Performance Based Methodology for Tracing the Response of Restrained Steel Beams Exposed to Fire

Venkatesh Kodur and Mahmud Dwaikat
Michigan State University
Outline

• Fire Hazard
• Need for Structural Fire Safety
• Fire Resistance Assessment
• PBD Methodologies
• Response of Beam-Columns
  • Experimental Studies
  • Numerical Models
  • PBD Approach
  • Design Applications
• Fires cause thousands of deaths & billions of $$ of damage each year

• Fires pose major security & economic threat
  – Home land security
  – Economic activity

• Fire risk can be mitigated through conscientious design and maintenance
  – It is impossible to prevent ALL major fires

• Fire safety depends on numerous factors:
  – Fire prevention, suppression and extinction
  – Successful evacuation of occupants
  – Structural fire safety
Fire Problem in the US.

- Every 22 seconds a fire department responded to a fire.
- One vehicle fire was reported every 134 seconds.
- One outside fire was reported every 45 seconds.
- One home structure fire was reported every 82 seconds.
- One civilian fire injury was reported every 31 minutes.
- One civilian fire death occurred every 2 hours and 38 minutes.

Source: Fire Loss in the United States During 2008, by Michael J. Karter, Jr., NFPA, Quincy, MA, August 2009
Fire - Severe Hazard & Threat

• 2008 Data
  – 1.45 million fire incidents
  – 3320 fire deaths, 16,705 injuries
  – $15.7 billion property losses
  – Total cost > $70 billion

• Residential fires are the most significant
  - 83% of fire deaths, 27% of fires, 60% of the total $ loss

• Fire can be
  – Primary event – natural origin (e.g., lightning, accidental)
  – Secondary event - Post EQ, blast, explosion, impact

• Fire represents most severe condition
  – Buildings, Transit systems, Tunnels

• Structural elements – Fire resistance
  – Safe evacuation of occupants & fire personnel
  – Minimize property damage
  – Control spread of fire

• Structural fire safety – Least developed area
  – Important for Homeland Security, economic activity
Recent Fire Disasters in US

- **WTC Disaster - Sept. 11, 2001**
  - Fires - crucial to collapse
    - 2850 deaths ( > 450 ER)
    - Damage ( $10’s B)
    - Collapsed/damaged buildings - 40
  - Towers standing today! (if no fires)

- **Oakland Bridge - April 29, 2007**
  - Gasoline tanker crashed into the bridge
  - Collapse by fire (22 mins)
  - Traffic disruption

- **CA Tunnel - October 12, 2007**
  - 550 ft long tunnel
  - Burned for 7 hrs - 1400C
  - Severe damage - Spalling of concrete

- **MI I96 Bridge - July, 2008**
  - Gasoline tanker crashed into the bridge
  - Significant damage by fire
  - Traffic disruption
Fire Incidents in Europe

- April 13, 2009: Hostel fire, Kamień Pomorski, Poland, 21 ppl died.


- Apr. 15. 2005: Paris Opera Hotel, France, 24 deaths

- February 12, 2005: Windsor Tower Fire, Madrid, Spain. Partial collapse - Demolished

- Nov. 24, 2003: Fire in Student Hostel due to Electrical Fault, Moscow, Russia. 36 deaths.

- May 15, 2003: Hotel in La Plaine district, Marseilles, France, 10 deaths

- April 18, 2002: A plane crashed into the upper floors of the 30-story Pirelli Tower in Milan, Italy, 3 deaths.

- December 2001: Home for elderly people, Buccino, South Italy, 21 deaths.

- Euro Tunnel Fire – Nov. 18, 96
  - Severe damage, spalling of concrete
  - Major repairs – damages (£ 50 M)
Recent Fire Disasters

• DELFT Faculty of Architecture Bldg -  
  May 13, 2008
  – 13 storey RC building
  – Cause – Short circuit in coffee machine
    at 6th floor
  – Huge amount of fire load
    • Wood (Formwork, Arch.
      Studios)
    • Sprinklers Ineffective
      ✓ due to water damage
    • Fire Fighting Called off
      – Bldg collapsed - 7 hrs
      – Fire extinguished - 21 hrs
      – Losses – 100’s of millions of Euros

Fire in Technical University of Delft, Architecture Building
• Fire resistance

• Measure of the ability of a building element to resist a fire
  – Usually expressed in time as the duration during which a building element exhibits resistance with respect to:
    • Structural integrity
    • Stability
    • Temp transmission during a fire-resistance test

- Methods of Evaluating Fire resistance
  • Prescriptive-Based Approach
  • Performance-Based Approach

  – Performance of structural systems under fire conditions
    • Fire severity
    • Material properties
    • Structural parameters and member interactions
      - Load, restraint, member interactions

Fire scenarios for compartment fires
Fire resistance depends on

- **Properties of constituent materials**
- Reliable high temperature properties are critical for realistic analysis
- No matter how complex numerical model is, improper material properties can give misleading answers
- **Conventional construction materials**
  - Concrete, steel (protected), masonry, GWB
  - Good FR properties
  - Limited Performance problems
  - Large Variation in H.T. properties
Fire Resistance Analysis
Structural Parameters & Interactions

Complex problem:
- Advanced thermo-mechanical analysis
  - Loading, Restraint
  - Member interaction
  - Failure criteria
  - 3D modeling
  - Spalling, Charring, Local buckling
  - System level analysis
MSU Research Project: Performance Based Methodology for Tracing the Response of Restrained Steel Beams Exposed to Fire
Steel Framed Buildings

- Steel framed buildings are vulnerable to fire attack
- Fires can cause severe strength and stiffness degradation in steel structures
- Steel members in framed buildings are typically restrained, and thus axial force and bending moments develop due to restraint under fire exposure
- The fire induced forces can change the fire response and fire resistance
- The continuity/restraint effects are not accounted for in current codes of practice.

Fire in Windsor Tower in Madrid, Feb. 2005
Beam-Column – Response under Fire

- Beams and columns in buildings:
  - Primary load bearing elements
  - Stability under fire
  - External fire insulation

- At room temperature steel beams are designed for flexure

- Under fire, steel expands non-uniformly due to thermal expansion

- Restrained beams develop significant axial force & bending moment due to restraining of expansion

- Beam will no longer behave like a beam, but like a beam-column:

\[
\frac{M_u}{\Phi M_n} + \frac{P_u}{\Phi P_n} \leq 1.0
\]

Beam-Columns in Fire

Layout of typical Steel frame

Simply supported beam

Deflected shapes

$M = wL^2/8$

Restrained beam

$M = wL^2/8 + P \Delta - M_r$

Perimeter column

Thermal gradient

Bending moment and axial force

$M = P \Delta + M_r$
The current methods for evaluating FR can be categorized under two broad approaches:

- **Prescriptive-Based Approach**
  - Based on thermal criterion (critical temp. $T_{cr}$)
  - $T_{cr}$ is the temperature at which steel loses 50% of its yield strength
  - Standard fire exposure, no consideration to: loading, end-restraint, design fire exposure, or beam geometry.
  - Still used in the U.S. (*For structural steel*: $T_{cr} = 538^\circ C$)

- **Performance-Based Approach**
  - Based on realistic conditions
  - Failure based on thermal as well as strength, stability, deflection, and rate of deflection limit states
  - Design fire exposures, member continuity, material and geometric nonlinearities and effect of end-restraint are considered
Fire Resistance Provisions in Codes and Standards

- Steel members as treated as simply supported members (beams/columns), and use *sectional analysis* to compute capacity.
- Failure criterion is based on critical temperature $T_{cr}$
- Eurocode 3 (EC3 2005), New Zealand Standards (SNZ 1997), and Japanese Building Code (Harada et al. 2004) provide semi-empirical formulas for computing $T_{cr}$

\[
T_{cr}^{\text{EC3}} = 39.19 \ln \left[ \frac{1}{0.967 \times r^{3.833}} - 1 \right] + 482
\]

\[
T_{cr}^{\text{SNZ}} = 905 - 690 \times r
\]

\[
T_{cr}^{\text{JBC}} = 700 - 375 \times r
\]

$r$ is load ratio defined as the ratio between the bending moment ($M_p$) resulting from reduced load during fire to the room-temperature plastic moment capacity of the steel beam ($M_p$).
Fire Response of Restrained Steel Beams

Elastic Stage
- Expansion
- Fire induced axial force

\[ \frac{P}{k_y(T)P_y} + \frac{M}{k_y(T)M_y} > 1.0 \]

Elasto-plastic Stage
- Spread of plasticity, \( P-\Delta \) effect
- Softening, Reduction in \( P \)

\[ M_o > k_y(T)M_u \]

Catenary Action Stage
- Tensile force
- Improved response

Failure Stage
- Reaching tensile capacity
- Connections

1. Yield
2. 1st plastic hinge
3. 2nd plastic hinge

Development of Design Approach

• **Experimental studies**
  – Beam-columns
  – Standard and design fires
  – Thermal gradients in different orientations
  – Different load scenarios

• **Finite element analysis**
  – Material nonlinearities
    • Nonlinear temperature-dependent stress-strain curves
    • High-temperature creep
  – Geometrical nonlinearities
    • Local and global instabilities
  – Validated using MSU tests and tests from literature

• **Design approach**
  – Simplified equations suitable for office design
    • Computation of thermal gradient
    • Design equations based on strength criteria
    • Design equation based on deflection criteria under fire

• **Applications**
  – Design of beam-columns under strength and deflection limit states
Preparation of Specimens

W8x48

Columns C1-S and C2-S

Columns C1-W and C2-W

Average insulation thickness: 44 mm
Columns C1-W and C1-S

Average insulation thickness: 38 mm
Columns C2-W and C2-S

(a) Thermocouple locations for C1-S and C2-S at A-A, B-B, C-C and D-D

(b) Thermocouple locations for C1-W and C2-W at A-A, B-B, C-C and D-D

(c) Strain gauges at D-D for C1-S and C2-S

(d) Strain gauges at D-D for C1-W and C2-W

bare steel
Experimental Studies

Test Setup

Test Results

Finite Element Analysis

- ANSYS finite element software:
  - SUR151 and PLANE55 elements for thermal analysis
  - SHELL93 element for structural analysis

- Temperature obtained from thermal analysis is applied on the structural mesh.

- Non-uniform temperature over the cross-section, and uniform along the heated length.

- Kinematic restraint is imposed on top by applying measured rotations

- High-temp. steel properties as a function of steel temperature

- ANSYS Creep Model 11: Generalized high-temperature creep, including primary and secondary creep strains

- Transient non-linear analysis
Physical properties of structural steel (EC3)

- Specific heat
- Thermal conductivity
- Thermal strain

Steel Temperature-stress-strain curves: Poh model (2001)

Thermal properties used for the insulation material “CAFCO 300”

<table>
<thead>
<tr>
<th>Temp. (°C)</th>
<th>Thermal Conductivity (W/m-K)</th>
<th>Specific Heat (J/kg-K)</th>
<th>Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.078</td>
<td>900</td>
<td>310</td>
</tr>
<tr>
<td>1200*</td>
<td>0.3*</td>
<td>1400*</td>
<td>310*</td>
</tr>
</tbody>
</table>

*Assumed values based on previous experimental data (NIST 2005)

High-Temp. Creep

- Creep: Time-dependent plastic strain under constant stress and temperature.
- Three phases of creep strain: Primary, secondary, and tertiary creep
- At elevated temperature creep strain rate becomes very high, leading to very significant creep deformations
- Creep material tests and models: constant stress with time \( (d\sigma_s/dt = 0) \)

**ANSYS** Creep Model “11” was calibrated using two independent material tests.

\[
\Delta \varepsilon_{\text{creep}}^{\text{eq}} = \varepsilon_{\text{primary}} + \varepsilon_{\text{secondary}} = \left( \frac{c_2^s c_3 + 1}{c_3 + 1} \right) e^{-c_4/T_s} + \left( \frac{c_5^s}{c_3 + 1} \right) e^{-c_7/T_s}
\]

Validation:
Li and Guo’s Restrained Beam Test (2008)

Validation:
Li and Guo’s Restrained Beam Test (2008)

Predictions using Poh (2001), ASCE and Eurocode temperature-stress-strain models

Effect of high-temperature creep on predictions (using Poh constitutive model,

Recorded and predicted deflection and restraint force as a function of fire exposure time

Validation:
MSU Beam-Column Tests (2009)

- Partial Simulation: Temperature from test
- Full simulation: Temperature from thermal analysis
- Using Estimated restraint stiffnesses $K_a = 25000$ kN/m, $K_r = 2500$ kN-m/rad
- Load history applied from test
- For partial simulation: Temperature zones

Validation:
MSU Beam-Column Tests (2009)

Predicted and measured axial deformation and moment for beam-column C2-W

a) Axial deformation

b) Bending moment (at D-D)
- Higher load ratio leads to higher midspan deflection
- Load ratio reduces fire resistance under deflection or strength limit states
- Local buckling has minor influence on deflection due to catenary action

Parametric Studies
Effect of Axial Restraint (AR)

- Higher axial restraint leads to higher initial midspan deflection
- Axial restraint improves fire resistance based on strength limit state
- Local buckling has minor influence on deflection due to catenary action

Higher rotational restrain leads to lesser midspan deflection
Rotational restraint improves fire resistance
Local buckling has minor influence on deflection due to catenary action

- Moving restraint to the bottom flange improves overall response
- This is due to the counter-acting moment that develops at support
- Local buckling has minor influence on deflection since it is followed by catenary action

- Thermal gradient increases elastic deflection due to thermal bowing
- Thermal gradient has minor effect on the response in the catenary phase due to change in load bearing mechanism

- Three fire scenarios (including EC1 design fires) were selected
- Response is better under design fires due to the cooling phase
- Failure occurs under standard fire
- Partial recovery of deflection under design fire

Development of Performance-Based Engineering Approach

Restrained beam exposed to fire

Use realistic “design” fire scenario

Predict steel temperature “with thermal gradient”

Summary of proposed approach

- Compute steel temperature and thermal gradient
- Compute restraint forces
- Compute deflection

Strength/Deflection/Thermal criteria can be applied at any step

Predict the response of restrained beam during fire

Predict the fire-induced forces and deflection of restrained beam
**Step 1: Steel temperature**

**Standard Fire**

**General Heat Transfer Equation**

\[ k\nabla^2 T + Q = \rho c \frac{\partial T}{\partial t} \]

\[ Q = Q_{\text{con}} + Q_{\text{rad}} = h_{\text{con}}(T - T_f) + 4e\sigma(T^4 - T_f^4) \]

- **Assumptions**
  - Uniform steel temperature
  - Radiation \(\rightarrow\) Equivalent convection
  - Thin insulation
  - Fire temperature: \(T_f = a \ t^n\)

\[ \frac{dT_s}{dt} = F_1(T_f - T_s) - F_2 \frac{dT_f}{dt} \]

\[ (F_p/A_s)_{CF} = \frac{2t_F + B_F - t_w}{t_F \times B_F} \]

\[ (F_p/A_s)_{\text{web}} = \frac{2(d - 2t_f) - 2t_w}{t_w \times (d - 2t_f)} \]

\[ (F_p/A_s)_{BF} = \frac{2t_F + 2B_F - t_w}{t_F \times B_F} \]

Step 1: Steel temperature

Design Fire

\[ T_s = \alpha t^2 + \beta t + \gamma \]

At point A (\( t = t_1 \)):
\[ T_s = T_{s1} \text{ (using previous Eq. at } t = t_1 \text{), and} \]
\[ dT_s/dt = \text{slope from previous Eq. at } t = t_1 \]

At point B (\( t = t_{s,max} \)):
\[ T_s = T_f, \text{ and } dT_s/dt = 0. \]

Steel Temperature Comparison to F.E.A.

### Parameter Table

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min.</th>
<th>Max.</th>
<th>Step</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d$ (mm)</td>
<td>200</td>
<td>600</td>
<td>200</td>
</tr>
<tr>
<td>$b$ (mm)</td>
<td>200</td>
<td>600</td>
<td>200</td>
</tr>
<tr>
<td>$t_b$ (mm)</td>
<td>10</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>$t_w$ (mm)</td>
<td>7</td>
<td>14</td>
<td>7</td>
</tr>
<tr>
<td>$t_p$ (min)</td>
<td>0</td>
<td>30</td>
<td>10</td>
</tr>
<tr>
<td>$k_p$ (W/m.K) @20°C</td>
<td>0.07</td>
<td>0.21</td>
<td>0.14</td>
</tr>
<tr>
<td>$\rho \times c_p$ (J/m³.K) @ 20°C</td>
<td>250×900</td>
<td>350×900</td>
<td>150×900</td>
</tr>
<tr>
<td>Gamma factor ($\Gamma$)</td>
<td>0.5</td>
<td>1.5</td>
<td>0.5</td>
</tr>
<tr>
<td>$t_1$ (min.)</td>
<td>30</td>
<td>120</td>
<td>30</td>
</tr>
<tr>
<td>$t_2$ (min.)</td>
<td>$t_1 + 30$</td>
<td>$t_1 + 150$</td>
<td>60</td>
</tr>
</tbody>
</table>

Step 2: Plastic P-M Interaction under Thermal Gradient

- The P-M diagrams are the main tool to check capacity of beam-columns.

- Provisions in codes and standards provide plastic P-M relationships for uniform temperature conditions:
  \[
  \frac{M_u}{\Phi M_n} + \frac{P_u}{\Phi P_n} \leq 1.0
  \]

- However, under thermal gradient, the shape of plastic P-M diagrams changes.

Plastic P-M Interaction Diagrams

Comparison to Tests and F.E.

Predicted capacity envelop for the tested beam-column C1-S

Predicted capacity envelop for the tested beam-column C1-W

Step 3: Fire Induced Deflection in Restrained Beams

- **Deflection Limit State**

  - Temperature at yield: 
    \[
    T_y = \frac{1-M_o/M_y - 0.5F_R \Delta T}{F_A(1+YA_S/S_X)+a_2}
    \]

  - Catenary temperature: 
    \[
    T_c = \frac{1}{a_2}\left(1 - \frac{M}{M_u} - \frac{M_y}{M_u} \frac{F_R \Delta T}{2}\right)
    \]

  - Deflection at \( T_c \): 
    \[
    \Delta_c = \frac{L}{2} \sqrt{2\alpha \times (T_c - 20)}
    \]

  - **Deflection Criteria**
    - Either \( L/20 \) or \( L/30 \)

- **Design Fire Scenarios**

  - Assume full recovery of elastic deflection \( \Delta_y \) after \( T_{s,max} \) (Maximum steel temperature) is conservative measure

- **Buckling (local and global) limit states are not considered since it is generally followed by tensile catenary action**

Deflection of Restrained Steel Beams
Comparison to Test Data \{ Li and Guo Test (2008) \}

\[ K_{\alpha}, K_r \]

\[ w \]

\[ K_{\alpha}, K_r \]

Fire exposure time, min

0 5 10 15 20 25 30 35 40 45

Midspan deflection, mm

-400 -300 -200 -100 0 100 200 300

-500 -400 -300 -200 -100 0 100 200 300

Fire induced axial force, kN

Time, min

0 10 15 20 25 30 35 40 45

(a) Predicted and measured deflection

(c) Predicted and measured fire-induced axial force

Comparison of fire response predictions from the proposed approach with results from finite element analysis and from fire test

Deflection of Restrained Steel Beams
Comparison to Finite Element Analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Span length (L)</td>
<td>6m, 9m, 12m</td>
<td>Total length</td>
</tr>
<tr>
<td>Load ratio (LR)</td>
<td>30%, 50%, 70%</td>
<td>$LR = \frac{M_{\text{max}}}{(F_yZ_x)}$</td>
</tr>
<tr>
<td>Thermal gradient (ΔT)</td>
<td>0°C, 100°C, 200°C</td>
<td>$\Delta T = T_{\text{TF}} - T_{\text{BF}}$</td>
</tr>
<tr>
<td>Location of restraint</td>
<td>0, d/2</td>
<td>Measured downward form the centroid of the section</td>
</tr>
<tr>
<td>Axial stiffness (K_a)</td>
<td>0, 0.1, 0.3EA/L and infinity</td>
<td>Relative to room-temperature beam stiffnesses</td>
</tr>
<tr>
<td>Rotational stiffness (K_r)</td>
<td>0, 0.1, 0.3Ed/L and infinity</td>
<td></td>
</tr>
</tbody>
</table>

**Problem:**
Compute the maximum compressive force \( P \) attained in the beam-column with the following characteristics

**Given:**
- A beam-column is exposed to ASTM E119 standard fire (ASTM 2008)
- Beam-column section W14x176 \( (F_y = 345 \text{ MPa}) \)
- Effective and unbraced length of the beam-column is \( 4.5 \text{ m} \)
- Average section temperature \( T_{ave} = 500^\circ \text{C}, \text{thermal gradient} \Delta T = 200^\circ \text{C} \)
- Initial bending moment \( Mo = 320 \text{ kN.m} \)

### Critical Capacities

<table>
<thead>
<tr>
<th>( M_{cr} \text{ kN.m} )</th>
<th>AISC 2005</th>
<th>EC 3 2005</th>
<th>T&amp;D 2007</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_{cr} \text{ kN} )</td>
<td>1329</td>
<td>985</td>
<td>1131.5</td>
</tr>
<tr>
<td>Max. ( P \text{ kN (Eq. 1)} ) using current provisions</td>
<td>7150</td>
<td>5690</td>
<td>4812</td>
</tr>
<tr>
<td>Max. ( P \text{ kN (Eq. 7)} ) using proposed approach</td>
<td>3707</td>
<td>1530.4</td>
<td>2090</td>
</tr>
<tr>
<td>Max. ( P \text{ kN (ANSYS)} ) Finite element solution</td>
<td>1935.5</td>
<td>1273</td>
<td>1783</td>
</tr>
<tr>
<td>1660</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
• **Problem:**

Design the beam for 2 hours of fire exposure under ASTM E119 standard and specified design fire. Use deflection limit state of $LF = L/30$.

• **Given:**
  
  – Beam length and section: 7000 mm, W24x76.
  – Loading: uniformly distributed dead and live service loads: $w_D = 35$ kN/m, $w_L = 70$ kN/m.
  – Axial restraint stiffness ($K_a$): 41.3 kN/mm ($\approx 0.1EsA_s/L$).
  – Rotational restraint stiffness ($K_r$): 50 kN.m/milirad ($\approx 2.0EsI/L$)
  – Initial thermal gradient ($\Delta T$) = 150°C.
  – Steel properties: Grade 50 steel; $F_y = 355$ MPa and $F_u = 445$ MPa.

\[ M_m = 285.8 \text{ kN.m} \]

\[ M_s = 143 \text{ kN.m} \]

\[ w_L = 70 \text{ kN/m, } w_D = 35 \text{ kN/m} \]

\[ L = 7 \text{ m} \]
Design Applicability
Deflection Limit State Temperature

\[ T_y = \frac{1 - M_o / M_y - 0.5F_R \Delta T}{M_y} = \frac{1 - 285.8/1023.8 - 0.5 \times 0.0032 \times 150}{1023.8} = 411^\circ C \]

\[ T_c = \frac{F_A + a_2}{a_2} \left( \frac{M_s}{M_u} \right) = \frac{1}{0.0008} \left( 1 - \frac{285.8}{1308.9} \times \frac{2}{1308.9} \right) = 878.8^\circ C \]

\[ \Delta_y = \frac{5wl^4}{384kE_J} + \alpha \left( \frac{L^2 \Delta T}{8d} \right) \left( 1 - \frac{F_R}{a} \frac{F_y}{aE_y} \right) = 15mm \]

\[ \Delta_c = \frac{L}{2} \sqrt{2 \times \alpha(T_c - 20)} = \frac{7000}{2} \sqrt{2 \times 14 \times 10^{-6}(878.8 - 20)} = 542mm \]

- Under standard fire: \( T_{DLS} \) needs to be delayed for 2 hours.
  Based on thermal analysis: Supply 25 mm thickness spray-applied insulation (thermal conductivity of 0.1 W/m.°C and heat capacity of 375 kJ/m3.°C).

- Under design fire: The maximum a steel temperature must not exceed \( T_{DLS} \)
  Check using temperature equations developed earlier
  \( T_{s,max} = 597^\circ C < T_{DLS} = 605^\circ C \) (at 90 min. of fire exposure)

<table>
<thead>
<tr>
<th>Fire resistance (minutes)</th>
<th>Deflection limit state (L/30)</th>
<th>Strength limit state</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proposed approach</td>
<td>120</td>
<td>218</td>
</tr>
<tr>
<td>Japanese Building Code</td>
<td>132</td>
<td>132</td>
</tr>
<tr>
<td>Eurocode 3</td>
<td>160</td>
<td>160</td>
</tr>
<tr>
<td>New Zealand Standard</td>
<td>170</td>
<td>170</td>
</tr>
<tr>
<td>Finite element analysis</td>
<td>128</td>
<td>202</td>
</tr>
</tbody>
</table>
Conclusions

- Provisions of appropriate fire resistance measures are critical for minimizing fire induced damage/collapse in steel framed buildings.
- For evaluating realistic fire response of structural systems, factors such as end restraints, thermal gradient, fire scenario and failure criteria need to be properly accounted.
- Restrained beams and columns can develop significant fire induced forces and these forces transform their response to that of beam-columns.
- Current design methods do not fully account for the influence of thermal gradient and end restraint conditions on the fire response of beam-columns.
- The proposed approach accounts for the effect of end restraints, thermal gradient, fire scenario and failure criteria, and can be applied in design situations.
Acknowledgments

National Institute of Standards and Technology

NIST

NATIONAL SCIENCE FOUNDATION

MICHIGAN STATE UNIVERSITY
Thank You

Questions
The current design approaches may not be fully applicable for undertaking performance-based design which provides rational and cost-effective fire safety solutions.

The proposed design approach provides a convenient way of obtaining fire response and fire resistance of restrained steel beams, and thus can be used for estimating fire resistance in lieu of full-scale standard fire resistance tests.

The proposed approach will facilitate a rational fire design under a performance-based code environment. Such a rational design approach will contribute to reduced loss of life and property damage in fire incidents.
Fire Resistance Strategy

- **Steel Structures**
  - 1-4 hours
  - Stability, no collapse
    - **Steel Columns, Decks**
      - Applied protection
      - Limiting temperature

- **Problems-Insulation**
  - Critical for fire performance
  - Problems – stickability
    (adhesion/cohesion) Ex: WTC 5
  - LG Steel – local buckling
  - ICC – New provisions
Variation in Properties - Carbon Steel

Yield strength

Thermal conductivity

Outinen & Mäkeläinen 2004
Outinen et al. 1997
Mäkeläinen et al. 1998
Chen et al. 2006
Li et al. 2003
EC3 model
ASCE model
Poh model

Outinen & Mäkeläinen 2004
Outinen et al. 1997
Mäkeläinen et al. 1998
Chen et al. 2006
Li et al. 2003
EC3 model
ASCE model
Poh model

Rempe & Knudson 2008
Dale & Prasad 2007
Touloukain 1972
Yawata 1969
Powel 1956
EC3 model
ASCE model
Performance Problems - Concrete

Fire Resistance Strategy

• Concrete Structures
  – 45 min to 4 hours
  – Stability, Integrity
    • RC columns, slabs
      ✓ Cover to rebar
      ✓ Limiting temp. in rebar

• Problems
  • Spalling under fire exposure
  • Bond between concrete & rebar
  • New type of concrete
    ✓ H.T. properties
Variation in Properties - Concrete

Compressive strength

Thermal conductivity
Performance Problems - Wood

Fire Resistance Strategy

• Wood Structures
  – 30 minutes to 2 hours

• Columns/beam
  – Insulation
  – Limit temp rise

• Walls/floor
  – GWB/insulation protection
  – Limit temp. rise

• Problems
  – Wide range of timber
  – Charring
  – Glue (Parallam)
  – Insulation/protection materials
Variation in Properties - Wood

Tensile strength ratio vs. Temperature (°C)

- Lie
- Schaffer
- Thomas
- Knudson
- Best fit

Thermal diffusivity (mm²/sec) vs. Temperature (°C)

- Conventional wood
- Engineered lumber
- T&G wood
- OSB

Tensile strength

Thermal diffusivity
Fire Resistance - High Performing Materials

- HPM - HSC, FRP, HPS
  - Benefits
    - Superior performance
      - Strength, Durability
      - Corrosion resistance
  - Applications
    - Bridges, Infrastructure projects
    - Buildings, Parking garages
      - FRP - Internal & External reinforcement
        - Retrofitting – columns, beams
        - Rebars and prestressing rods
      - HSC - replacing NSC
    - Major Concern – Fire Performance
      - FR properties - not good
        - Serious performance problems
        - New design approaches needed
Performance Problems - FRP

• Design Considerations
  – Smaller c/s size
  – Min. cover - Corrosion free
  – Directly exposed to fire

• Complexities - FRP
  – Various types, Resin-matrix composite
  – Lower critical Temp
  – Combustible
  – Material properties - high temp.

• Failure criterion
  – Tg, FRP burning, Debonding
  – Conventional failure criteria may not apply

• Need innovative solutions
New Concretes: Performance Problems

- New types of concrete – HSC, HPC, FRC, FAC
- Advantages
  - Superior strength
  - Higher stiffness
  - More durable
- Characteristics
  - Low w/c
  - Admixtures
  - Silica Fume
  - Dense/compact
  - Low permeability
  - Brittle
- Problems
  - Fire behavior is different
  - Faster degradation of strength & stiffness
  - Fire induced spalling
- Current FR provisions may not be applicable

Variation of comp. strength with T for materials
Material Nonlinearities

- Strain hardening at 400°C
- Strength increases from 0.6Fy to 1.0Fy due to strain hardening effect.
- This increases improves fire resistance of steel members, and needs to be accounted for.
- In the approach, it is accounted for in computing $T_c$ (the catenary temperature)