An integrated computational environment for simulating structures in real fires

Liming Jiang (Presenter) and Asif Usmani
School of Engineering, The University of Edinburgh, UK

With acknowledgements to (other previous and current PhD students): Jian Zhang, Yaqiang Jiang, Jian Jiang, Panagiotis Kotsovinos, Shaun Devaney, Ahmad Mejbas Al-Remal, & the IIT Roorkee and Indian Institute of Science teams, and China Scholarship Council!

& special acknowledgement to Frank McKenna at University of California, Berkeley for

OpenSees @ Bristol University
Introduction

Background | Review | Motivation
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
When does MODELLING become SIMULATION?
Is deterministic analysis satisfactory in this context?

The “spectrum” of modelling | multi-hazard
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
The “spectrum” of modelling | probabilistic-whole life

Life-cycle analysis

- **Perfomance**
  - 100%
  - Tolerance threshold for deterioration in performance
  - Extreme event
  - Repair
  - Maintenance

- **Time**
  - Initial design life
  - Normal deterioration (no repair or maintenance)
  - Material durability and cyclic load/deformation induced cumulative damage
  - Accelerated deterioration (no repair or maintenance)
  - Following a short duration extreme event, e.g. blast, fire, windstorm, earthquake

- **Likely scenarios in current practice**

- **Extended life & near 100% performance with regular repair/maintenance**
The “spectrum” of modelling

Model complexity

Computational cost (log scale)

Analytical

2D sub-frames

Ideal fires (unif.)

3D sub-frames

Non-uniform fires

3D sub-frames

Uncertainty

Real fires (CFD)

3D sub-frames

Uncertainty

Multi-hazard
Whole building
Uncertainty
Life-cycle analysis

CURRENT FOCUS
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

o Uniform temperature rise $\Delta T$;
o Unrestrained;
o Thermal expansion:

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

Thermal expansion coefficient of steel $\alpha \approx 1.2 \times 10^{-5}$

Thermally induced deformation | Thermal expansion

Uniform temperature rise $\Delta T$

$l$

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

$\varepsilon_{\text{mechanical}} = \varepsilon_{\text{III}} = 0$
1. Thermal gradient \((T_{y})\) over the depth,
\[
T_y = \frac{T_2 - T_1}{d}
\]

2. A uniform curvature \((\phi)\) is induced along the length,
\[
\phi = \alpha T_y
\]

3. Curvature reduces the distance between the ends. Interpreted as a contraction strain \(\varepsilon_{\phi}\) (analogous to the thermal expansion strain \(\varepsilon_T\) earlier),
\[
\varepsilon_{\phi} = 1 - \frac{\sin \frac{\phi}{2}}{\frac{\phi}{2}}
\]
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

\[ \Delta T_y = \frac{\sigma}{E \alpha} \]

Stocky beam (Yielding):

The yield temperature increment \( \Delta T_y \)

- Yield strength : 300 Mpa
- Elastic Modulus: 2e5 Mpa
- Thermal expansion coefficient: 1.2e-5
- Yield temperature increment : 125 oC

Slender beam (Buckling):

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

- \( r \) is the radius of gyration
- \( \lambda \) is the slenderness ratio \((l/l')\)
- \( l \) 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

Therefore different collapse mechanisms become possible.

**Concrete**

**Steel**

\[ \text{lower } \Delta T \]

\[ \text{higher } T_{z} \]

\[ \text{therefore more} \]

**Temperature**

\[ T(z) \]

**Higher**

\[ \text{lower } \Delta T \]

\[ \text{higher } T_{z} \]

\[ \text{therefore more compression} \]

**Therefore different collapse mechanisms become possible.**
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 long enough period.

Issues
1. How long should a structural member be protected for?

2. Cause (heating) and effect (reduced load capacity and displacements) works reasonably well for simple structures such as... but not for...
Why do we need an “integrated computational environment”? 

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
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 release in 2002, and continuing work is ongoing. A number of new features and adding 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 thermomechanical 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.
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
✓ 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 and thermo-mechanical analyses

- 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;

………
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
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 localised 1D Heat Transfer analyses.

Heat transfer analysis

- Localised heat flux
- 2D section with localised BC
- 1D section with localised BC
- $q$: convection + radiation
- $q$: heat flux input
• 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!
• 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
Thermo-mechanical analysis
Thermo-mechanical analysis

- Thermo-mechanical classes:
  - Heat Transfer
    - 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

Diagram:
- Node i to node j
- Integration point
- Beam2dThermalAction (Load)
- Fiber(yLoc,O,area,matTag) (Temperature)
- FiberSection2dThermal
- Uniaxial Material (Thermal)
Thermo-mechanical analysis

- Tcl commands for material, section, and elements

```tcl
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

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

- Using Linear Load pattern

```tcl
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>
  ...
}
```

- Using Fire Load pattern for further non-uniform profile

![Diagram of beam section with temperature zones and fiber interpolation](image)
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>;
  ...
}
```

**Time**  T1 (corresponding to y1) ..............................  T9 (corresponding to y9)

<table>
<thead>
<tr>
<th>Time</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
<th>T4</th>
<th>T5</th>
<th>T6</th>
<th>T7</th>
<th>T8</th>
<th>T9</th>
</tr>
</thead>
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<tr>
<td>60</td>
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<td>47.3834</td>
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<td>105.762</td>
<td>106.516</td>
<td>106.698</td>
<td>106.516</td>
<td>105.762</td>
<td>103.735</td>
<td>104.494</td>
</tr>
</tbody>
</table>

| ....  |             |             |             |             |             |             |             |             |             |

**BeamTA/element1.dat**
Thermo-mechanical analysis

- Tcl commands for defining beam thermal actions

- Non-uniform along beam length and depth

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

Apply Nodal thermal action

Source external temperature file

```tcl
load $nodeTag -nodalThermal -source $filePath $y1 $y2;
...
```
Thermo-mechanical analysis

- Tcl commands for defining beam thermal actions

  - ThermalAction for 3D I section beams

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

Upper Flange Temperature
T7,9,11,12,15

Lower Flange Temperature
T6,8,10,12,14

Web Temperature
T1,2,3,4,5
Examples  [Available@UoE Wiki]
Examples - Simply supported beam

- A simply supported steel beam;
- Uniform distribution load \( q = 8 \text{N/mm} \);
- Uniform temperature rise \( \Delta T \);
- Using FireLoadPattern

**Tcl script**

```tcl
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)

Material degradation

UDL applied

Beam end displacement

Graphs showing midspan vertical displacement and transnational displacement over load time.
Examples - Restrained Beam under thermal expansion

- 2D elements, Fixed ends;
- Element 1 with $\Delta T \neq 0$, 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
};
```

```
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
};
```

2D beam element 3D beam element
Examples - Restrained Beam under thermal expansion

- 2D elements, Fixed ends;
- Element 1 with $\Delta T \neq 0$, 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
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

LIMING JIANG AND ASIF USMANI
23 JUNE 2014