PROGRESSIVE COLLAPSE ANALYSIS OF STEEL FRAMES IN FIRE

Ruirui Sun

Supervisors: Ian Burgess, Zhaohui Huang

University of Sheffield, UK
• **Member-based structural fire engineering** simply does not work for large, complex buildings (see the NIST report on WTC7).

• **Performance-based SFE design** inevitably has to depend on non-linear numerical modelling of large subframes of the structure.

• If the building is to avoid the possibility of **disproportionate collapse** in fire, this numerical modelling must be capable of predicting real structural collapse, rather than the first loss of stability.
Threads for the Research

- Development of global SFE modelling (*Vulcan*).
  - Static/dynamic formulation.

- Interest in scenario-based robustness analysis in fire.
  - Different forms of global/severe local failures.

- Development of high-temperature component-based connection element for global analysis.

Practical SFE global analysis including collapse.
Introduction of VULCAN

- Finite element software specialized in Structural Fire Engineering;
- Developed for over ten years;
- The steel-framed composite buildings are modelled as assemblies of finite beam–column, connection and layered floor slab elements;
Static-Dynamic Procedure

1. Read in Model
2. Static Analysis With Temperature Rising
   - Yes: Numerical Singularity? Yes → Dynamic Analysis
   - Yes: Numerical Singularity? No → Re-stabilization?
   - No: Static-Dynamic Procedure End

- Dynamic Analysis
- Re-stabilization?

Progressive Collapse Modelling of Steel Frames under Fire
COST Young Researcher Training School, Malta
Explicit time integration method is adopted for dynamic analysis. The kinetic conditions, including displacement, velocity and acceleration, is determined by that of the previous step. Small time step is required.

1. Initial conditions and initialization:
   Set initial value of material state variables and $u_0, \dot{u}_0$. Compute mass matrix $M$ and initially estimate the time step.
2. Initialize the nodal internal force.
3. Compute the accelerations $\ddot{u}_i^0 = (M^0)^{-1}(Q_i^0 - F_i^0 - D_i^0)$
4. Time update: $t_{i+1} = t_i + \Delta t_i; \Delta t_{i+1/2} = (\Delta t_i + \Delta t_{i+1}) / 2$
5. First partial update nodal velocities: $\dot{u}_{i+1/2}^0 = \dot{u}_{i-1/2}^0 + \Delta t_i \ddot{u}_i^0$
6. Enforce boundary conditions
7. Update the nodal displacements: $u_{i+1}^0 = u_i^0 + \Delta t_{i+1/2} \dot{u}_{i+1/2}^0$
8. Calculate the nodal internal forces.
9. Compute $\ddot{u}_i^0$
10. Second partial update nodal velocities: $\dot{u}_i^0 = \dot{u}_{i+1/2}^0 + (t_{i+1} - \Delta t_{i+1/2}) \ddot{u}_{i+1}$
11. Check energy balance at time step $i+1$
13. Update counter: $i = i + 1$
14. Output, if simulation not complete, go to 4.
Validation

Snap-through Test

Section: UC 356x368x177
Load: F1=F2=F3=400KN

Displacement (mm)

Temperature (°C)

Static analysis
Current model
ABAQUS

At ambient temperature:
σ_y=275MPa
E=210GPa

Truss Frame Test

Section 1: IPE 500
Section 2: HS 100×100×5
Section 3: HS 120×120×6
Section 4: HS 80×80×4
Section 5: HS 60×60×4
Section 6: HS 50×50×3

Rigid bases
Pinned bases

Progressive Collapse Modelling of Steel Frames under Fire

COST Young Researcher Training School, Malta
Collapse Mechanism of Frames in Fire

Progressive Collapse Modelling of Steel Frames under Fire

COST Young Researcher Training School, Malta
Collapse Mechanism of Frames in Fire

Stage I

Stage II

Stage III

Force

Displacement

\[ F_p \]

\[ K_s = \tan \theta \]
Collapse Mechanism of Frames in Fire

Progressive Collapse Modelling of Steel Frames under Fire

COST Young Researcher Training School, Malta
Key issues:
1. Buckling of critical column
2. Yielding of beams connected to heated columns
3. Fracture of connections between beams and columns
4. Load sharing and buckling of adjacent columns
5. Pull-in of adjacent columns
Influence of load ratio

Higher load ratios:
Low buckling temperatures of C1; Lack of lateral restraint.

Lower load ratios:
Higher failure temperature of C1; adjacent columns buckle simultaneously.
Influence of beam sections

Strongest beam sections:
Stiff restraint to the heated column; high failure temperature; all adjacent columns buckle simultaneously.

Smaller beam sections:
Lower collapse temperature; pull-in of adjacent columns induces total collapse.
Collapse Mechanism of Frames in Fire

Progressive Collapse Modelling of Steel Frames under Fire

COST Young Researcher Training School, Malta
Collapse Mechanism of Frames in Fire

Progressive Collapse Modelling of Steel Frames under Fire

C1 C2 C3
B1 BR3 BR4

20°C

(a) 120°C
(b) 487°C
(c) 673°C

The University of Sheffield
Collapse Mechanism of Frames in Fire
• Connection is important for robustness of steel structure in fire.

• Component-based model is widely developed for modelling the connection behaviour in changed temperature.

• Connection is simulated by assembly of springs with known characteristic.

• Analysis terminates after first component fails due to numerical singularity.
Progressive Collapse Modelling of Steel Frames under Fire

1. Read in model
2. Static Analysis with Changing Temperature
3. Numerical Singularity?
   - Yes: Explicit Dynamic Procedure
   - No: Re-stabilize?
     - Yes: Progressive failure of components
     - No: Connection detachment from members
       - No: Delete the falling beams
       - Yes: Motion of beams
4. Re-stabilize?
   - Yes: Progressive Failure of Connections in Fire
   - No: Static Analysis with Changing Temperature

COST Young Researcher Training School, Malta
Progressive Failure of Connections in Fire

- UDL = 25KN/m

Dimensions:
- UB 305x127x48
- UC 254x254x73
Progressive Failure of Connections in Fire

Temperature and force in components against rotation at J1

Rotation - Temperature
- Rotation at beam ends
Rotation - Force of components
- First Component
- Second Component
- Third Component
- Fourth Component
- Fifth Component

Displacement of top of column C1 against Temperature

Progressive Collapse Modelling of Steel Frames under Fire

COST Young Researcher Training School, Malta
Ductility Demand of Connections in Fire

Tested beam with connections

Simplified Connection Model

Tension Row

Compression Row
**Ductility Demand of Connections in Fire**

**Beam Span**

- **Mid-span displacement of beam**
  - Longer beam---Larger compressive force---Buckling of beams
  - Little influence on the tensile normal forces
Sufficient compressive ductility avoid large compressive force in beams

No influence on the failure temperature of connections
Tensile Ductility

<table>
<thead>
<tr>
<th>Beam Section</th>
<th>Span</th>
<th>Tensile Ductility ($T_p$)</th>
<th>Rotation Capacity (rad)</th>
<th>Failure Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UB 533x210x122</td>
<td>9m</td>
<td>0.2</td>
<td>.6099</td>
<td>679</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.4</td>
<td>.9530</td>
<td>735</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.6</td>
<td>No Failure</td>
<td>No Failure</td>
</tr>
<tr>
<td>UB 533x210x122</td>
<td>12m</td>
<td>0.2</td>
<td>.4659</td>
<td>689</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.4</td>
<td>.7089</td>
<td>739</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.6</td>
<td>No Failure</td>
<td>No Failure</td>
</tr>
</tbody>
</table>

Tensile ductility contributes more to avoiding total connection failure and enhancing their rotation capacity, by reducing the catenary force necessary for beams to carry their loads at high temperatures.
Ductility Demand of Connections in Fire

Tensile Ductility

The catenary force decreases as the deflection and temperature increase.
### Ductility Demand of Connections in Fire

**Ductility Demand of Connections**

<table>
<thead>
<tr>
<th>Span (m)</th>
<th>Ultimate limited states (KN/m)</th>
<th>Fire limited states (KN/m)</th>
<th>Cross section</th>
<th>Ductility Index</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>97.3</td>
<td>62.1</td>
<td>UB406×178×60</td>
<td>633</td>
</tr>
<tr>
<td>9</td>
<td>97.3</td>
<td>62.1</td>
<td>UB533×210×101</td>
<td>583</td>
</tr>
<tr>
<td>12</td>
<td>97.3</td>
<td>62.1</td>
<td>UB610×305×149</td>
<td>553</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Failure Temperature(°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
</tr>
<tr>
<td>9</td>
</tr>
<tr>
<td>12</td>
</tr>
</tbody>
</table>

Beams with larger span require higher ductility of connection to retain the integrity.
Further Application and Discussion

Localized Cracking Modelling

Load

Dynamic Solver

Displacement

Test results by Foster.
Further Application and Discussion

Practical global collapse analysis in fire

Fire modelling
Accurate prediction of temperature in members
Detailed and Comprehensive Element Formulations

Beam-column elements with local buckling
Component-based connection model
Slab elements with proper cracking and crushing model
Dealing with debris loading and impact
Further Application and Discussion

Computational Efficiency

High non-linearity and complexity slow down the computational speed.
Thank you!