Strategies for Mitigating Fire Hazard in Steel Bridges

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Outline

• Magnitude of Fire Hazard in Bridges
• Approach for Classification of Bridges based on Fire Risk
• Research - Experimental and Numerical Studies
• Factors Influencing Fire Performance of Bridges
• Strategies for Enhancing Fire Performance of Bridges

Importance of Bridges

• Transportation is the backbone of the economy for moving people and goods
• Most of the transportation happens either through roads or railways
• Bridges are a major component of roads and railways for facilitating flow of traffic over natural obstacles or constructed facilities
• Recent trends of urbanization and higher traffic demand led to increase the number of bridges on highways/railways
• Bridges are key elements in highway system;
  — Controls the capacity of the traffic network.
  — Highest cost per mile of the overall highway.
  — Failure leads to collapse of the entire traffic grid.

Fire Problem in Bridges

• Bridges are to be designed for number of hazards including earthquake, wind, and impact
• Fire is one of the hazards that occur in bridges
• In recent decades, due to increasing transport of hazardous materials, bridge fires have become a growing concern

Fire in bridges can lead to:
  • loss of life
  • Traffic delay (detours)
  • Significant economic and public (fire) losses
  • Partial or complete collapse of structural members

Causes of fire in bridges:
  • Gasoline tanker strikes the bridge
  • Gasoline tanker hits other automobiles near the bridge
  • Others, such as electrical problems, Repair work-welding etc.

Proper inspection & maintenance is required before the bridge is opened to traffic.
• Shutting down a bridge for maintenance will lead to significant traffic delays and losses.
Bridges fires, resulted from gasoline fires are much more intense than fires in buildings and are representative by hydrocarbon fires.  
- The high intense bridge fires can pose a severe threat to structural members and can lead to collapse of bridges depending on many factors including; intensity of the fire, type, and material of the bridge.  
- Structural members in bridges are typically made of conventional materials such as concrete and steel.  
- High temperature induce significant capacity degradation, due to loss of strength & stiffness.  
- Steel – Highly susceptible to fire, rapid rise in temp., local buckling, connections  
- Timber – Combustible, connections  
- Concrete – Possible spalling

The high intense bridge fires can pose a severe threat to structural members and can lead to collapse of bridges depending on many factors including; intensity of the fire, type, and material of the bridge. Structural members in bridges are typically made of conventional materials such as concrete and steel. High temperature induce significant capacity degradation, due to loss of strength & stiffness. Steel – Highly susceptible to fire, rapid rise in temp., local buckling, connections Timber – Combustible, connections Concrete – Possible spalling

Therefore, steel bridges can be more vulnerable than concrete bridges to fire induced collapse

As a result, steel members exhibit low fire resistance as compared to concrete members and steel structural member can lose its load carrying capacity rapidly and collapse in 20-30 minutes since its unprotected

Therefore, steel bridges can be more vulnerable than concrete bridges to fire induced collapse

Factors such as temperature induced creep, and local buckling can produce high deformations in steel girders  

Composites are representative by hydrocarbon fires. In general, composites are more stable due to thermal conductivity.

Steel bridges

Concrete bridges

The fire problem in bridges has been demonstrated recently because of the increasing fire incidents in bridges  

New York department of transportation carried out a nation wide survey and reported 1766 cases of bridge collapse occurred in 1960–2008 period (NYDOT, 2008).

This survey carried out across 18 states in US including California and studied the type of bridge, material type, and cause of bridge collapse.

Out of 1766 bridge collapse incidents:
- 1061 bridges collapsed due to flood
- 515 bridges collapsed due to collisions
- 52 bridges collapsed due to fire
- 19 bridges collapsed due to earthquake

Out of 52 bridge collapse due to fire:
- 23 Steel bridges
- 5 Concrete bridges
- 24 Timber bridges

Steel bridge girders

Concrete bridge girders

NYDOT survey, collapse is defined considering serviceability limit state

In NYDOT survey, collapse is defined considering serviceability limit state

Magnitude of Fire Problem in Bridges

Major Bridge Fires in the Last 15 Years in USA

Bridge Location | Date of Fire | Cause of Fire | Material Type on Structural Members | Damage Description
--- | --- | --- | --- | ---
150 Bridge, near Emeryville, CA | May 22, 2015 | A tanker truck carrying 53,000 gallons struck the bridge and caught fire | Concrete deck + steel girders + reinforced concrete slab | Concrete deck + steel girders + reinforced concrete slab | Minor structural damage

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--- | --- | --- | --- | ---
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*Note: The data and information presented here are based on the information provided in the document. The actual events may have different specifics.*
Recent Fires in Bridges - US

- I-80 freeway at MacArthur Maze interchange, Oakland, CA (April 28, 2007):
  - Fuel tanker transporting 32,500 liters of fuel overturned under the bridge.
  - Intense heat (temp. around 1100˚C).
  - Strength & stiffness of steel girders deteriorated leading to large deflections.
  - Significant fire induced forces in girders & connections led to partial collapse in 22 min.
  - Losses estimated at $9 million.

- I-95 Howard Avenue Overpass, Bridgeport, CT (March 23, 2003):
  - Collision between a car & a fuel tanker transporting 50,000 liters of heating oil.
  - Fire lasted for two hours & the temp. reached about 1100˚C.
  - Fire caused significant buckling of steel girders & partial collapse of steel girders.
  - Fire damage costed $11.2 million.

- I-75 Expressway near Hazel Park, MI (July 15, 2009):
  - Fuel tanker carrying highly flammable fuel crashed into a truck.
  - Steel girders weakened & collapsed in 20 min.
  - The collapse of the overpass caused significant losses & major traffic delays.

Recent Fires in Bridges - Europe

- Wiehltalbrücke Bridge fire, Germany (August 26, 2004):
  - Main structural members: Steel.
  - Car collided with a fuel tanker transporting 33,000 liters of fuel.
  - Tanker broke through a guardrail, fell off the bridge & exploded, killing the driver.
  - Fire caused severe structural damage to the bridge.
  - Bridge was closed for weeks until repairs were completed.
  - A 20 m × 31 m segment was replaced.
  - Repairs cost €7.2 million.

- Rio–Antirrio bridge, Greece (Jan. 25, 2005):
  - Main structural members: Steel
  - World's longest multi-span cable-stayed bridge.
  - One of the cable links of the bridge snapped after a lightning strike.
  - Cable snapped 40 min after the lightning strike.
  - Work has begun on replacing the roughly 300 m long broken cable & another damaged cable.
  - It was reopened to limited traffic prior to cable replacement.

Fire Safety in Building vs in Bridges

- In buildings, fire safety is achieved through active and passive fire protection system.
- In case of bridges, no fire safety provisions are required because fire in bridge is an open fire and life safety is not a major concern.
- Since, active fire protection system cannot be used in bridges, the only provision that can be incorporated in bridges is to enhance the fire resistance of structural members.
- There is large research data on fire response of structural members in buildings.
- In case of bridge members exposed to severe and rapid fires, no research has been done.
- The available information on building elements might not be directly applicable to bridge members due to number of differences.

Bridge Fires vs. Building Fires

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Bridge</th>
<th>Building</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel source</td>
<td>Gasoline based</td>
<td>Wood/plastic based material</td>
</tr>
<tr>
<td>Ventilation</td>
<td>Unlimited supply of O₂</td>
<td>Restricted supply of O₂</td>
</tr>
<tr>
<td>Fire severity</td>
<td>Hydrocarbon fire/ ASTM E1529</td>
<td>ASTM E119/ISO 834/ Natural fire</td>
</tr>
<tr>
<td>Enclosure</td>
<td>Open area</td>
<td>Compartmentation</td>
</tr>
<tr>
<td>Fire protection features</td>
<td>None</td>
<td>Active &amp; passive systems</td>
</tr>
<tr>
<td>Failure limit state</td>
<td>Flexural/Shear</td>
<td>Flexural</td>
</tr>
<tr>
<td>Connections</td>
<td>Bearing of the bottom flange</td>
<td>Web and/or the flange</td>
</tr>
<tr>
<td>Sectional slenderness</td>
<td>Web slenderness ratio (150 with no longitudinal stiffeners)</td>
<td>Web slenderness ratio (50)</td>
</tr>
<tr>
<td>Loading</td>
<td>DL+ (very little LL)</td>
<td>DL+LL (0.577)</td>
</tr>
</tbody>
</table>
**Fire Scenarios in Bridges**

- **Buildings**
  - Fuel: cellulose based
  - Compartment burning
  - Fire intensity: Moderate
  - ASTM E119/ISO 834 fire (Max temperature at 120 minutes = 1007 °C, at 8 minutes T= 645 °C)
  - External fire (Max. Temperature = 680 °C; at 8 minutes T=645 °C)

- **Bridges**
  - Fuel: hydrocarbon based
  - Open burning
  - Fire intensity: High
  - Rapid rise in Temp.
  - Hydrocarbon fire (Max. Temperature = 1100 °C; at 8 minutes T=1008 °C)

**Response of Steel Bridge under Fire**

- A typical steel bridge comprises of piers, abutments, steel-girders, lateral bracing, and concrete-slab deck.
- Girders are the main load carrying structural members in bridges.
- Under fire incidents, steel girders are much more vulnerable as compared to piers and abutments that are made of concrete.
- Behavior of steel girders under fire conditions is of critical concern from fire safety point of view.

**State of-the-Art - Knowledge Gaps**

- No information on the relative risk of fire hazard in bridges
- There is a lack of experimental data on fire response of structural members in bridges. Such data from fire experiments is critical to validating finite element model to trace the response of bridge girders under fire conditions.
- No residual strength data are available on fire exposed structural members in bridges. Data from post-fire tests is crucial for validating finite element model to evaluate the residual strength of fire exposed structural members in bridges.
- There is a lack of experimental data on the post-fire material properties on high-strength low-alloy (HSLA) steel that is used in bridge applications.
- There is lack of data on high temperature creep on steel that is used in bridge structural members.
- The effect of key factors such as composite action, fire scenarios, fire insulation, realistic restraint configuration, and creep on the response of fire exposed bridges were not considered in previous studies.
- Residual strength assessment of fire exposed bridges is necessary for opening the bridge to traffic.

**Fire Resistance Studies on Bridges @ MSU**

**Key Objectives:**

- **Identify knowledge gaps**
  - Carry out a detailed state-of-the-art review on the fire exposed steel bridge girders and identify knowledge gaps relating to fire response of steel bridges
  - Approach to identify bridges based on fire risk
  - Develop importance factor based on critical nature of bridges

- **Experimental studies**
  - Undertake fire resistance experiments on typical steel bridge girders to generate needed data for model validation on the behaviour of steel girders under fire conditions. Also, carry out high-temperature mechanical property tests on structural steel commonly used in bridge applications
  - Numerical model
  - Develop a numerical model to trace the response of typical steel bridge girders under realistic fire, loading and boundary conditions using the commercially available finite element program
  - Validate the finite element model by comparing results from analysis with those obtained from fire tests

- **Parametric studies**
  - Carry out a set of parametric studies to quantify the critical factors governing the fire response of steel bridge girders
  - Practical Strategies for mitigating fire hazard
  - Utilize data from fire tests and parametric studies and develop a strategy to enhance fire resistance of steel bridge girders. Also, develop a simplified approach to evaluate residual capacity after fire exposure
Fire Risk in Bridges

- Fires are rare in bridges.
- Fire incidents are random events.
- They follow a stochastic (probabilistic) approach.
- Absence of accurate estimation of bridges fires is due to lack of:
  - Data related to traffic state and fire conditions of bridge fires.
  - Mathematical (statistical) models to represent interaction of different parameters.

Poisson distribution:
- Discrete probability distribution that expresses probability of a given number of events occurring in a fixed interval of time if these events occur with a known average rate and independently of the time.
- Function:
  \[ P = 1 - e^{-\rho T} \]
  where,
  - \( P \): probability of a certain event
  - \( \rho \): mean (average rate)
  - \( T \): number of years

Importance Factor for Fire Design

- Fire is a rare event.
- Not all fires lead to collapse.
- Not economical or practical to design all bridges for fire hazard.
- But fire on critical bridges has severe safety, security, & economic consequences.
- Hence, critical bridges need to be identified.
- Importance factor is one way of identifying critical bridges.
- For evaluating fire risk, an importance factor similar to that used for evaluating snow or wind loading in the design of buildings, can be useful.

<table>
<thead>
<tr>
<th>State</th>
<th>Total number of bridges</th>
<th>Fire incidents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Michigan</td>
<td>10,818</td>
<td>4500</td>
</tr>
<tr>
<td>Texas</td>
<td>51,019</td>
<td>480,500</td>
</tr>
<tr>
<td>Ohio</td>
<td>30,617</td>
<td>503</td>
</tr>
<tr>
<td>Illinois</td>
<td>26,326</td>
<td>16</td>
</tr>
<tr>
<td>California</td>
<td>25,033</td>
<td>225</td>
</tr>
<tr>
<td>Missouri</td>
<td>24,209</td>
<td>503</td>
</tr>
<tr>
<td>Indiana</td>
<td>18,635</td>
<td>16</td>
</tr>
<tr>
<td>New York</td>
<td>17,405</td>
<td>225</td>
</tr>
<tr>
<td>Alabama</td>
<td>15,843</td>
<td>16</td>
</tr>
<tr>
<td>Wisconsin</td>
<td>13,966</td>
<td>225</td>
</tr>
<tr>
<td>Virginia</td>
<td>13,212</td>
<td>16</td>
</tr>
<tr>
<td>Maryland</td>
<td>5,157</td>
<td>16</td>
</tr>
<tr>
<td>DC</td>
<td>199</td>
<td>16</td>
</tr>
<tr>
<td>Others</td>
<td>------</td>
<td>16</td>
</tr>
<tr>
<td>Bridges in US</td>
<td>607,380</td>
<td>480,500</td>
</tr>
</tbody>
</table>

Probability of fire occurrence and fire-induced collapse in buildings and bridges:

- Probability of fire occurring in buildings:
  - Overall: 2.27% (2000) vs 20.0% (2012-2002)
  - Probability of a fire breaking out (as a whole year): 2.27% vs 20.0%
  - Number of collapsed structures due to fire: 16 vs 225
  - Probability of collapse due to fire: 3.1% vs 12.1%

Factors Influencing Fire Performance of Bridges

- Importance factor is a function of fire performance.
- Fire performance of bridges is directly related to fire resistance.
- Three key factors that influence fire performance of a bridge:

1. Vulnerability of a bridge (structural members) to fire:
   - Geometrical features
   - Materials used in construction
   - Loading & restraint conditions
   - Fire intensity
2. Critical nature of bridge:
   - Bridge location
   - Traffic density
3. Fire mitigation strategies:
   - Security/monitoring systems
   - Insulation on steel
   - Performance based design approach

Factors Influencing Fire Performance of Bridges

- Critical nature of bridge (Strategic factors):
  - Bridge location
  - Traffic density
  - Economic impact (losses)

Approach for Evaluating Importance Factor

"Weighted factors" approach based on critical factors influencing fire performance of a bridge.

- Step 1: Collecting data & statistics on the bridge under consideration
- Step 2: Assigning weightage factors (φ) for various parameters
- Step 3: Calculation of individual class coefficients (Δx)
- Step 4: Calculation of overall class coefficient (λ)
- Step 5: Calculation of updated overall class coefficient (λu)
- Step 6: Obtaining risk grade & Importance Factor (IF)
Step 1: Identify key parameters & sub-parameters.

Class I: Geometrical features, material properties and design
- Key characteristics that define the importance of a bridge: Vulnerability of a bridge to fire

Class II: Hazard (fire) likelihood
- Classes grouped under 2 classes
- Class coefficient (Δφ
i
x
j
k

)

Class III: Traffic demand
- Parameters grouped under 2 classes
- Factors weightage factors (φ
1
x
j
k

)

Class IV: Economic impact
- Parameters grouped under 2 classes
- Factors weightage factors (ψ
i
x
j
k

)

Class V: Expected fire losses
- Parameters grouped under 5 classes
- Factors weightage factors (ψ
i
x
j
k

)

Step 3: Evaluate importance

Step 4: Evaluate a site

Factor Approach for Evaluating Importance

- Factor for fire damage
- Factor for collision with a bridge pier
- Factor for fire due to fuel freight ship
- Factor for A fuel tanker collision & fire
- Factor for A large truck collision & fire
- Factor for A small vehicle fire above the bridge

Factor Approach for Evaluating Importance

- Factor for fire due to fuel freight ship
- Factor for collision with a bridge pier
- Factor for fire due to fuel freight ship
- Factor for A fuel tanker collision & fire
- Factor for A large truck collision & fire
- Factor for A small vehicle fire above the bridge
**Approach for Evaluating Importance Factor**

Step 5: Evaluate overall Class coefficient ($\lambda$) as the summation of the product of Class coefficient ($\lambda_i$) & corresponding Class factor ($\phi_i$).

$$\lambda = \sum \lambda_i \phi_i$$

Step 6: Evaluate updated overall Class coefficient ($\lambda_u$) as the product of fire mitigation strategies class coefficient ($\lambda_{fms}$) and corresponding class factor is subtracted from the overall class coefficient ($\lambda$).

$$\lambda_u = \lambda - \lambda_{fms} \phi_{fms}$$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Subparameter</th>
<th>Weightage factor</th>
<th>Max. weightage factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire protection &amp; insulation</td>
<td>On-site firefighting equipment</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Use of flooding agents/foam deluge systems</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>2 hr Insulation to main structural members</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Implementing structural fire design for bridge</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Geometrical features, material properties &amp; design characteristics</td>
<td>44%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Traffic demand</td>
<td></td>
<td>11%</td>
<td></td>
</tr>
<tr>
<td>Hazard (fire) likelihood</td>
<td></td>
<td>23%</td>
<td></td>
</tr>
<tr>
<td>Economic impact</td>
<td></td>
<td>13%</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Expected fire losses</strong></td>
<td></td>
<td>9%</td>
</tr>
</tbody>
</table>

**Validation of Importance Factor**

- Approach was validated by evaluating importance factor for several bridges that experienced major fire accidents.
- Case 1: Fire on I-95 Howard Avenue Overpass in Bridgeport, CT. (March 23, 2003)
  - Factors:
    - Source: Collision between a car & a fuel tanker
    - Steel bridge
    - Span is 22 m
    - Fire duration is 2 hours
  - Overall class coefficient ($\lambda$): 0.64
  - Risk grade: High
  - Importance Factor: 1.2

<table>
<thead>
<tr>
<th>Risk grade</th>
<th>Overall class coefficient ($\lambda$)</th>
<th>Importance factor (IF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical</td>
<td>≥0.95</td>
<td>1.5</td>
</tr>
<tr>
<td>High</td>
<td>0.51-0.94</td>
<td>1.2</td>
</tr>
<tr>
<td>Medium</td>
<td>0.20-0.50</td>
<td>1.0</td>
</tr>
<tr>
<td>Low</td>
<td>&lt;0.20</td>
<td>0.8</td>
</tr>
</tbody>
</table>

- Implementing fire detection systems, limiting transport size to 20,000 liters and applying structural fire engineering principles.
- Updated overall class coefficient ($\lambda_u$) reduces to 0.47 => Medium risk grade

**Experimental Studies - Fire Tests**

- Structural Member Level
  Three steel girders were designed and fabricated according to AASHTO specification.
Experimental Studies- Fire Tests

The main variable in these test specimens included load level, web slenderness and spacing of stiffeners.

Table: Summary of sectional dimensions, test parameters, and loading conditions of tested girders

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Girder G1</th>
<th>Girder G2</th>
<th>Girder G3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Girder shape</td>
<td>Rolled section W24x62</td>
<td>Built-up plate girder</td>
<td>Built-up plate girder</td>
</tr>
<tr>
<td>Span (between supports), mm</td>
<td>3658</td>
<td>3658</td>
<td>3658</td>
</tr>
<tr>
<td>Total length (end to end), mm</td>
<td>4167</td>
<td>4167</td>
<td>4167</td>
</tr>
<tr>
<td>Flange plate (b_x_t), mm</td>
<td>177.8 x 12.7</td>
<td>177.8 x 12.7</td>
<td>177.8 x 12.7</td>
</tr>
<tr>
<td>Web plate (D x t), mm</td>
<td>577.9 x 11.1</td>
<td>587.4 x 4.8</td>
<td>587.4 x 4.8</td>
</tr>
<tr>
<td>Concrete slab (b_eff x t_s), mm</td>
<td>813 x 140</td>
<td>813 x 140</td>
<td>813 x 140</td>
</tr>
<tr>
<td>Web slenderness ratio (D/t_w)</td>
<td>52</td>
<td>123.3</td>
<td>123.3</td>
</tr>
<tr>
<td>Stiffener spacing aspect ratio (a/D)</td>
<td>N/A</td>
<td>1</td>
<td>1.5</td>
</tr>
<tr>
<td>Bearing stiffeners (w x t_stf), mm</td>
<td>76.2 x 12.7</td>
<td>76.2 x 15.87</td>
<td>76.2 x 15.87</td>
</tr>
<tr>
<td>Intermediate stiffeners (w x t_stf), mm</td>
<td>N/A</td>
<td>76.2 x 8.5</td>
<td>76.2 x 8.5</td>
</tr>
<tr>
<td>Applied load/flexural capacity</td>
<td>40%</td>
<td>40%</td>
<td>33%</td>
</tr>
<tr>
<td>Applied load/shear capacity</td>
<td>40%</td>
<td>35%</td>
<td>35%</td>
</tr>
<tr>
<td>Fire exposure</td>
<td>80 conditioning</td>
<td>80 conditioning</td>
<td>80 conditioning</td>
</tr>
</tbody>
</table>

Test results

- Temperature in steel girder increases with fire exposure time
- Temperature rise in steel girder is much faster than concrete slab (due to heat sink effect)
- This leads to development of thermal gradients
- Temperature in web reaches 700°C at 40 min
Numerical Model: Approach for Evaluating Fire Resistance of Bridges

Start

Stage 1
- Room temperature mechanical properties
- Evaluating the capacity at room temperature

Stage 2
- High temperature thermal and mechanical properties
- Evaluating the response during fire exposure

Stage 3
- Residual strength mechanical properties
- Evaluating the residual strength after cooling

Flow chart illustrating stages involved in fire resistance/residual strength analysis of fire exposed bridge girders

Experimental Studies - Fire Tests

Numerical Model: Fire Resistance Evaluation

- Selection of steel bridge girder
  
  To evaluate the response of a typical bridge girder under fire conditions, a simply supported steel highway overpass bridge girder designed by FHWA is selected for analysis.

- Numerical Model
  
  ANSYS finite element software
  - Thermal model
    - SOLID70 → girder, slab, and the stiffeners.
    - SURF152 → for various load and surface effect applications to simulate the effect of both thermal radiation and heat convection from ambient air to the exposed boundaries of the section.

- Elevation and transverse section of the bridge girder

- The thermal analysis results are applied as thermal/ body load on the structural model uniformly along the girder span.
Fire Resistance Evaluation – Discretization

- Structural Model
  - SHELL181 → Steel girder
  - SOLID185 → Concrete slab
  - LINK9 → Steel reinforcement
  - COMBIN8 → Shear studs
  - CONTA173/TARGET170 → nonlinear surface to surface contact → Steel-concrete interface

- High temperature material model
  - Steel model
    - To simulate the behavior of steel in compression and tension, a multilinear stress-strain relationship with kinematic hardening plasticity model is used.
    - The stress-strain relationships for steel is obtained using Eurocode3 model.
  - Concrete model
    - The stress-strain relationships for concrete in compression is obtained using Eurocode2 model.

Fire Resistance Evaluation – Material Models

- Eurocode3 stress-strain model for steel used in analysis
  - Strain (\( \varepsilon \))
    - Stress (\( \sigma \))
      - \( f_{y,T} \)
      - \( f_{p,T} \)
      - \( \alpha \)
      - \( \varepsilon_{y,T} \)
      - \( \varepsilon_{s,T} \)
      - \( \varepsilon_{u,T} \)
      - \( \varepsilon_{t,T} \)
      - \( E_{s,T} \)
      - \( f_{u,T} \)

- Eurocode2 stress-strain model for concrete used in analysis
  - Strain (\( \varepsilon \))
    - Stress (\( \sigma \))
      - \( f_{c,T} \)
      - \( \varepsilon_{c,T} \)
      - \( \varepsilon_{c,u,T} \)

Fire Resistance Evaluation – Failure Limit States

- Failure limit states
  - Different limiting criteria are to be considered at each time step, namely:
    - Flexural limit state: occurs once bending moment due to applied loading exceed the moment capacity at a critical section.
    - Shear limit state: occurs once shear force due to applied loading exceed the shear capacity at a critical section.
    - Deflection limit states:
      - \( L/20 \)
      - Rate of deflection reaches \( (L/2000d) \).
    - Temperature limit state:
      - Unexposed temp. exceeding certain Temp. (139°C)

Fire Resistance Evaluation – Validation

- Model validation
  - There is lack of fire test data on fire resistance of bridge girders under fire conditions. Therefore, the validation of the above developed ANSYS model was carried out on a steel beam-concrete slab assembly (4.5 m span), typical to that in buildings.
  - Tested beam–slab assembly selected for validation
  - Comparisons of predicted and measured response parameter in fire exposed beam-slab assembly
  - Validated against test data from girders with varying parameters
**Parametric Studies**

Typical steel bridge selected for analysis (FHWA)

(a) Longitudinal section

(b) Traverse section near supports

Longitudinal and traverse sections of the typical steel bridge

**Summary of parametric Studies**

<table>
<thead>
<tr>
<th>Case</th>
<th>Varied Parameter</th>
<th>Parameters variation and scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td>23</td>
<td>0%</td>
<td>Hydrocarbon fire, $D/t_w = 50$</td>
</tr>
<tr>
<td>24</td>
<td>10%</td>
<td>Hydrocarbon fire, $D/t_w = 50$</td>
</tr>
<tr>
<td>25</td>
<td>30%</td>
<td>Hydrocarbon fire, $D/t_w = 50$</td>
</tr>
<tr>
<td>26</td>
<td>50%</td>
<td>Hydrocarbon fire, $D/t_w = 50$</td>
</tr>
<tr>
<td>27</td>
<td>100%</td>
<td>Hydrocarbon fire, $D/t_w = 50$</td>
</tr>
<tr>
<td>28</td>
<td>200%</td>
<td>Hydrocarbon fire, $D/t_w = 50$</td>
</tr>
<tr>
<td>29</td>
<td>Fully restraint</td>
<td>Hydrocarbon fire, $D/t_w = 50$</td>
</tr>
<tr>
<td>30</td>
<td>0%</td>
<td>Hydrocarbon fire, $D/t_w = 50$</td>
</tr>
<tr>
<td>31</td>
<td>30%</td>
<td>Hydrocarbon fire, $D/t_w = 50$</td>
</tr>
<tr>
<td>32</td>
<td>50%</td>
<td>Hydrocarbon fire, $D/t_w = 50$</td>
</tr>
<tr>
<td>33</td>
<td>100%</td>
<td>Hydrocarbon fire, $D/t_w = 50$</td>
</tr>
<tr>
<td>34</td>
<td>200%</td>
<td>Hydrocarbon fire, $D/t_w = 50$</td>
</tr>
<tr>
<td>35</td>
<td>0%</td>
<td>Hydrocarbon fire, $D/t_w = 50$</td>
</tr>
<tr>
<td>36</td>
<td>30%</td>
<td>Hydrocarbon fire, $D/t_w = 50$</td>
</tr>
<tr>
<td>37</td>
<td>50%</td>
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</tr>
<tr>
<td>38</td>
<td>100%</td>
<td>Hydrocarbon fire, $D/t_w = 50$</td>
</tr>
<tr>
<td>39</td>
<td>200%</td>
<td>Hydrocarbon fire, $D/t_w = 50$</td>
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</tbody>
</table>

**Effect of fire scenario**

Fire scenarios used in parametric studies

Thermal gradients along the depth of bridge girder section

**Effect of fire scenario on the fire response of steel bridge girder**

Failure modes under different fire scenarios
Failure modes under different exposure scenarios

Summary of Test Parameters and Results from Case Study

<table>
<thead>
<tr>
<th>Case</th>
<th>Parameter</th>
<th>Fire Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>No composite action</td>
<td>Hydro. fire</td>
</tr>
<tr>
<td>Case 2</td>
<td>Full composite action</td>
<td>Hydro. fire</td>
</tr>
<tr>
<td>Case 3</td>
<td>Fire scenario</td>
<td>External fire</td>
</tr>
<tr>
<td>Case 4</td>
<td>Fire insulation (12.5mm)</td>
<td>Hydro. fire</td>
</tr>
<tr>
<td>Case 5</td>
<td>Fire insulation (25mm)</td>
<td>Hydro. fire</td>
</tr>
</tbody>
</table>

Fire Resistance Evaluation – Different Fire Scenarios

1. At 20 minutes, the thermal gradients are 880 °C in Case 2, as opposed to 420 °C in Case 4.
2. In Case 2 (hydrocarbon fire scenario) at 60 minutes, the thermal gradient is 950 °C as opposed to 520 °C in the Case 3 (external fire scenario).

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Effect of web slenderness

Load level=30%

Yielding of bottom flange

Web crippling due to compressive force delivered through flange

Fire Resistance of Bridge Girders: Thermal Response

- 2m to 3m mid-span zone exposure
- 3m to 4m mid-span zone exposure
- 4m to support zone exposure
- Load level=50%
- Time = 25 min

Fire Resistance of Bridge Girders: Thermal Response

- 4.2 m mid-span zone exposure
- Significant web buckling

Failure modes under different exposure scenarios

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</tr>
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<tr>
<td>Case 5</td>
<td>Fire insulation (25mm)</td>
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<td>Fire scenario</td>
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<tr>
<td>Case 4</td>
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<td>Hydro. fire</td>
</tr>
<tr>
<td>Case 5</td>
<td>Fire insulation (25mm)</td>
<td>Hydro. fire</td>
</tr>
</tbody>
</table>

Fire Resistance of Bridge Girders: Structural Response under Different Scenarios

<table>
<thead>
<tr>
<th>Case</th>
<th>Parameter</th>
<th>Fire Scenario</th>
<th>Time to Failure (minutes)</th>
<th>Max. Midspan Deflection (mm)</th>
<th>Max. Axial Displacement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>No composite action</td>
<td>Hydrofire</td>
<td>12</td>
<td>326.6</td>
<td>167.7</td>
</tr>
<tr>
<td>Case 2</td>
<td>Full composite action</td>
<td>Hydrofire</td>
<td>21</td>
<td>164.6</td>
<td>110.2</td>
</tr>
<tr>
<td>Case 3</td>
<td>Fire scenario</td>
<td>External fire</td>
<td>No failure</td>
<td>91.7</td>
<td>113.4</td>
</tr>
<tr>
<td>Case 4</td>
<td>Fire insulation (12.5mm)</td>
<td>Hydrofire</td>
<td>61</td>
<td>191.6</td>
<td>112.1</td>
</tr>
<tr>
<td>Case 5</td>
<td>Fire insulation (25mm)</td>
<td>Hydrofire</td>
<td>107</td>
<td>185.2</td>
<td>119</td>
</tr>
</tbody>
</table>

Strategies for Enhancing Fire Performance of Steel Bridges

- Fire performance of steel bridges can be enhanced by enhancing FR of girders
- Identify fire risk in a bridge (IF)
- If the bridge is critical, implement strategies for enhancing fire resistance – fire insulation to steel
- Carry out detailed analysis to determine if the implemented strategies lead to required fire resistance

Strategies for Enhancing Fire Performance of Steel Bridges

- Passive fire protection systems
  - Minimize occurrence of fire
    - Encasement
    - Security measures
  - Fire protection to steel structural members
  - Minimize spalling in concrete members
  - Insulation to wood members
  - Design structural members for fire
    - Use rational design approaches

Fire Safety Provisions: Steel Bridges

- Innovations
  - Fire insulation to steel members
    - Cementitious based
    - Enhanced adhesion & cohesion
    - Improved spray-on techniques
- Connections:
  - Protection of connections for fire
  - Accounting for fire induced forces
- Composite construction
  - Concrete filling/encasing to steel abutments/piers
- Use of rational fire design approaches
Design Strategies

Strategies for enhancing fire resistance in steel bridge girders

<table>
<thead>
<tr>
<th>Case</th>
<th>Insulation type/configuraiton</th>
<th>Thickness</th>
<th>Constant parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>6.4 mm web plate (only on web 2 sides)</td>
<td>6.4 mm</td>
<td>Load level=30%, Hydrocarbon fire, D/tw =50</td>
</tr>
<tr>
<td>41</td>
<td>12.7 mm web plate</td>
<td>12.7 mm</td>
<td></td>
</tr>
<tr>
<td>42</td>
<td>19 mm web plate</td>
<td>19 mm</td>
<td></td>
</tr>
<tr>
<td>43</td>
<td>25.4 mm web plate</td>
<td>25.4 mm</td>
<td></td>
</tr>
<tr>
<td>44</td>
<td>6.4 mm steel section-3 sides</td>
<td>6.4 mm</td>
<td></td>
</tr>
<tr>
<td>45</td>
<td>12.7 mm steel section-3 sides</td>
<td>12.7 mm</td>
<td></td>
</tr>
<tr>
<td>46</td>
<td>19 mm steel section-3 sides</td>
<td>19 mm</td>
<td></td>
</tr>
<tr>
<td>47</td>
<td>25.4 mm steel section-3 sides</td>
<td>25.4 mm</td>
<td></td>
</tr>
<tr>
<td>48</td>
<td>2 mm Intumescent coating (steel section-3 sides)</td>
<td>2 mm</td>
<td>Load level=30%, Hydrocarbon fire, D/tw =50</td>
</tr>
<tr>
<td>49</td>
<td>5 mm Intumescent coating (steel section-3 sides)</td>
<td>5 mm</td>
<td></td>
</tr>
</tbody>
</table>

Practical Implication

Carry out a series of fire resistance analysis

Summary

• Fire represents a severe hazard & can induce significant damage in bridges.
• Typical steel girders can experience failure in less than 30 minutes under hydrocarbon fire exposure.
• The importance factor can be used as a benchmark to assess relative fire risk in bridges & develop appropriate strategies for mitigating fire hazard. About 5% of bridges fall under “critical” risk category.
• The fire resistance and failure mode is highly influenced by the fire intensity, exposure scenario, web slenderness, load level, and span length.
• Vulnerability of bridges in “critical” or “high” fire risk category, can be minimized by providing fire protection to structural members based on conventional prescriptive approaches.
• The fire resistance of steel bridge girders can be enhanced up to 2 hours through applying fire insulation in different configurations on steel girder.
• Advanced approaches such as performance based fire design methods can be applied to develop unique solutions to tackle fire risk.

Thank You

Questions ?????