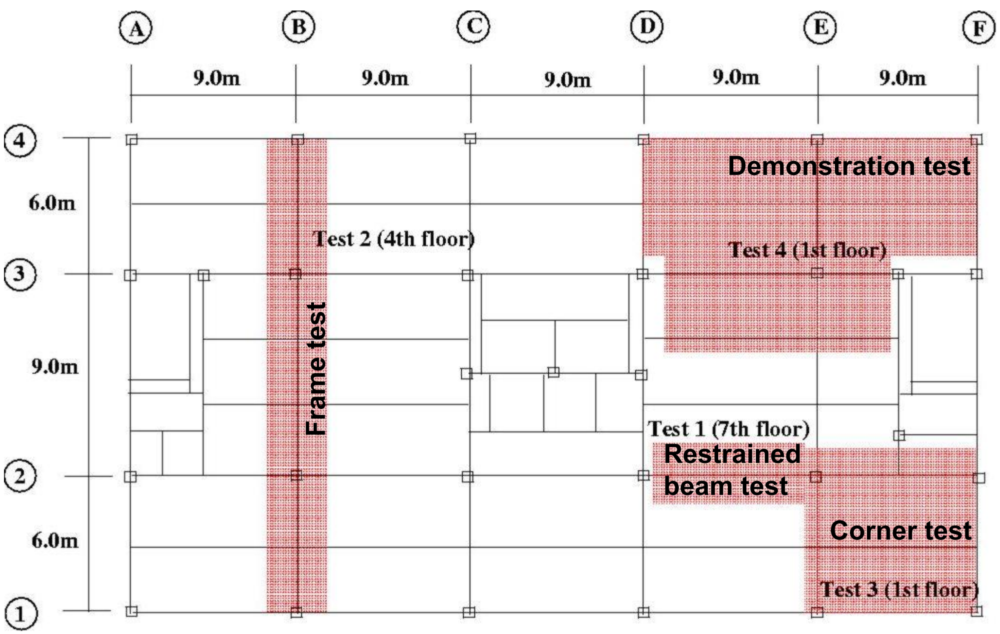
Source: *Stuctural fire Investigation of Broadgate Phase 8 fire* (SCI report), available from www.steelbiz.org

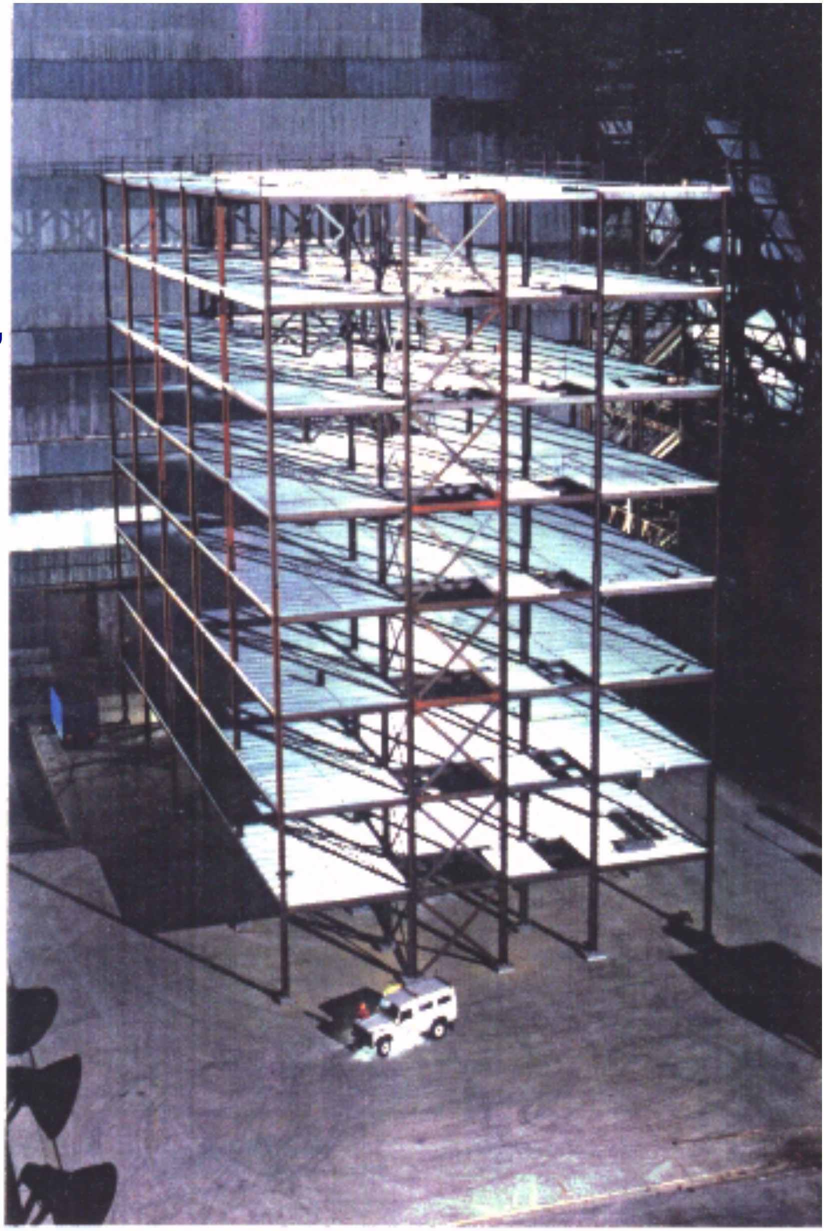
Cardington tests in the United Kingdom

8 Storey steel frame composite structure

2 tests by BRE

4 tests carried out by “British Steel” (Corus), shown on building plan below

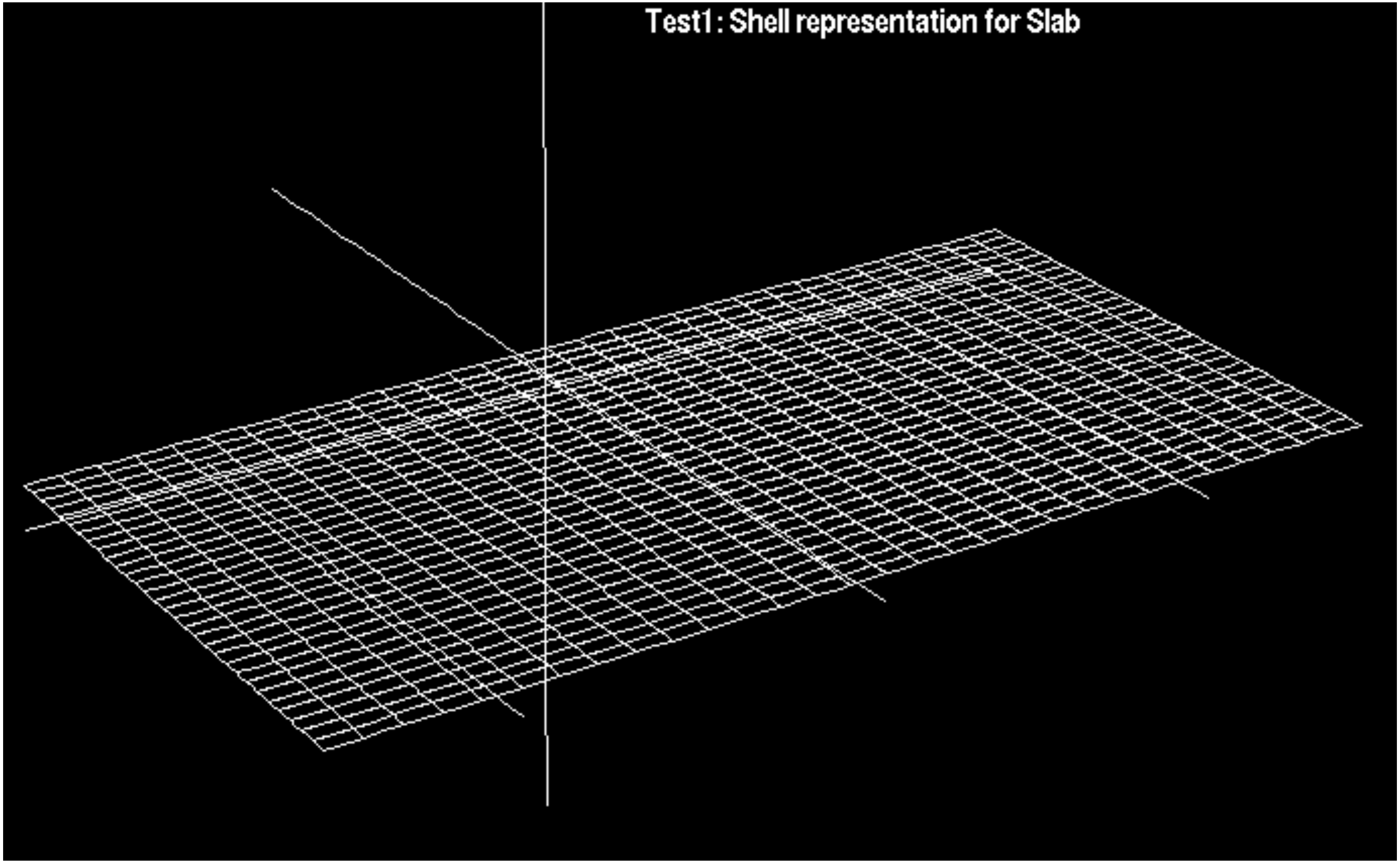




Download report from:
www.mace.manchester.ac.uk/project/research/structures/strucfire/DataBase/References/MultistoreySteelFramedBuildings.pdf

Restrained beam test (columns protected)

FE model of restrained beam test

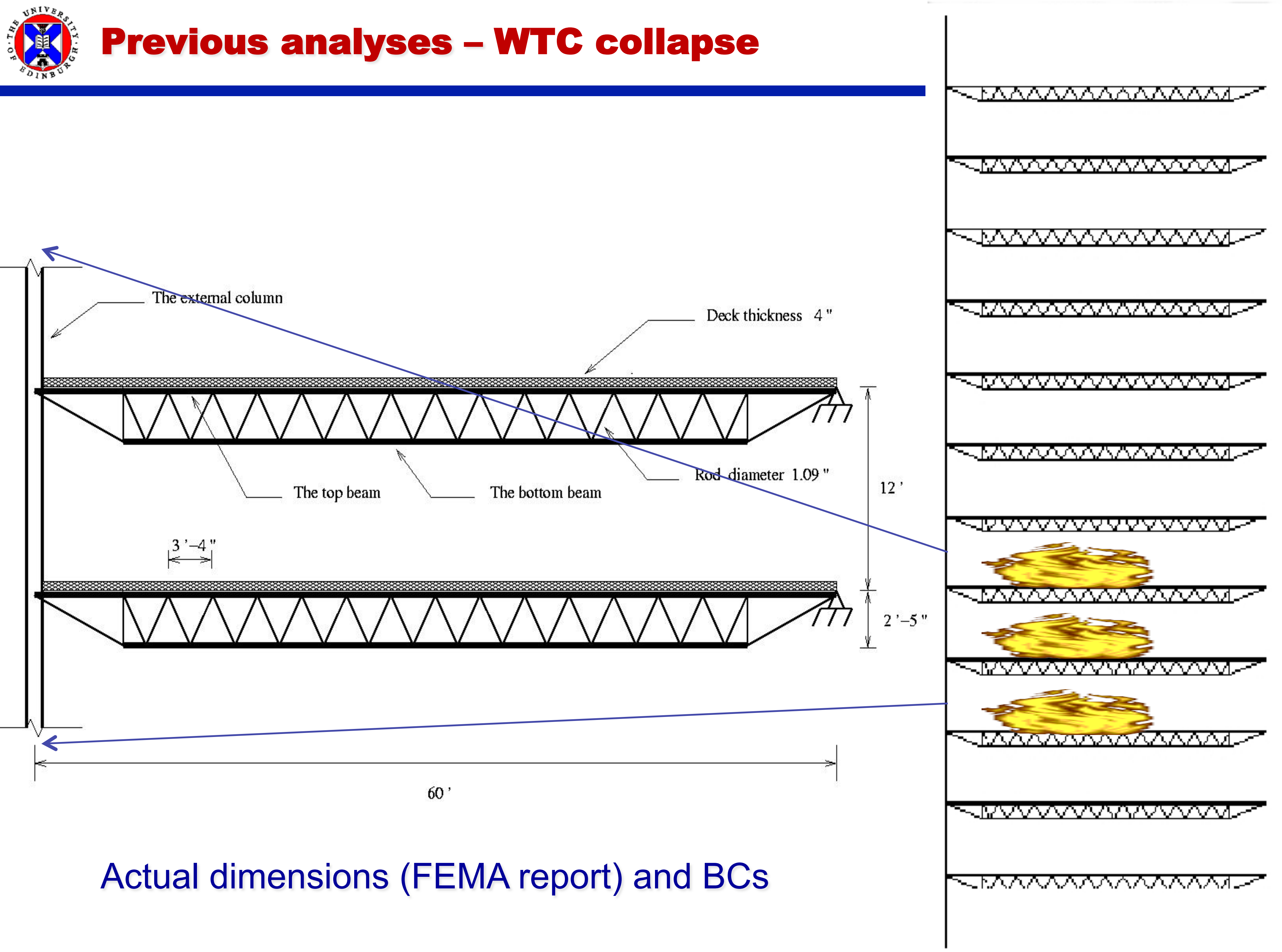


The WTC Collapses

It can be argued that a key factor in the collapse was the post-impact fire, as both buildings had remained stable after impact

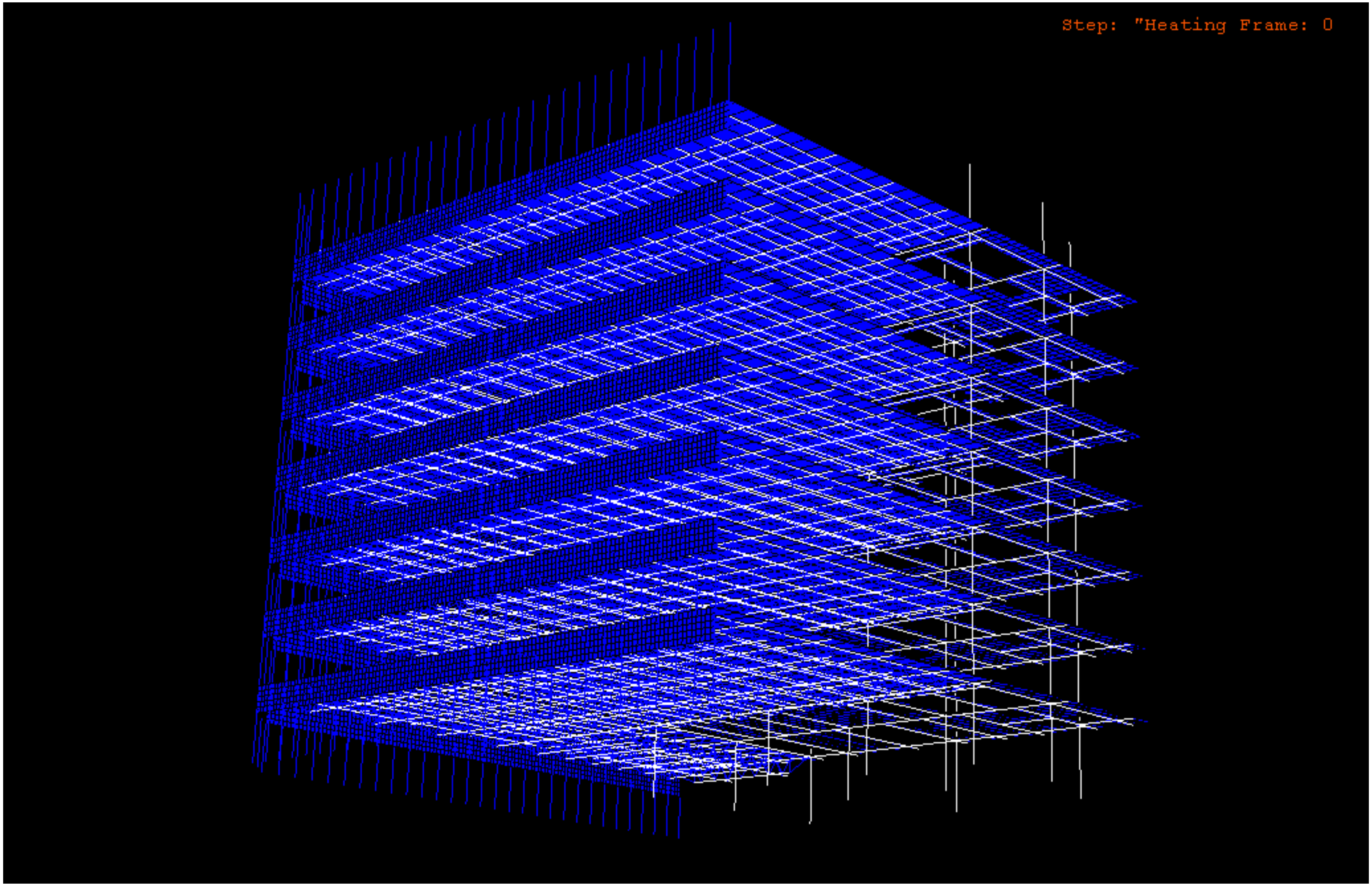
University of Edinburgh team studied the effect of multiple floor fires (ignoring impact damage) on the structure of the towers (before NIST investigation was completed) and highlighted many of the issues picked up by NIST

Previous analyses – WTC collapse



Actual dimensions (FEMA report) and BCs

3D Multi-storey model – 3 Floor Fire, 800^{o}C



Key references on whole structure modelling:

A structural analysis of the first Cardington test,
Journal of Constructional Steel Research, 57(6):581–601, 2001

A structural analysis of the Cardington British Steel Corner Test,
Journal of Constructional Steel Research, 58(4):427–442, 2002

How did the WTC Towers Collapse? A New Theory,
Fire Safety Journal, 38:501–533, 2003

Effect of Fire on Composite Long span Truss Floor Systems,
Journal of Constructional Steel Research, 62:303–315, 2006

Behaviour of small composite steel frame structures with protected and unprotected edge beams,
Journal of Constructional Steel Research, 63:1138–1150, 2007

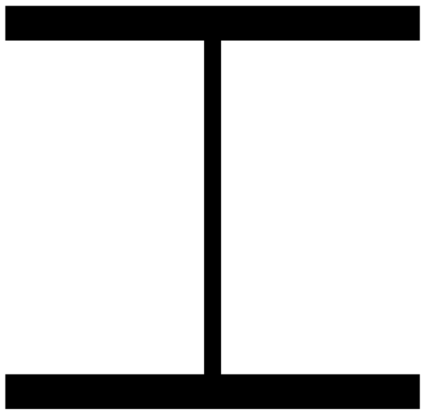
Structural response of tall buildings to multiple floor fires,
Journal of Structural Engineering, ASCE, 133(12):1719–1732, 2007

A very simple method for assessing tall building safety in major fires,
International Journal of Steel Structures, 9:17–28, 2009

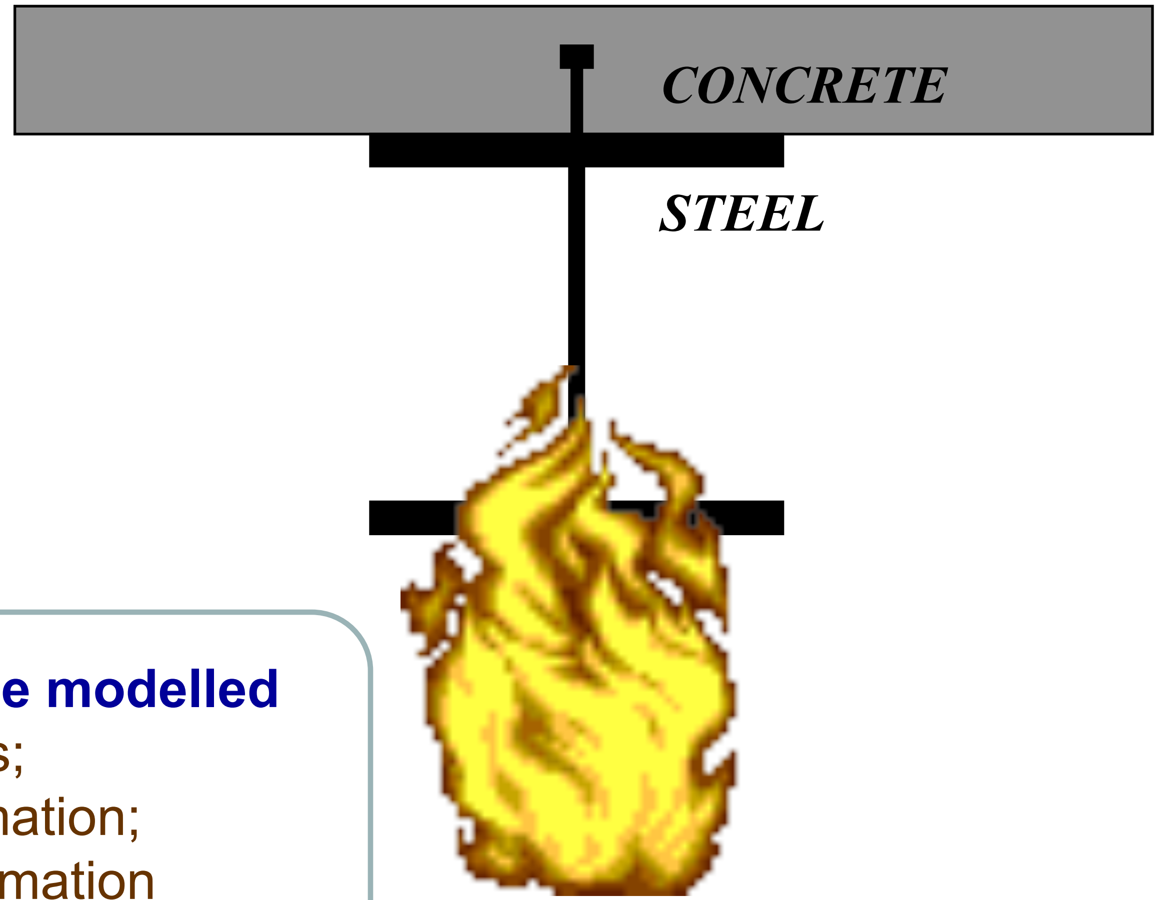
Tall building collapse mechanisms initiated by fire: Mechanisms and design methodology,
Engineering Structures, 36:90–103, 2012

Behaviour of structural members at elevated temperature

Isolated single structural member with simple boundary conditions (such as in a furnace)



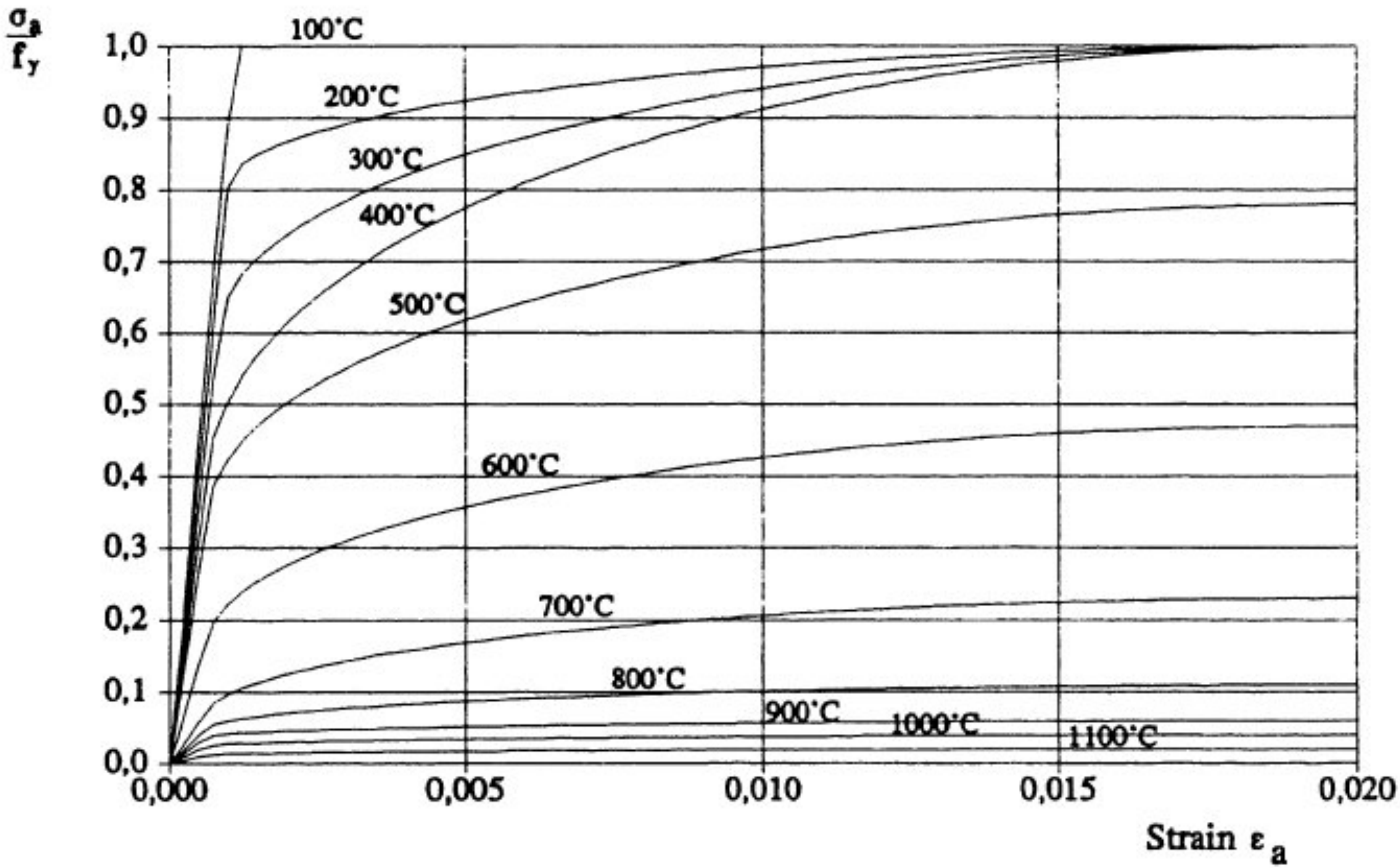
composite structural members with finite restraints against rotation/translation at boundaries



Three key effects must be modelled

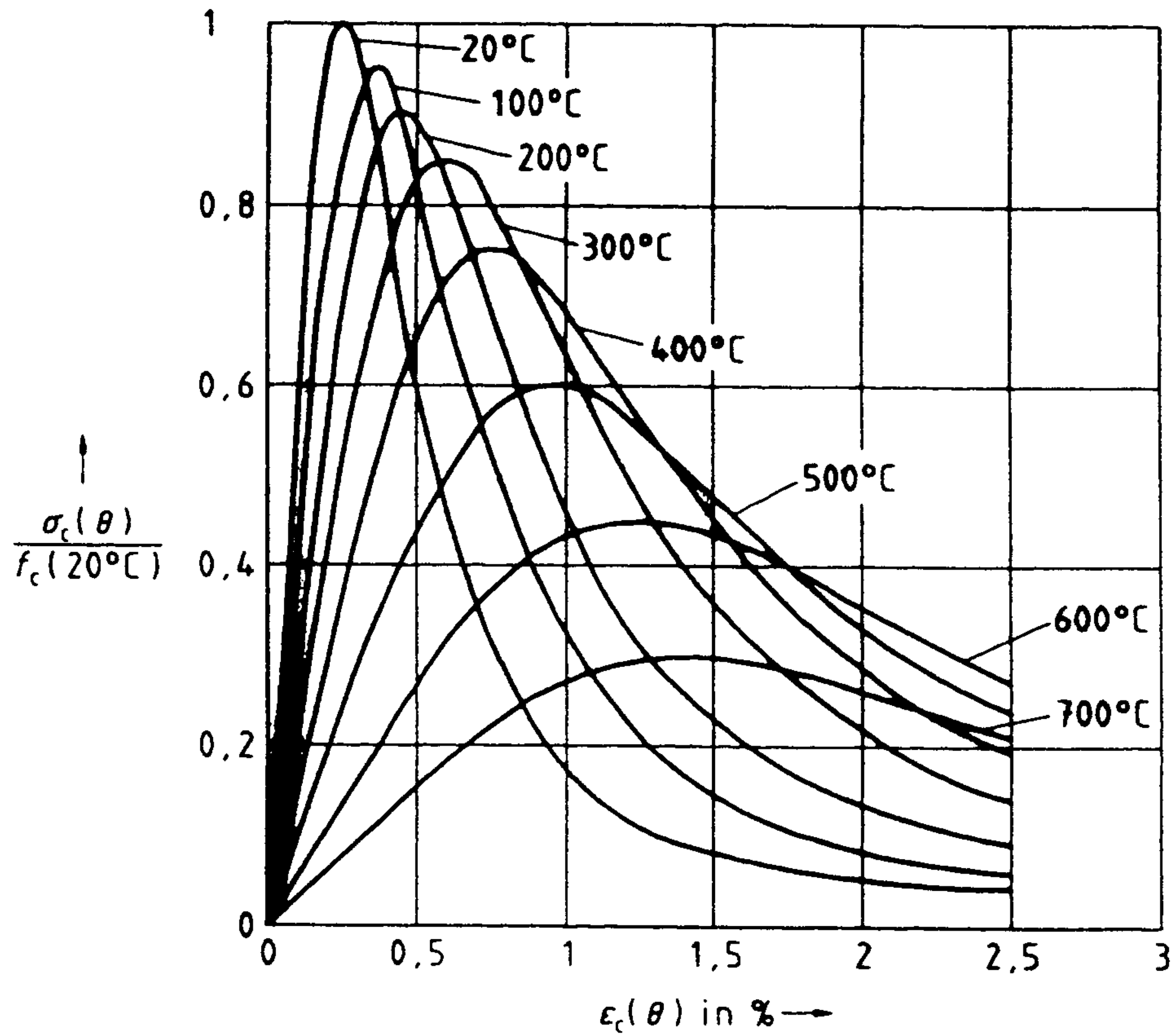
- Material property changes;
- Thermally induced deformation;
- Restraint to thermal deformation

Material property changes in structural steel



Source: ENV 1993-1-2:1995
(S235 steel)

Siliceous concrete stress-strain behaviour

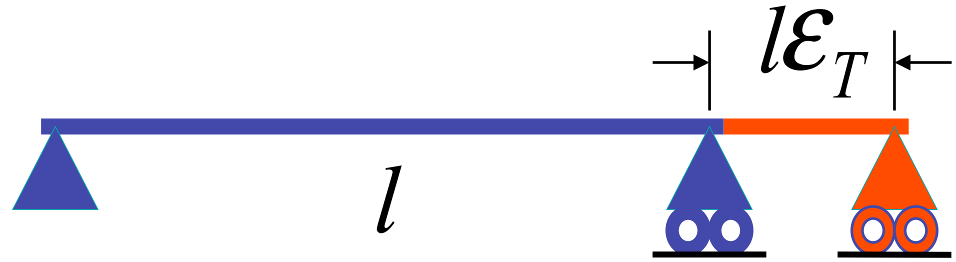


Source: ENV 1992-1-2:1995

Thermally induced deformation

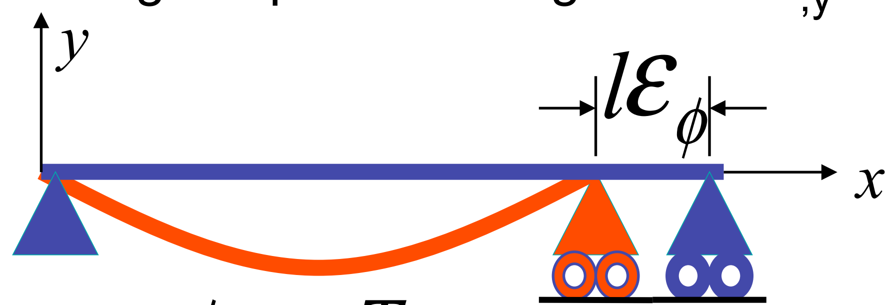
Thermal expansion induced by mean temperature increment DT

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



Thermal curvature f induced by through depth thermal gradient T$_{,y}$

$$\varepsilon_\phi = 1 - \frac{\sin {}^{l\phi}\!/_{2}}{{}^{l\phi}\!/_{2}}$$



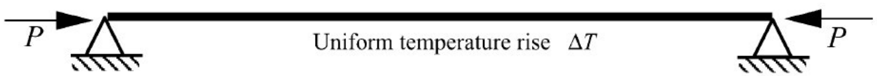
$$\phi = \alpha T_{,y}$$

Combination of the two effects leads to large deflections and often very low stresses (internal forces)

$$\varepsilon_T + \varepsilon_\phi$$

Restraint to thermal deformations

Thermal expansion with ends restrained against translation



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

$$\varepsilon_T = -\varepsilon_m$$

$$P = EA\varepsilon_m = -EA\varepsilon_T = -EA\alpha\Delta_T$$

Stocky beam (Yielding):

The *yield temperature increment* ΔT_y is,

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

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*

Thermal bowing with ends restrained against rotation

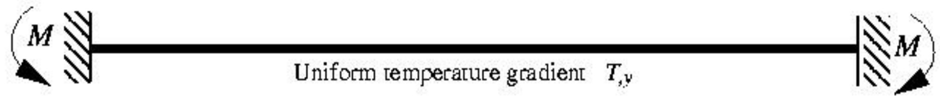


Figure 13: Fixed end beam subjected to a uniform thermal gradient

Uniform moment over the length,

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

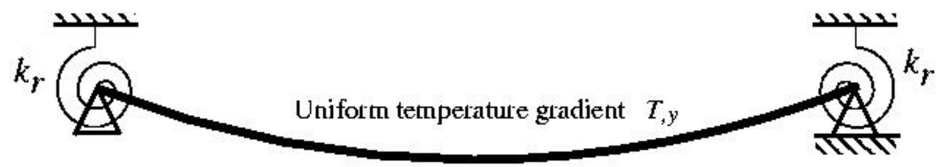


Figure 14: Beam with finite rotational restraint with a uniform thermal gradient

Restraining moment in the rotational springs

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

Key references on structural behaviour in fire:

Fundamental principles of structural behaviour under thermal effects
Fire Safety Journal, 36:721–744, 2001

Assessment of the fire resistance test with respect to beams in real structures
Engineering Journal, American Institute of Steel Construction, Inc., 40(2):63-75, 2003

Key events in the structural response of a composite steel frame structure in fire
Fire and Materials, 28:281–297, 2004

Behaviour of a small composite steel frame structure in 'long-cool' and 'short-hot' fires,
Fire Safety Journal, 39:327–357, 2004

Understanding the Response of Composite Structures to Fire
Engineering Journal, American Institute of Steel Construction, Inc., 42(2):83-98, 2005

A New Design Method to Determine the Membrane Capacity of Laterally Restrained Composite Floor Slabs in Fire, Part 1: Theory and Method, *The Structural Engineer*, 83(19):28–33, 2005

A New Design Method to Determine the Membrane Capacity of Laterally Restrained Composite Floor Slabs in Fire, Part 1: Validation, *The Structural Engineer*, 83(19):34–39, 2005

RC Test frame and test rig for simulated seismic damage

Fire Test setup

Flashover

RC Frame after fire

Why Opensees

- Structural response to real fires (e.g. localised or moving) is very tedious using commercial packages

- OpenSees offers possibility of linkage with Open CFD packages to model the whole problem

- Multi-hazard modelling (such as fire following earthquake)

- Developing an international community of researchers and collaborators around common computational tools

- Software robustness, longevity and sustainability

Material classes:

Steel01Thermal, Steel02Thermal, Concrete02Thermal

Section class: FiberSection2dThermal

Element class: DispBeamColumn2dThermal

Load class: Beam2dThermalAction

LoadPattern class: FireLoadPattern

OpenSees work-- material classes

❑ Steel01Thermal

- Based on Steel01, with temperature dependent properties defined (Strucutral steel, EN1993-1-2:2005)
- Tcl command:

```
uniaxialMaterial Steel01Thermal $matTag $Fy $E0 $b <$a1 $a1 $a1 $a1>
```

❑ Steel02Thermal

- Based on Steel02, with temperature dependent properties defined (Structural steel, EN1993-1-2:2005)
- Tcl command:

```
uniaxialMaterial Steel02Thermal $matTag $Fy $E0 $b $R0 $cR1 $cR2 <
$a1 $a1 $a1 $a1>
```

❑ Concrete02Thermal

- Based on Concrete02, with temperature dependent properties defined (Concrete, EN1992-1-2:2004)
- Tcl command:

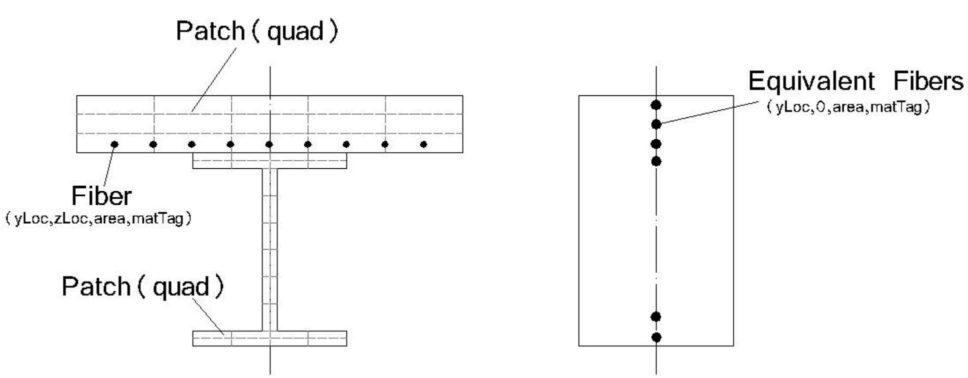
```
uniaxialMaterial Concrete02Thermal $matTag $fpc $epsc0 $fpcu $epsU
$lambda $ft $Ets
```

OpenSees work--New section class

❑ FiberSection2dThermal

- Based on FiberSection2d;
- Functions defined for considering thermal stresses;
- Interfaces to load class(Beam2dThermalAction);
- Transferring temperature data to material models;
- Tcl command:

```
section FiberThermal $secTag {
    fiber $yLoc $zLoc $A $matTag
                         …
   <patch  quad $matTag $numSubdivIJ $numSubdivJK $yI  $zI $yJ $Zj $yK $zK $yL $zL>
   <patch circ $matTag $numSubdivCirc $numSubdivRad $yCenter $zCenter…>
                        …
  <layer straight $matTag $numBars $areaBar $yStart  $zStart $yEnd $zEnd>
}
```



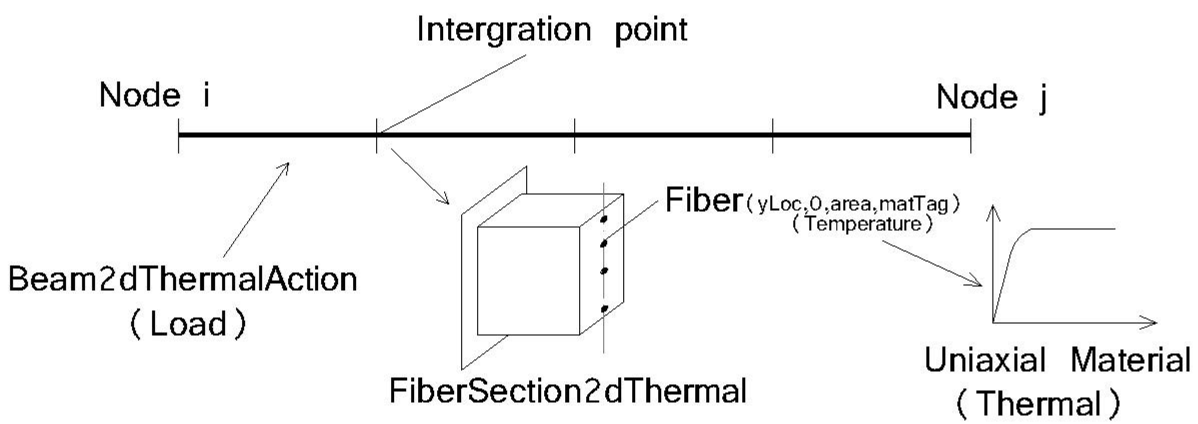
❖ FiberSection**2d**Thermal

OpenSees work--New element class

❑ DispBeamColumn2dThermal

- Based on DispBeamColumn2d;
- Considering thermal stresses in resisting forces;
- Interfaces to load class(Beam2dThermalAction);
- Transferring temperature data to FiberSection2d;
- Tcl command:

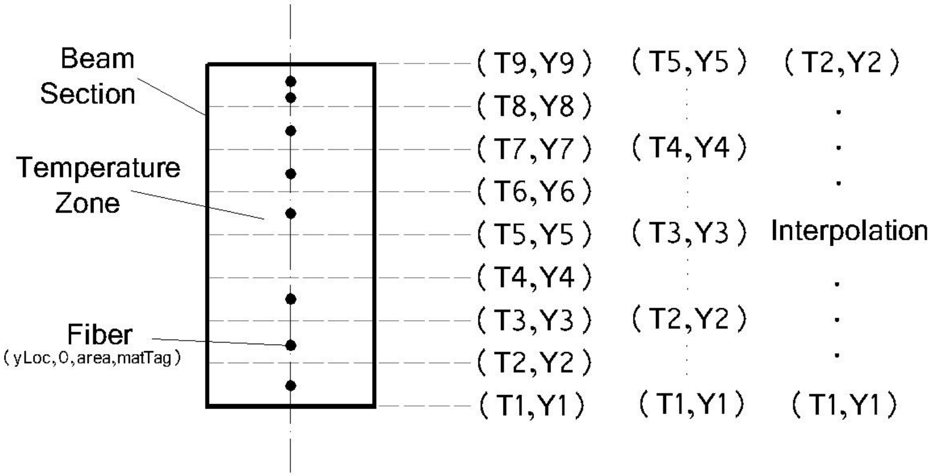
```
element dispBeamColumnThermal $eleTag $iNode $jNode
    $numIntgrPts $secTag $transfTag <-mass $massDens>
```



OpenSees work--New load class

- **Beam2dThermalAction**
- Co-working with load pattern (Plain pattern, FireLoadPattern);
- Providing 9 data points (y-coordinate, T, LoadFactor) across beam section
- 2,5,9 data-point input
- Tcl command:

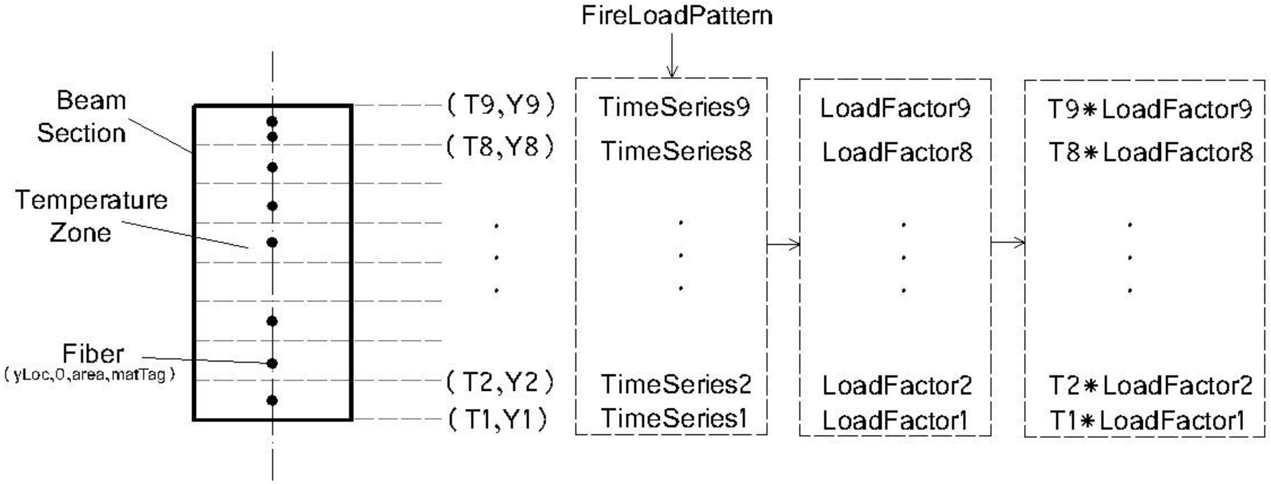
```
eleLoad -ele $eleTag -type -beamThermal $T1 $Y1 $T2 $Y2

eleLoad -ele $eleTag -type -beamThermal $T1 $Y1 $T2 $Y2 $T3 $Y3 $T4
$Y4 $T5 $Y5

eleLoad -ele $eleTag -type -beamThermal $T1 $Y1 $T2 $Y2 $T3 $Y3 $T4
$Y4 $T5 $Y5 $T6 $Y6 $T7 $Y7 $T8 $Y8 $T9 $Y9
```



OpenSees work--New LoadPattern class

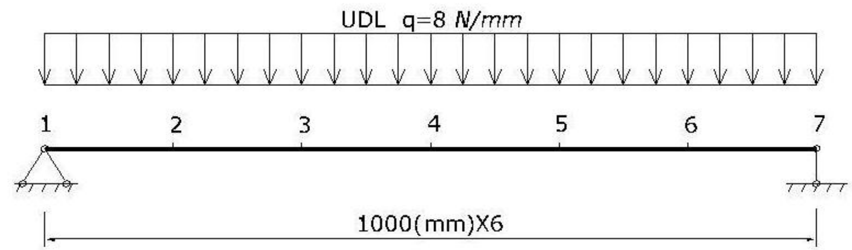
- **FireLoadPattern**
- Co-working with TimeSeries definition;
- Generating a load factor vector ;
- Interface to Beam2dThermalAction;
- Tcl command:

```
pattern Fire $PatternTag $Path $Path $Path $Path $Path $Path $Path $Path $Path {

eleLoad -ele $eleTag -type -beamThermal $T1 $Y1 $T2 $Y2 < $T3 $Y3… $T9 $Y9>
…
eleLoad -ele $eleTag -type -beamThermal $T1 $Y1 $T2 $Y2 < $T3 $Y3… $T9 $Y9>
}
```



Examples-Simply supported beam

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



❖ Element definition

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

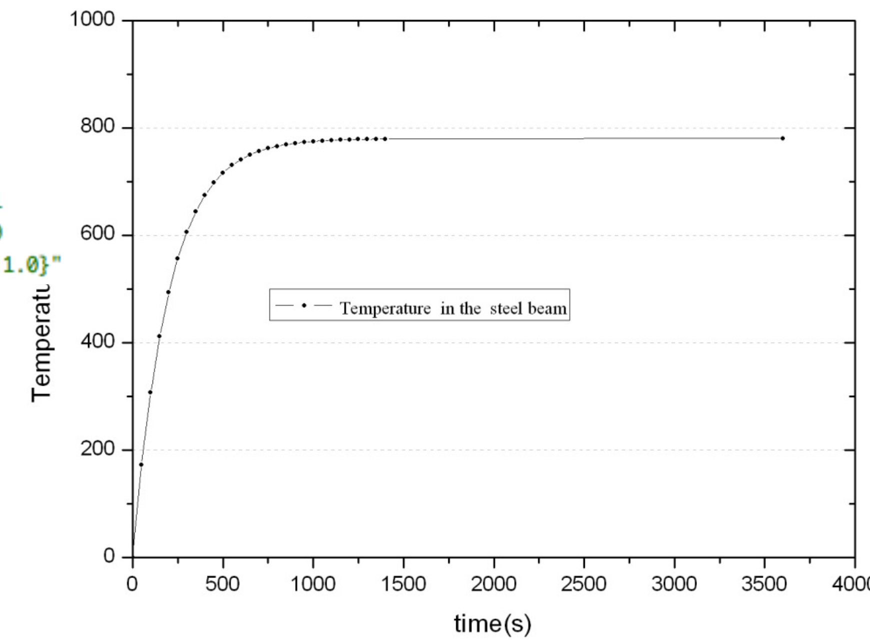
❖ Path series definition for FireLoadPattern

```
set Path "Series -time {0.0 50 100 150 200 250 300 350 400 450 500 550 600
    650 700 750 800 850 900 950 1000 1050 1100 1150 1200 1250 1300 1350
    1400 3600} -values {0.0 0.221199217 0.39346934 0.527633447 0.632120559
    0.713495203 0.77686984 0.826226057 0.864664717 0.894600775 0.917915001
    0.936072139 0.950212932 0.961225792 0.969802617 0.976482254 0.981684361
    0.985735766 0.988891003 0.991348305 0.993262053 0.994752482 0.995913229
    0.996817219 0.997521248 0.998069546 0.998496561 0.99882912 0.999088118 1.0}"
```

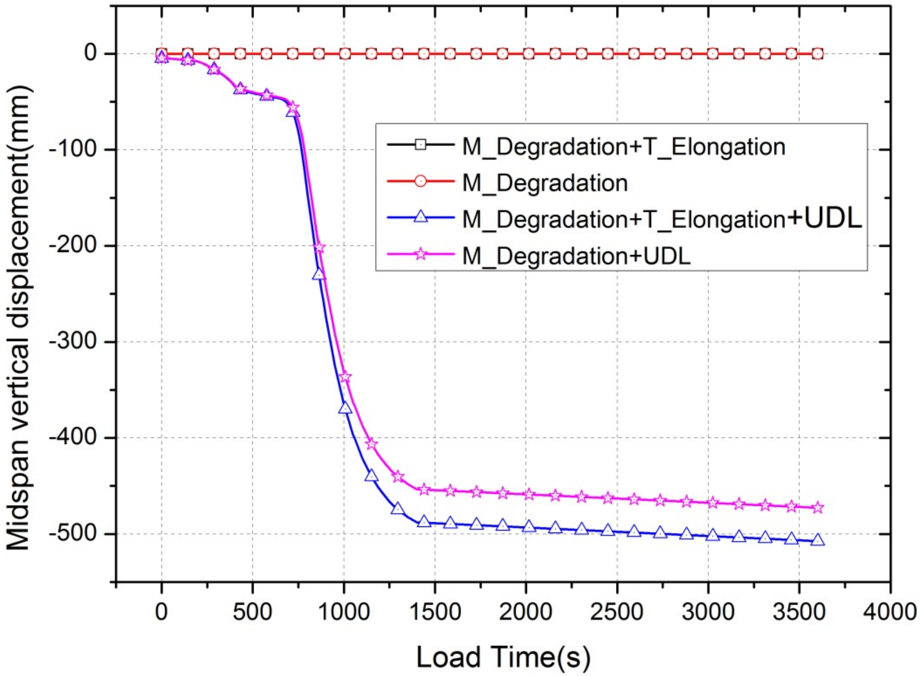
❖ Defining Beam2dThermalAction within FireLoadPattern

```
    pattern Fire 2 $Path $Path $Path $Path $Path $Path $Path $Path $Path {
    set Tbeam 780; #max temperature
    set Lbeam 177.5

    for {set level 1} {$level <= 6} {incr level 1} {
    set eleID $level
    eleLoad -ele $eleID -type -beamThermal $Tbeam -$Lbeam $Tbeam $Lbeam;
    }
    }
```

❖ Temperature-time curve defined by FireLoadPattern:



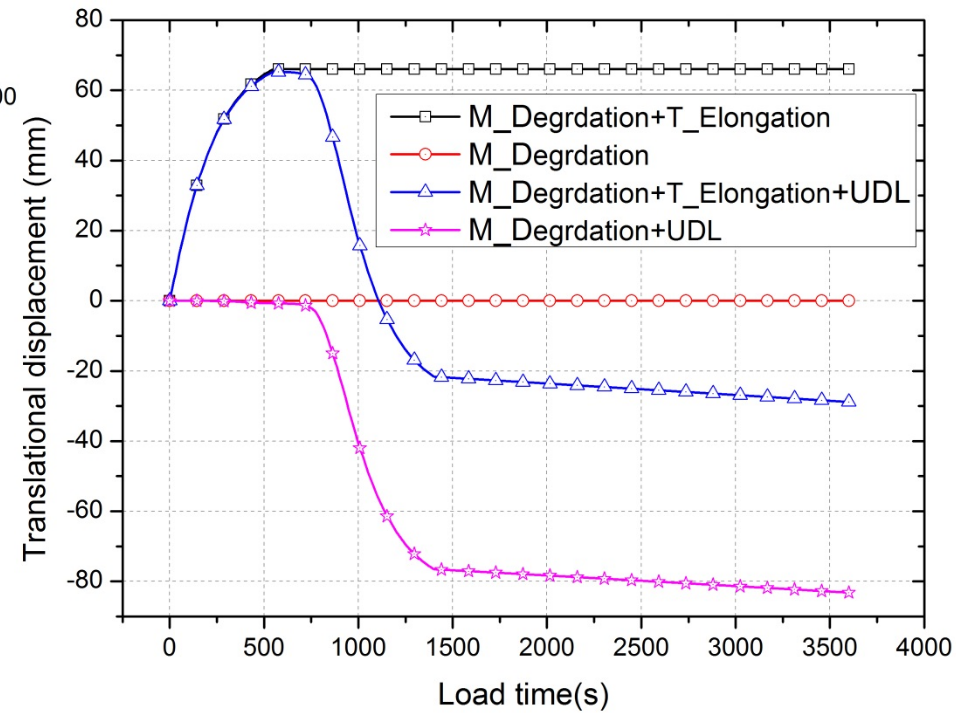
Examples-Simply supported beam



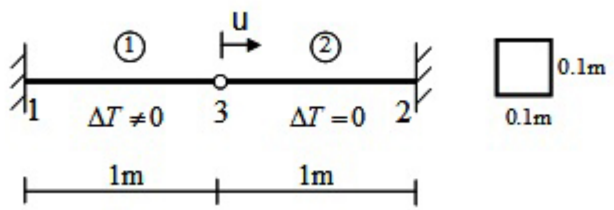
1) if without thermal elongation?
2) Or remove the UDL?

❖ Deformation shape (without UDL)

❖ Deformation shape (with UDL)



Examples-Restrained Beam under thermal expansion




```
fix 1 1 1 1;
fix 2 1 1 1;
fix 3 0 1 1;
```

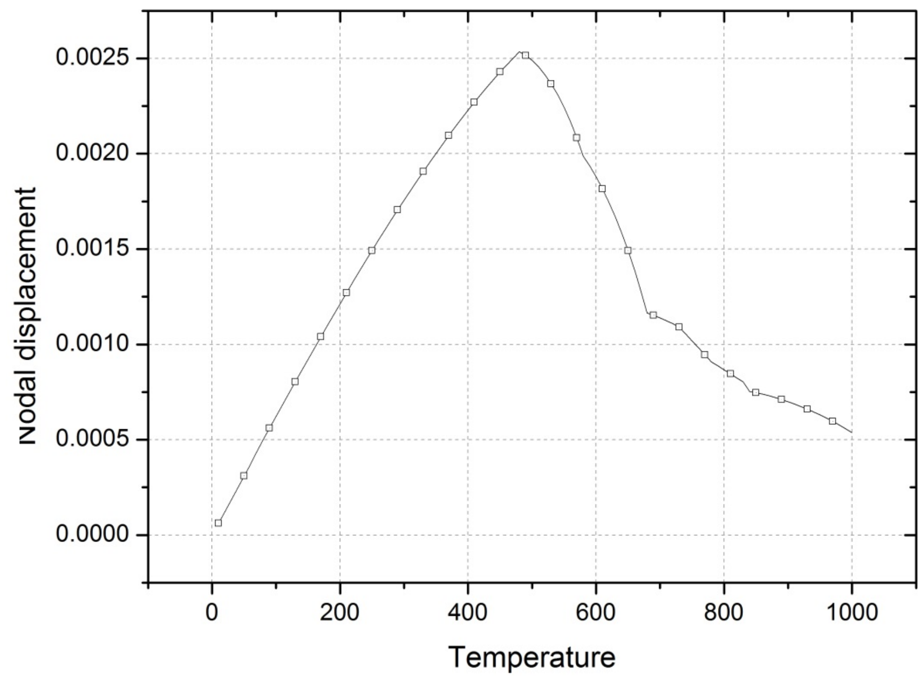
```
uniaxialMaterial Steel02Thermal 1 2e11 2e11 0.01;
```

```
    section FiberThermal $secTag {
     fiber -0.025 0 0.005 1;
     fiber 0.025 0 0.005 1;
     };
```

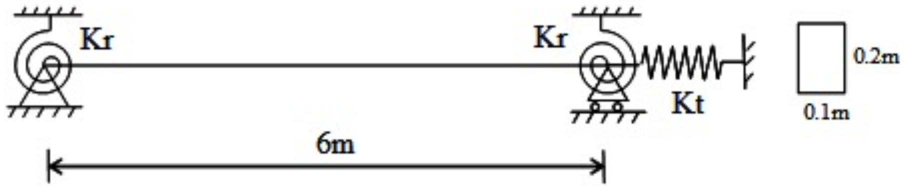
```
element dispBeamColumnThermal 1 1 3 3 1 1;
element dispBeamColumnThermal 2 3 2 3 1 1;
```

```
pattern Plain 1 Linear {
eleLoad -ele 1 -type -beamThermal 1000 -0.05 1000 0.05
eleLoad -ele 2 -type -beamThermal 0 -0.05 0 0.05
};
```

- An example demonstrating the effects of Thermal expansion, stiffness degradation (no strength loss), and restrained effects;
- 2D elements, Fixed ends;
- Element 1 with ΔT ≠0 , Node 2 has only one DOF;
- Nodal displacement output :



Examples-Beam under finite restraints

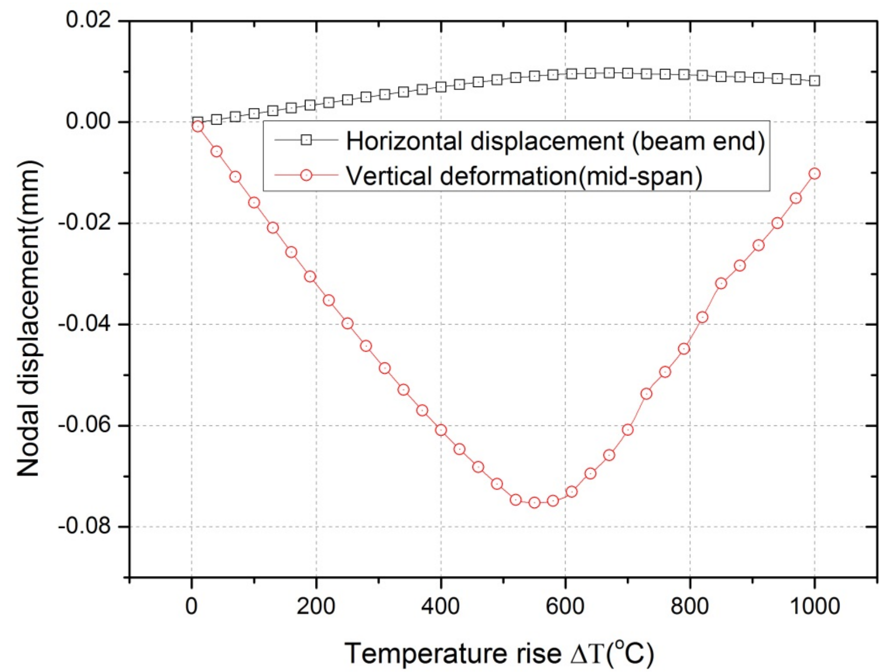


- A steel beam with finites restraints;
- Rotational and translational springs;
- Uniform temperature rise

```
# Single point constraints -- Boundary Conditions
fix 1 1 1 0;
fix 9 0 1 0;

fix 21 1 1 1;
fix 22 1 1 1;
```

```
uniaxialMaterial Elastic 2 3e6;             #translational spring
uniaxialMaterial Elastic 3 6.666666666667e8;# rotational spring
```

```
#define element for traslational&rotational spring
element zeroLength 121 1 21 -mat 2 -dir 6; #rotational spring
element zeroLength 922 9 22 -mat 2 -dir 6; #rotational spring
element zeroLength 933 9 22 -mat 3 -dir 1; #translational spring
```

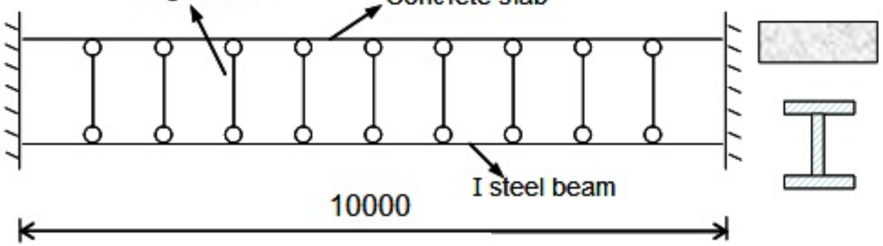


- ❖ Deformation shape at ΔT=400

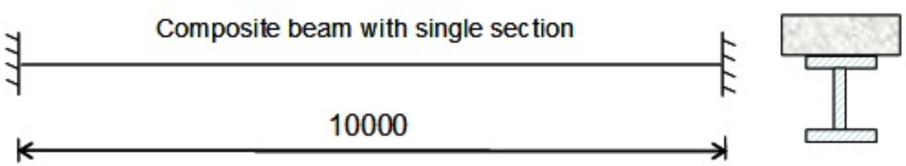
- ❖ Deformation shape at ΔT=1000

Examples-Composite Beam

- Composite beams simulated in two different ways:
  (a) steel I section beam + concrete slab (beam elements) + Rigid Links
  (b) Single section



(a)Model of composite beam connected by rigidLink



(b) Model of composite beam with single section

- Node definition and boundary conditions (a)

```
# define NODAL COORDINATES FOR BEAM
for {set level 1} {$level <=11} {incr level 1} {
    set X [expr ($level-1)*1000];
    set nodeID $level
    node $nodeID $X 0;      # actually define node
}

# define NODAL COORDINATES FOR SLAB
for {set level 101} {$level <=111} {incr level 1} {
    set X [expr ($level-101)*1000];
    set nodeID $level
    set loc 249.0
    node $nodeID $X $loc;       # actually define node
}

fix 1 1 1 1;
fix 101 1 1 1;
fix 11 1 1 1;
fix 111 1 1 1;
```

- Node definition and boundary conditions (b)

```
# define NODAL COORDINATES FOR composite beam
for {set level 1} {$level <=11} {incr level 1} {
    set X [expr ($level-1)*1000];
    set nodeID $level
    node $nodeID $X 0;      # actually define node
}

fix 1 1 1 1;
fix 11 1 1 1;
```

Examples-Composite Beam

- Rigid-Links (a)

```
#define RIGID LINKS
for {set level 2} {$level <=10} {incr level 1} {
    set masterNodeTag $level;
    set slaveNodeTag [expr $level+100]
    rigidLink $type $masterNodeTag $slaveNodeTag;
}
```

- Definition of sections for beam and slab (a)

```
#I steel beam section
section fiberSecThermal 1   {

    fiber -196.85 0 609.74 1;
    ...
    ...
    fiber 196.85 0 609.74 1;
    }

#Concrete section
#rectangular section 4000x100(width x height)
section fiberSecThermal 2   {
    fiber -43.75 0 50000 2;
    ...
    ...
    fiber 43.75 0 50000 2;
    layer straight 3 13 28.275 -25 -1950 -25 1950
    }
```

- Section definition (b)

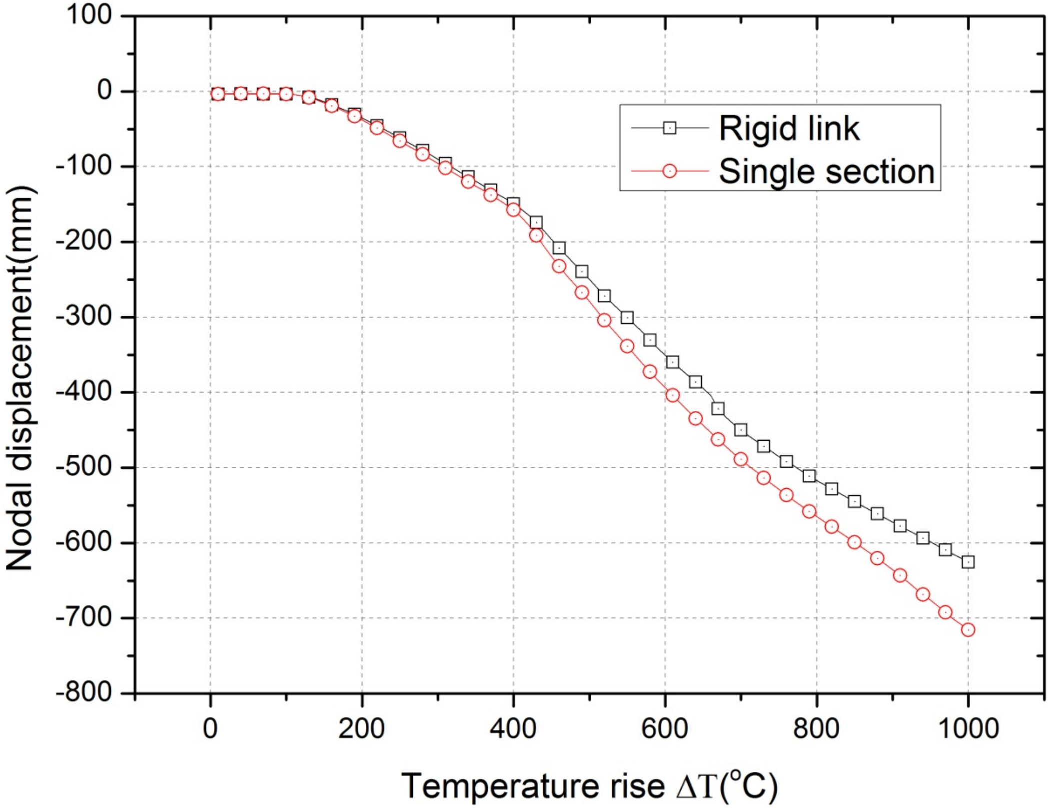
```
section fiberSecThermal 1   {
    #slab section
    fiber -43.75 0 50000 2;
    ...
    ...
    fiber 43.75 0 50000 2;
    layer straight 3 13 28.275 -25 -1950 -25 1950

    #I steel beam section
    fiber -52.15 0 609.74 1;
    ...
    ...
    fiber -445.85 0 609.74 1;
    }
```

Examples-Composite Beam

❑ Composite beams simulated with rigid link and single section

❖ Deformation shape (rigid links)

❖ Deformation shape (single section)



❖ Mid-span nodal displacement

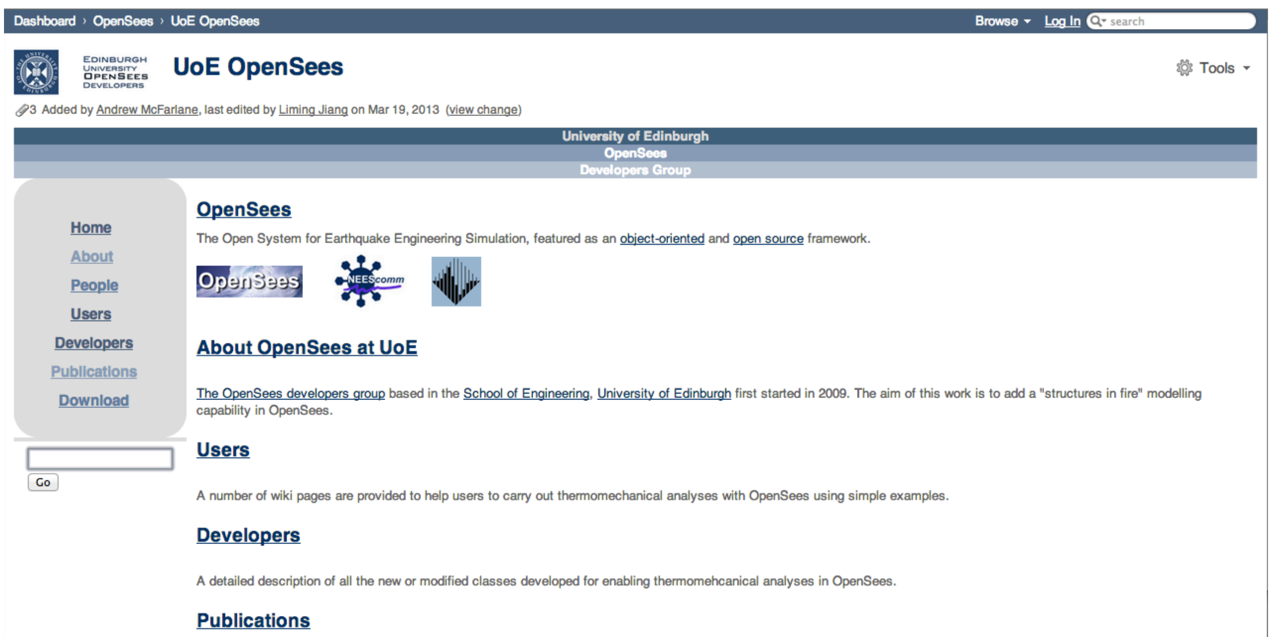
Planned work

- Next webinar?
  -- 2D frame modelling to collapse;
  -- 3D beam and shell frame models

- Heat Transfer analysis in OpenSees (completed but not yet available with Tcl)

- Coupled heat-transfer & thermo-mechanical analyses

- Our Wiki Pages
  -- Updates for bug-fixing, new elements, new materials, advanced examples)
  -- URL: https://www.wiki.ed.ac.uk/display/opensees



3D beam and shell elements

- **New elements**
  DispBeamColumn3dThermal, ShellMITC4Thermal

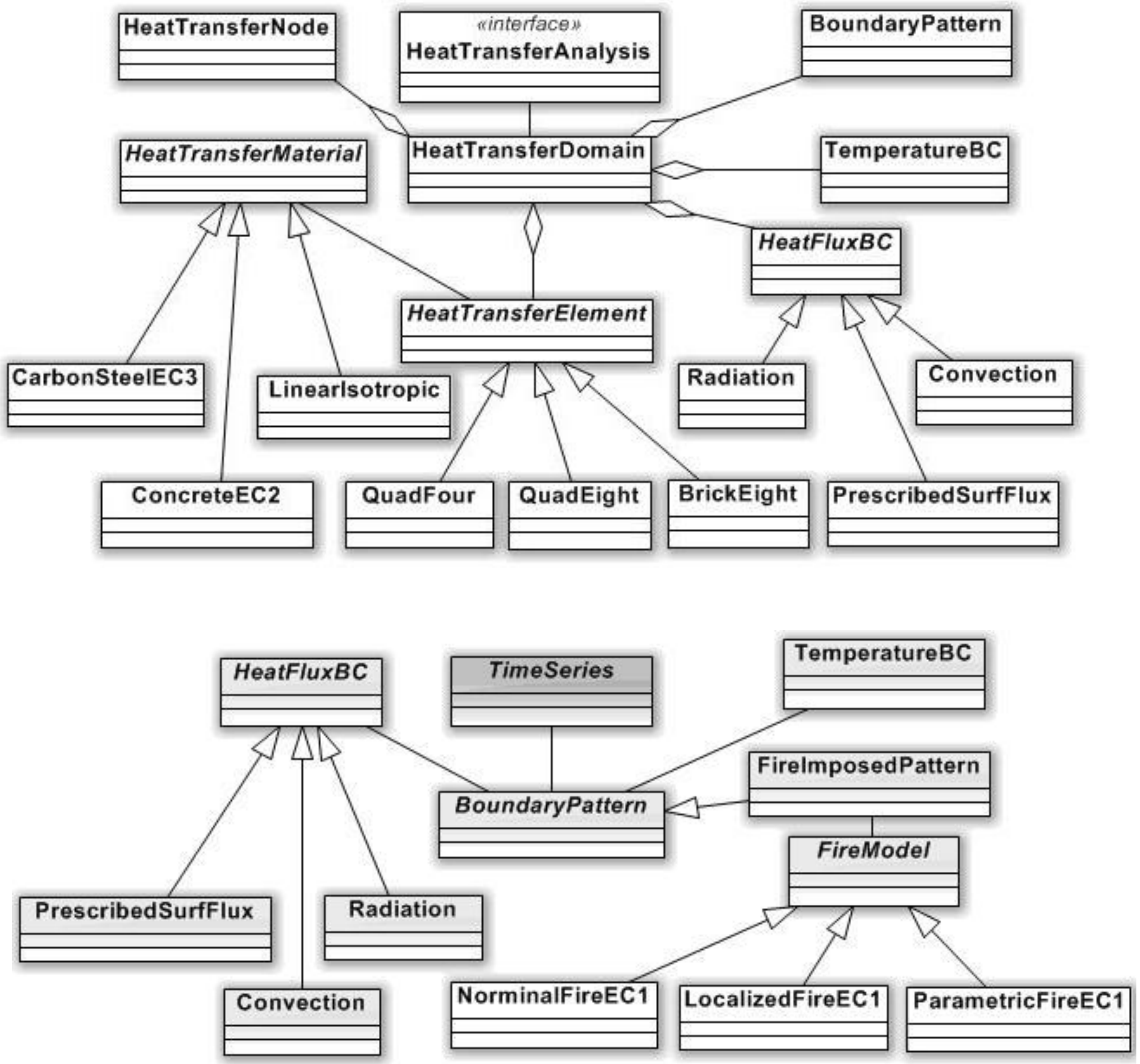
- **New sections working with 3D beam and shell elements**
  FiberSection3dThermal (Beam with No torsion),
  FiberSectionGJThermal (Beam considering torsion)
  MembranePlateFiberSectionThermal (Shell section)

- **New Materials working with 3D beam and shell elements**
  Druckerpragerthermal (nD material for shell section)
  ElasticIsotropic3DThermal (nD material for shell section)

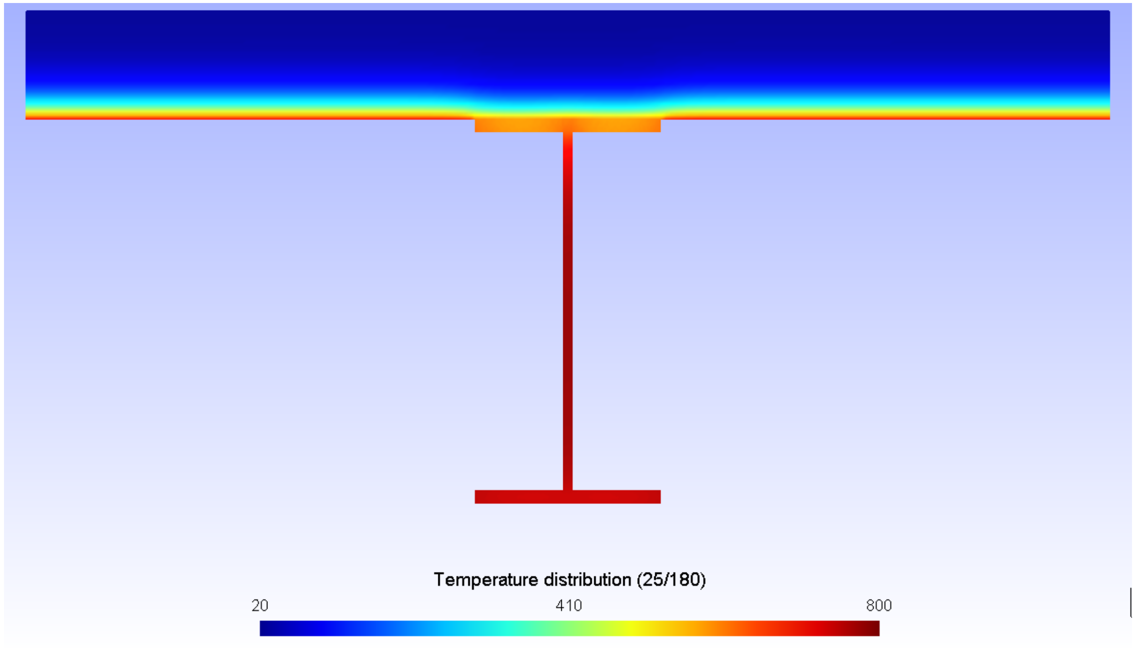
…

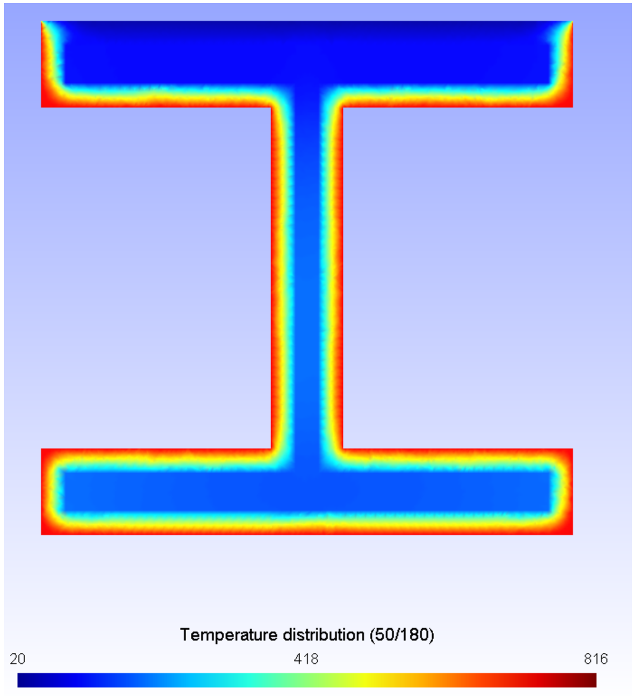
…

Heat Transfer analysis



Heat Transfer analysis





composite section exposed to heat flux from fire

heat transfer into fire protected column

Thank you