An integrated computational environment for simulating structures in real fires

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Key components of simulating structures in fire

1. Modelling fire and smoke

2. Modelling structural member temperature evolution

3. Modelling structural response to the point of collapse
Integrated computational environment for structures in fire

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

**Heat transfer**
- OpenSees, ABAQUS, ANSYS

**Heat transfer - thermomechanics middleware**

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

**Integrity failure**

**Structure – fire coupling**
Why do we need an “integrated computational environment”? 

Current widespread practice is “prescriptive” (standard fire + isolated member).

Architects are pushing boundaries with larger and taller buildings, internal partitions are disappearing, more unusual architectural shapes are being used, demand for sustainability is bringing in new materials (and hazards), built-environments are getting more complex and dense creating higher risk (consequences of disaster are increasing) => “alternative” or performance-based engineering (PBE) approaches are in order.

Even when PBE approaches are used in general, uniform compartment fires are assumed (a single compartment temperature at a given instant in time – no spatial variation). 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”.

How do we learn from our failures (aviation industry is a great example!).

Just like the seismic hazard and the structure interact in earthquake engineering (necessitating e.g. soil-structure interaction for improved fidelity of modelling with reality) – fire and the structure also interact!
Modern structural engineering defines “limit states”

Expressed quantitatively in terms of the fundamental parameters

Load: “maximum” load sustainable (ultimate limit state)

Displacement: “maximum” allowable displacement (serviceability limit state)

Clear and quantifiable link between cause (load) and effect (displacement)

Concept easily extended to general structural frames and extreme loadings,

inter-storey drift in an earthquake
Performance in the context of struct. fire resistance

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

Solution
Protect all steel for a 1h

Issues with this approach:
1. How long should a structural member be protected for?
2. Cause (heating) and (and displacements) will be simple determinate but not for large redundant structures

But time on a standard fire curve has no physical meaning!
Responses of real structures depend upon the fire

Eurocode model of “natural fires” (valid for < 500 m² & < 4m ceiling height)

Short hot fire

Long cool fire

Behaviour of a small composite steel frame structure in ‘long-cool’ and ‘short-hot’ fires,
e.g. 2x2 generic frame (columns & edge beams protected)
Deflections - 2x2 generic frame

max. defl. = 365 mm @ 23 mins
max. steel temp. = 950 °C

Short hot fire

OF=0.08

max. defl. = 310 mm @ 78 mins
max. steel temp. = 750 °C

Long cool fire

OF=0.02
Different fires produce different structural responses.
Fires in large compartments

Fire tends to travel in large spaces

Source: NIST NCSTAR 1-5

Figure 6–29. Direction of simulated fire movement on floors 94 and 97 of WTC 1.
Permutations are potentially endless! an “integrated computational environment” is required to deal with them

Also, we cannot properly address this issue in a deterministic framework (earthquake engineers realised this long ago!)

However,

there are no tools available to easily implement “proper” Performance Based Structural Engineering for Fire Resistance

Our aim is to develop a prototype of such a tool based on the OpenSees framework
Two sub-structure models
Fire scenarios

- short-hot (parametric) fire
- long-cool (parametric) fire
Results from Model 1

- **470mm max deflection**
- **380mm max deflection**

All beams protected

Only secondary beams unprotected
Unprotected 10m panel (Model 2)
Protected 10m panel (Model 2)
Final Proposal (accepted)

Saving of £250K on Plantation Place
Engineers learn from failures

Ronan Point, UK (May, 1968)  I35W Bridge, Minneapolis, USA (Aug, 2007)

“disproportionate” and/or “progressive collapse” => “robustness requirements”
Why some structures collapse and others don’t in large fires?

Have we learnt anything?

If so, what has changed?
Concrete structures do fail in fire!

Gretzenbach, Switzerland (Nov, 2004)

Delft University Architecture
Faculty Building, May 2008

Concrete structures do fail in fire!
Gretzenbach, Switzerland (Nov, 2004)
How can we learn from failures?

Modelling and Simulation
The “spectrum” of modelling (analytical solutions)

\[ \delta_z = \delta_{\text{circ}}(\epsilon_\phi) \approx \delta_{\sin}(\epsilon_\phi) \]
\[ \delta_x = (\epsilon_T - \epsilon_\phi)l \]

\[ P = EA(\epsilon_T - \epsilon_\phi) \]
\[ M = EI\phi \]

Deflections assuming \( \epsilon_T > \epsilon_\phi \)

**Pre-buckling deflections**

\[ \delta_z = \delta_{\text{circ}}(\epsilon_\phi) + \frac{C\delta_{\text{circ}}(\epsilon_\phi)}{1 - C} \]

where, \( C = \frac{0.3183l^2A}{\pi I}(\epsilon_T - \epsilon_\phi) \)

from thermal bowing
from P-\( \delta \) moments

**Post-buckling deflections**

add to \( \delta_z \) above a \( \delta_{\sin}(\epsilon_p) \) calculation

where, \( \epsilon_p = \epsilon_T - \epsilon_\phi - \frac{\pi^2}{\lambda^2} \)
The “spectrum” of modelling (computational)
The “spectrum” of modelling (multi-hazard)

Is deterministic analysis satisfactory in this context?
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

- 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
- Extended life & near 100% performance with regular repair/maintenance

Likely scenarios in current practice

Tolerance threshold for deterioration in performance
The “spectrum” of modelling

Model complexity

Analytical

Ideal fires (unif.)
2D sub-frames

Non-uniform fires
3D sub-frames
Uncertainty

Real fires (CFD)
3D sub-frames
Uncertainty

Multi-hazard/multi-scale
Whole building
Uncertainty
Life-cycle analysis

CURRENT FOCUS

Computational cost (log scale)
Previous modelling work reproduced using OpenSees
Cardington frame

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
Modelling of Cardington tests using OpenSees

Restrained beam test

Corner test

Temperature of the joist lower flange at mid span (°C)

Midspan deflection of joist (mm)
WTC Towers Collapse models (3 Floor Fire – no damage)
WTC Towers Collapse models (3 Floor Fire – no damage)
3D model: Truss deformations
Collapse mechanism from 3D model
WTC2: East Face

Time: 9:21:29 AM
~18 minutes post impact

Maximum inward bowing of columns approximately 10 inches

© 2001, Allen Murabayashi

Photograph from NIST report
Inward Bowing of Perimeter Columns About 2 Minutes Prior to Collapse: WTC 2 East Face

9:58:56 a.m.

©2001. New York City Police Department. All rights reserved.
Are there generic collapse mechanisms?

(a) Stiff column weak floor mechanism

(b) Stiff floor weak column mechanism
Model to test generic mechanisms

<table>
<thead>
<tr>
<th></th>
<th>Universal Beam</th>
<th>Universal Column</th>
<th>Beam udl (N/mm)</th>
<th>Column load (N)</th>
<th>Floor span</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong beam</td>
<td>533x210x92</td>
<td>305x305x198</td>
<td>45</td>
<td>6000</td>
<td>10</td>
</tr>
<tr>
<td>Weak beam</td>
<td>305x102x28</td>
<td>305x305x198</td>
<td>45</td>
<td>6000</td>
<td>10</td>
</tr>
</tbody>
</table>

![Diagram showing the floor span and load distribution](image)
Model results

Weak floor mechanism

Strong floor mechanism
OpenSees models

2D model of WTC collapse
Current status of the work on the “Integrated Computational Environment for Structures in Fire”
Integrated computational environment for structures in fire

**Fire models**
- Standard
- Natural/parametric (short hot/long cool)
- Localised
- Travelling

**OpenSees**

**Heat transfer**
- OpenSees, ABAQUS, ANSYS

**Heat transfer - thermomechanics middleware**

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

Eventually all to be packaged within a "wrapper" software capable of carrying out PBE and probabilistic analyses currently.

Matlab

later

OpenSees

structure – fire coupling

Integrity failure

Open source and freely downloadable from UoE and later main OpenSees site at PEER/UC Berkeley
UoE OpenSees Wiki site

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

Pages
UoE OpenSees

- Command manual
- Demonstration examples
- Downloading executable application
- Browsing source code
Scheme for Modelling Structure in fire

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

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

- **Heat Transfer**
  - Heat transfer to the structural members due to fire action

- **Thermo-mechanical**
  - Structural response to the elevated temperatures
SiF Builder

- 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
Why is this needed?

Example showing complexities (currently ignored in practice!) of modelling even a simple real structure.

- Heat flux distribution from a localised Fire (at a single instant)
- Typical beam X-sections
- Typical column X-sections
- Fire exposed surface
OpenSees heat transfer analysis of RC column X-section

Temperature distribution in the RC column after 1 hour of EC1 localised fire

Temperature distribution in the RC column after 2 hours of EC1 localised fire
OpenSees heat transfer analysis of RC beam-slab X-section

Temperature distribution in the RC beam after 1 hour of EC1 localised fire

Temperature distribution in the RC beam after 2 hours of EC1 localised fire
Idealised Fires

- Uniform (no spatial variation) fires
  - Standard fire: ISO fire curve
  - Hydrocarbon fire: EC1
  - Empirical Parametric fire: EC1 Parametric fire model

- Non-uniform (spatial and temporal variation) fires
  - Localised fire
  - Alpert ceiling jet model
  - Travelling fire
Heat Transfer modelling

- **Fire**
- **Heat Transfer**
- **Tcl interpreter**

- **Still under development**
- **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
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
**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.

**Strategy for efficient heat transfer modelling**
Composite beam
Length: 3m
Steel beam: UB 356 $\times$ 171 $\times$ 51
Concrete slab: 1.771 $\times$ 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:
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 modelling

- 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:

- Integration point
- Node i
- Node j
- Beam2dThermalAction (Load)
- FiberSection2dThermal
- Uniaxial Material (Thermal)
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:**
- Beam Section
- Temperature Zone
- Fiber
Thermo-mechanical analysis

♡ Tcl commands for defining beam thermal actions

- Importing external temperature history file

```tcl
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)

<table>
<thead>
<tr>
<th>Time</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>47.2327 46.4181 47.3834 47.5978 47.6355 47.5978 47.3834 46.4181 47.2327</td>
</tr>
<tr>
<td>120</td>
<td>75.5848 74.8791 76.5169 77.0164 77.1223 77.0164 76.5169 74.8791 75.5848</td>
</tr>
<tr>
<td>180</td>
<td>104.494 103.735 105.762 106.516 106.698 106.516 105.762 103.735 104.494</td>
</tr>
</tbody>
</table>

....
Thermo-mechanical analysis

- Tcl commands for defining beam thermal actions

- Non-uniform along beam length, either through depth

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

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:
1) without thermal elongation?
2) UDL removed?

- Deformation shape (without UDL)
- Deformation shape (with UDL)
♦ 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;

2) Being pulled back by Catenary action

- Deformation shape
Thank you