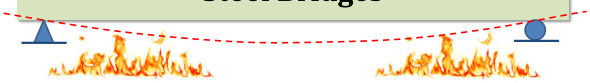
COLLEGE OF ENGINEERING

CIVIL & ENVIRONMENTAL ENGINEERING

Strategies for Mitigating Fire Hazard in Steel Bridges



Kodur V.K.R.

PhD Students & PDF's: Naser M.Z., Aziz, E.

Michigan State University

Sponsor: NSF

Collaborator: Princeton University

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 gird.

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.


I-75 Hazel park bridge fire, 2009, MI


Oakland bridge fire, 2007, CA

Fire Problem in Bridges

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


Steel bridge girders


Concrete bridge girders

Fire Problem in Steel Bridges

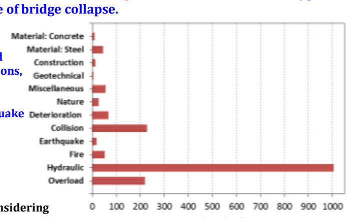
- Steel members are very sensitive to high temperature due to high thermal conductivity and fast degradation of strength and stiffness of steel
- Factors such as temperature induced creep, and local buckling can produce high deformations in steel girders
- As a result, steel members exhibit low fire 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


I-65 / I -20 - I 59 Interchange Birmingham, 2006, AL

Magnitude of Fire Problem in Bridges

- The fire problem in bridges has been demonstrated recently because of the increasing of fire incidents in bridges
- New York department of transportation carried out a nation wide survey and reported 1746 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 1746 bridge collapse incidents:
  - 1001 bridges collapsed due to flood
  - 515 bridges collapsed due to collisions, overload and deterioration
  - 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

In NYDOT survey, collapse is defined considering serviceability limit state



Causes for bridge collapse based on US-wide survey by NYDOT

Major Bridge Fires in the Last 15 Years in USA

Bridge/location	Date of fire incident	Cause of fire	Material type used in structural members	Damage description
I-375 bridge over I-75 in Detroit, MI	May 24, 2015	A gasoline tanker carrying 9000 gallons crashed over the bridge and caught into fire	Composite deck (steel girders + reinforced concrete slab)	Concrete deck was damaged significantly by the fire. Also, the steel girders experienced some damage
I-15 at Cajon, Hesperia, CA	MAY 5, 2014	Workers cutting rebar with blowtorches spread the fire into the "falsework" of the bridge	Composite deck (steel girders + reinforced concrete slab)	Structure collapsed
Bridge over freeway 60, Los Angeles, CA	December 14, 2011	A tanker truck carrying 128 m3 of gasoline caught fire, and burned out underneath the bridge	Concrete deck (precast prestressed I girders + cast in place reinforced concrete slab)	Concrete girders were damaged significantly by the fire. The bridge was demolished and replaced
Big Four Bridge, Louisville, KY	May 7, 2008	Electrical problem of the lighting system	Steel truss bridge	Minor structural damage resulting in large amount of debris on the bridge
Tappan Zee Bridge, over Hudson River, NY	July 2, 2007	A car struck a tractor-trailer and caught on fire near the bridge	Steel truss, cantilever type bridge	Minor structural damage
I-95 Howard Avenue Overpass in Bridgeport, CT	March 26, 2003	A car struck a truck carrying 8,000 gallons of heating oil near the bridge	Composite deck (steel girders + reinforced concrete slab)	Collapse of the girders of southbound lanes and partial collapse of the northbound lanes
I20/I59/I65 interchange in Birmingham, AL	January 5, 2002	A loaded gasoline tanker crashed	steel girders	Main span of girders sagged about 3 meters (10 feet)
I-80W/I-580E ramp in Emeryville, CA	February 5, 1995	A gasoline tanker crashed	Composite deck (steel girders + reinforced concrete slab)	Deck, guardrail and some ancillary facilities were damaged

Recent Fires in Bridges - US

- **I-580 freeway at MacArthur Maze interchange, Oakland, CA (April 29, 2007):**
  - Fuel tanker transporting 32,500 litters 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

MacArthur Maze interchange

I-75 Expressway

Recent Fires in Bridges - Europe

- **Wiehltalbrücke Bridge fire, Germany (August 26, 2004):**
  - Main structural members: **Steel**
  - The **most expensive** traffic accident in German history.
  - Car collided with a fuel tanker transporting 33,000 litters 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**.

Wiehltalbrücke Bridge, Germany.

- **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 strik one of the cables.
  - Cable snapped **40 min** after the lighting strike.
  - Work has begun on replacing the roughly **300 m** long broken cabl and another damaged cable
  - It was reopened to limited traffic prior to cable replacement.

Rio–Antirrio bridge, Greece.

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.**

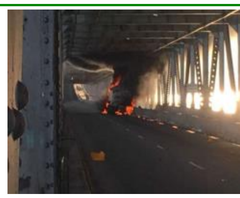
Bridge Fires vs. Building Fires

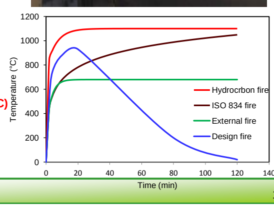
- **Significant differences between bridge and building fires**

Scenario		Bridge	Building
Fuel source		Gasoline based	Wood/plastic based material
Ventilation		Unlimited supply of O_2	Restricted supply of O_2
Fire severity		Hydrocarbon fire/ ASTM E1529	ASTM E119/ISO 834/ Natural fire
Enclosure		Open area	Compartmentation
Fire protection features		None	Active & passive systems
Structural members	Failure limit state	Flexural/Shear	Flexural
	Connections	Bearing of the bottom flange	Web and/or the flange
	Sectional slenderness	Web slenderness ratio (150 with no longitudinal stiffeners)	Web slenderness ratio (50)
	Loading	DL+ (very little LL)	DL+LL (0.5??)

Fire Scenarios in Bridges

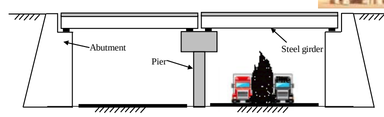
- Buildings
  - Fuel: cellulose based
  - Compartment burning
  - Fire intensity: Moderate
  - ASTM E119/ISO 834 fire (Max temperature at 120 minutes = 1007 °C , at 8 minutes T= 645 °C
  - External fire (Max. Temperature = 680°C; at 8 minutes T=645°C)
- Bridges
  - Fuel: hydrocarbon based
  - Open burning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



(a) Layout of typical steel bridge

State of-the-Art - Knowledge Gaps

- No information on the relative risk of fire hazard in bridges
- There is 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 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.

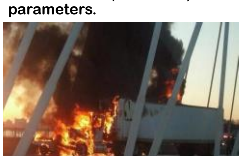
Fire Resistance Studies on Bridges @ MSU

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.
- Best described as a series of independent events that occur over time (Poisson distribution).
- Absence of accurate estimation of bridges fires is due to lack of:
  - Data related to traffic state and fire conditions of bridge fires.
  - Documentation of (major and minor) fire incidents on bridges
  - Mathematical (statistical) models to represent interaction of different parameters.



Zakim Bridge, MA, April 2014

I-75, MI, July 2009

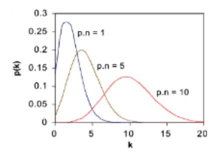
Fire Risk in Bridges

- 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
- ρ: mean (average rate)
- T: number of years



Poisson Probability

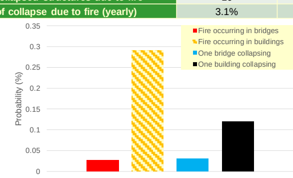
State	Total number of bridges
Michigan	10,818
Texas	51,019
Ohio	30,617
Illinois	26,326
California	25,033
Missouri	24,209
Indiana	18,635
New York	17,405
Alabama	15,843
Wisconsin	13,966
Virginia	13,212
Maryland	5,157
DC	199
Others	------
Bridges in US	607,380

- Naser M.Z., Kodur V.K.R. (2015). "A Probabilistic Assessment for Classification of Bridges Against Fire Hazard." Fire Safety Journal, Vol. 76
- US Bridge data (2015)

Fire Risk in Bridges

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

	Bridges	Buildings
	2000	2012*, 2002**
Total number of structures	691,060	118,000,000
Reported fire incidents	4500	480,500
Probability of a fire breaking out (yearly)	2.27%	29.5%*
Number of collapsed structures	503	225
Number of collapsed structures due to fire	16	29
Probability of collapse due to fire (yearly)	3.1%	12.1%**



U.S. Census Bureau. 2001. "Statistical abstract of the United States"

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.

I-75 Expressway, MI.

The Dewey Bridge, UT.

Factors Influencing Fire Performance of Bridges

- Importance factor is a function of fire performanc
- 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) t 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

MacArthur Maze in Oakland, Ca.

- Data from US DoT
- Kodur V.K.R., Naser M.Z. (2013). "Importance Factor for Design of Bridges Against Fire." Engineering Structures, Vol. 54.

Factors Influencing Fire Performance of Bridges

- Vulnerability of bridges (structural members) to fire:
  - Geometrical features
    - Slenderness of structural members
    - Lateral restraint
    - Concrete cover thickness
  - Materials used in construction
    - Concrete, steel, wood, FRP.
    - Thermo-physical & mechanical properties
    - Loss of strength & elastic modulus properties at high temperatures
    - Spalling of concrete cover
  - Loading & restraint conditions
    - Static & lower load level loading vs. dynamic, high load levels
  - Fire intensity
    - Duration
    - Fuel type & quantity
    - Combustible (formwork & materials (FRP))
  - Threat likelihood
    - Vandalism
    - Historical importance
    - Traffic route (flammables)

580 freeway which collapsed on April 29, 2007, in Oakland, Ca.

- Naser M.Z., Kodur V.K.R. (2015). "A Probabilistic Assessment for Classification of Bridges Against Fire Hazard." Fire Safety Journal, Vol. 76
- Kodur V.K.R., Naser M.Z. (2013). "Importance Factor for Design of Bridges Against Fire." Engineering Structures, Vol. 54, pp. 207-220.

Factors Influencing Fire Performance of Bridges

- Critical nature of bridge (Strategic factors):
  - Bridge location
    - Importance of a bridge is directly related to its location in the traffic network grid.
    - Any closure to bridges crossing natural obstacles with no alternative routes will affect traffic flow in the region.
  - Traffic density
    - loss of operation of on a congested highway or in the surroundings of urban area cause significant traffic disruptions.
  - 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 (Δ_x)
- **Step 4:** Calculation of overall class coefficient (λ)
- **Step 5:** Calculation of updated overall class coefficient (λ_u)
- **Step 6:** Obtaining risk grade & Importance Factor (*IF*)

Flow chart illustrating the steps involved for evaluating importance factor

Approach for Evaluating Importance Factor

- Step 1: Identify key parameters & sub-parameters
- Key characteristics that define the importance of a bridge; vulnerability & critical nature factors, are grouped into five classes:
  - Vulnerability of a bridge to fire: (grouped under 3 classes)
    - Class I: Geometrical features, material properties & design characteristics
    - Class II: Hazard (fire) likelihood
    - Class III: Traffic demand
  - Critical nature of a bridge: (grouped under 2 classes)
    - Class IV: Economic impact (in the aftermath of a fire incident)
    - Class V: Expected fire losses

Approach for Evaluating Importance Factor

- Step 2: Assign **weightage factors ($\phi_{c,p}$)** to sub-parameters.
- Weightage factors ($\varphi_{c,p}$), assigned on a scale of 1 to 5.
- Rationale for assigning weights was based on engineering judgment, recommendations of previous studies & current knowledge.

Classes I & II

Parameter	Sub-parameters	Weightage factor (φ)	Max. weightage factor (φ)
Class II: Hazard (fire) likelihood (ψ_h = 0.23)			
Response time (min)	<5	1	5
	5-10	2	
	10-20	3	
	20-30	4	
	>30	5	
Historical/architectural significance	Conventional	1	3
	Landmark	2	
	Prestigious	3	
Threat perception	None (low)	1	3
	Not available (medium)	2	
	Frequent (high)	3	
Fire scenario	A small vehicle fire above /under the bridge	1	5
	A large truck collision & fire with other vehicles	2	
	A fuel tanker collision & fire with bridge sub-structure	3	
	Major fuel tanker collision & fire with multiple vehicles & against bridge sub-structure	4	
	Fire due to fuel freight ship collision with a bridge pier	5	

Parameter	Sub-parameters	Weightage factor (φ)	Max. weightage factor (φ)
Class I: Geometrical features, material properties and design characteristics (ψ_g = 0.44)			
Structural system	Truss/Arch	1	5
	Girder - continuous	2	
	Girder - simply supported	3	
	Cable-stayed	4	
	Suspension	5	
Material type	Reinforced concrete bridge	1	5
	High strength/(prestressed) concrete bridge	2	
	Steel-concrete composite bridge	3	
	Concrete bridge strengthened with external FRP	4	
	Steel and timber bridges	5	
Span (m)	<50	1	4
	50-200	2	
	200-500	3	
	>500	4	
No. of lanes	2	1	3
	2-4	2	
	>4	3	
Age (years)	<15	1	4
	15-29	2	
	30-50	3	
	>50	4	
Current rating	100	1	5
	60-80	2	
	40-60	3	
	20-40	4	
	<20	5	
Additional service features	1 deck	1	5
	2 decks + pedestrians	2	
	Accommodates railroad	3	
	Multi-level	4	

Approach for Evaluating Importance Factor

- Step 2: Assign **weightage factors ($\phi_{c,p}$)** to sub-parameters (Continued).

Classes III, IV, V, VI

Parameter	Sub-parameters	Weightage factor (φ)	Max. weightage factor (φ)
Class III: Traffic demand (ψ_t = 0.11)			
ADT (vehicles/day)	<1,000	1	5
	1,000-5,000	2	
	5,000-15,000	3	
	15,000-50,000	4	
	>50,000	5	
Facility location	Rural	1	3
	Suburban	2	
	Urban	3	

Parameter	Sub-parameters	Weightage factor (φ)	Max. weightage factor (φ)
Class IV: Economic impact (ψ_e = 0.13)			
Closeness to alt. routes (km)	<10	1	3
	10-20	2	
	>20	3	
Time expected for repair (month)	<3	1	3
	3-9	2	
	>9	3	
Cost expected for repair	< 1 million	1	3
	1-3 million	2	
	>3 million	3	
Class V: Expected fire losses (ψ_f = 0.09)			
Life/property losses	Minimum to no injuries	1	3
	Minimum casualties	2	
	Many casualties	3	
Env. damage	Minor damage	1	3
	Significant damage	2	
	Unacceptable damage	3	

Approach for Evaluating Importance Factor

- Step 3: Evaluate a **Class factor (ψ_x)** knowing the max. weightage factor:

$$\psi_x = \frac{\sum \varphi_{x(\max)}}{\varphi_{total}}$$

where,
$\varphi_{x(\max)}$ is the maximum weightage factor of each parameter in class (x)
φ_{total} is the summation of maximum weightage factors of all parameters in the fire classes

- Step 4: Evaluate a **Class coefficient (Δ_x)**:

Class coefficient (Δ_x) is calculated as the ratio of the summation of the selected weightage factors of sub-parameters in class (x) to the summation of the maximum weightage factors of the same parameters in that class:

$$\Delta_x = \frac{\sum \varphi_{i,x}}{\sum \varphi_{x(\max)}}$$

where,
$\varphi_{i,x}$ is the weightage factor of sub-parameter (i) in class (x)
$\varphi_{x(\max)}$ is the maximum weightage factor of each parameter in class (x)

Approach for Evaluating Importance Factor

Step 5: Evaluate **overall Class coefficient (λ)** [risk] as the summation of the product of Class coefficient (Δ_x) & corresponding Class factor (ψ_x).

$$\lambda = \sum \Delta_x \psi_x$$

Step 6: Evaluate **updated overall Class coefficient (λ_u)** as the product of fire mitigation strategies class coefficient (Δ_{fms}) and corresponding class factor is subtracted from the overall class coefficient (λ).

$$\lambda_u = \lambda - \Delta_{fms} \psi_{fms}$$

Class VI: Fire mitigation strategies			
Parameter	*Sub-parameter*	*Weightage factor ()*	*Max. weightage factor ()*
Security	Monitoring systems	1	4
	Guards	2	
	Restricted access zones	3	
	Fire detection systems	4	
Laws & regulations	Provide distinguished exits for large fuel tankers	1	4
	Limit operation timings	2	
	Limit vehicle speed	3	
	Limit transport size (20,000 liters)	4	
Fire protection & insulation features	On site firefighting equipment	1	5
	Use of flooding agents and/or foam deluge systems	2	
	1 hr Insulation to main structural members	3	
	2 hr Insulation to main structural members	4	
	Implementing structural fire design for bridge	5	

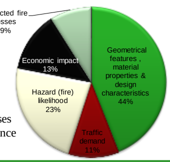
Approach for Evaluating Importance Factor

Step 7: Using overall Class coefficient (λ), assign **fire risk grade** for a bridge using the recommended risk grade Table.

- **Fire risk associated with bridges is grouped into four grades namely low, medium, high & critical.**
- **About 5% of bridges fall under "critical" risk category.**
- **About 10-15% of bridges fall under "high" risk category.**

Table 1 Risk grades & associated importance factors for fire design of bridges

Risk grade	Overall class coefficient (λ)	Importance factor (IF)
Critical	≥0.95	1.5
High	0.51-0.94	1.2
Medium	0.20-0.50	1.0
Low	<0.20	0.8



Contribution of different classes (factors) to the overall importance factor

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
  - Temperature around 1100˚C
  - Partial collapse of steel girders
  - Fire damage costs $11.2 million
- **Overall class coefficient (λ): 0.64**
- **Risk grade: High**
- **Importance Factor: 1.2**

Risk grade	Overall class coefficient (λ)	Importance factor (IF)
Critical	≥0.95	1.5
High	0.51-0.94	1.2
Medium	0.20-0.50	1.0
Low	<0.20	0.8

- **Implementing fire detection systems, limiting transport size to 20,000 liters and applying structural fire engineering principles;**
  - **Updated overall class coefficient (λ_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.

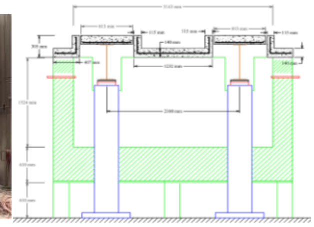
Table: Summary of sectional dimensions, test parameters, and loading conditions of tested girders

Parameter	Description	Girder G1	Girder G2	Girder G3
Sectional geometry	Girder shape	Rolled section W24x62	Built-up plate girder	Built-up plate girder
	Span (between supports), mm	3658	3658	3658
	Total length (end to end), mm	4167	4167	4167
	Flange plate (b_f x t_f), mm	177.8 x 12.7	177.8 x 12.7	177.8 x 12.7
	Web plate (D x t_w), mm	577.9 x 11.1	587.4 x 4.8	587.4 x 4.8
	Concrete slab (b_{eff} x t_s), mm	813 x 140	813 x 140	813 x 140
	End panel width (S), mm	254	254	254
	Web slenderness ratio (D/t_w)	52	123.3	123.3
	Stiffener spacing aspect ratio (a/D)	N/A	1	1.5
Stiffener	Bearing stiffeners- mid-span (w x t_{stf}), mm	76.2 x 12.7	76.2 x 15.87	76.2 x 15.87
	Bearing stiffeners- supports (w x tstf), mm	76.2 x 9.5	76.2 x 9.5	76.2 x 9.5
	Intermediate stiffeners (w x tstf), mm	N/A	76.2 x 9.5	76.2 x 9.5
Applied load	Applied load/flexural capacity	40%	40%	33%
	Applied load/total shear capacity	27%	56%	56%
	Fire exposure	ASTM E119	ASTM E119	ASTM E119

Experimental Studies- Fire Tests

Test setup and steel girders placement in the furnace

Girder layout in the furnace



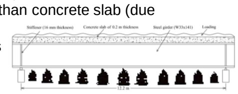
Traverse section

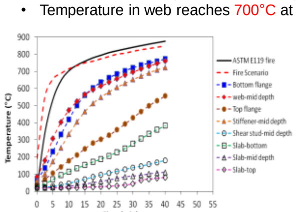
Placement of steel girder in the furnace at the structural fire testing facility at Michigan State University

Experimental Studies- Fire Tests

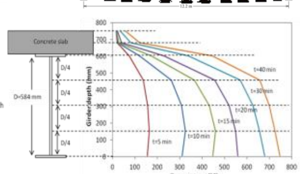
Test results

- 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





Measured temperature profiles in girders G1as a function of fire exposure time

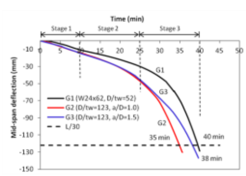


Temperature profile in steel girder G1

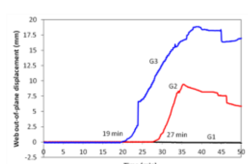
Experimental Studies- Fire Tests

Test results

- Girders undergo three stages of deflection
- Girders G2 and G3 (with slender web) experience large out-of-plane wed displacement
- Hot rolled girder (G1) fails in flexural yielding mode
- Plate girder (G2 and G3) fail due to combined effects of flexural-shear (yielding of steel flange and web buckling of web)

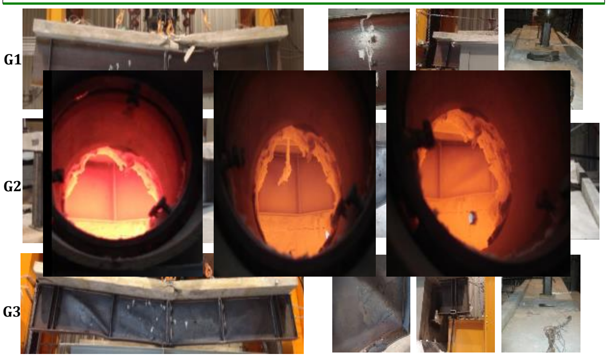


Mid-span deflection

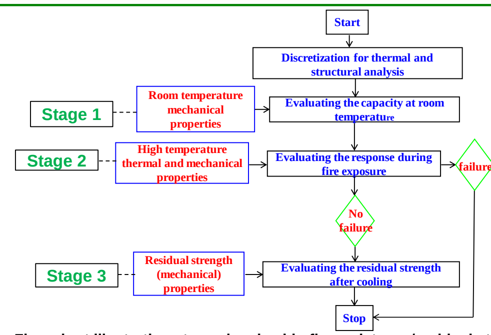


Web out-of-plane displacement

Experimental Studies- Fire Tests



Numerical Model: Approach for Evaluating Fire Resistance of Bridges

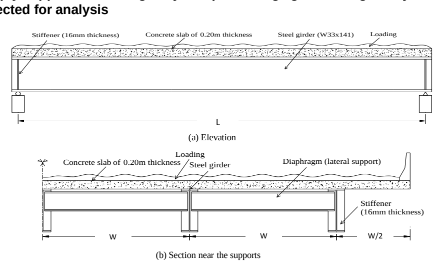


Flow chart illustrating stages involved in fire resistance/residual strength analysis of fire exposed bridge girders

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



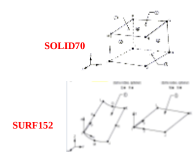
Elevation and transverse section of the bridge girder

Esam A. and Kodur, V.K.R., "An approach for evaluating the residual strength of fire exposed bridge girders", Journal of Constructional Steel Research, 88, pp. 34-42, 2013.

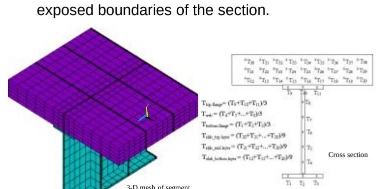
Fire Resistance Evaluation – Discretization

ANSYS finite element software

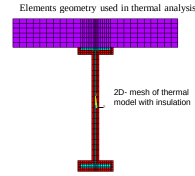
- **Thermal model**
  - **SOLID70** → girder, slab, and the stiffeners.
  - **SURF152** →for various load and surface effect applications→ to simulate the effect of both thermal radiation and heat convection from ambient air to the exposed boundaries of the section.



Elements geometry used in thermal analysis



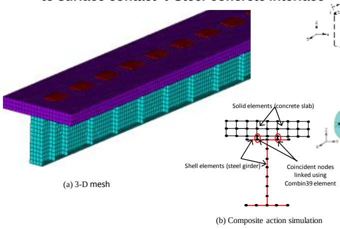
3D discretization of bridge girder for thermal analysis



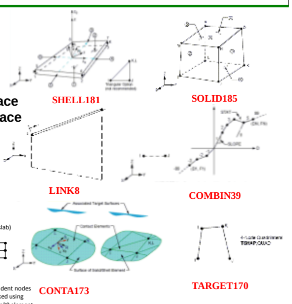
The thermal analysis results are applied as a thermal-body-load on the structural model uniformly along the girder span

Fire Resistance Evaluation – Discretization

- **Structural Model**
  - SHELL181 → Steel girder
  - SOLID185 → Concrete slab
  - LINK8 → Steel reinforcement
  - COMBIN39 → Shear studs
  - CONTA173/TARGET170 → nonlinear surface to surface contact → Steel-concrete interface



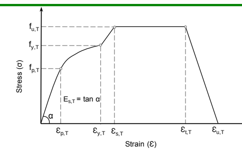
3D discretization of bridge girder for structural analysis



Elements geometry used in structural analysis

Fire Resistance Evaluation – Material Models

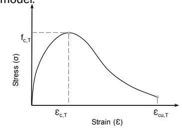
- **High temperature material model**
  - **Steel model →** To simulate the behavior of steel in compression and tension, a multilinear stress-strain relationship with kinematic hardening plasticity model is used. The stress-strain relationships for steel is obtained using Eurocode3 model.



Eurocode3 stress-strain model for steel used in analysis

Strain range	Stress σ(T)
Parameters	$\varepsilon_{p,T}=f_{p,T}/E_{s,T}$, $\varepsilon_{y,T=0.02}$, $\varepsilon_{s,T=0.04}$, $\varepsilon_{t,T=0.15}$, $\varepsilon_{u,T=0.20}$
$0.02 < \varepsilon < 0.04$	$\sigma_s=50(f_{u,T}-f_{y,T})\varepsilon+2f_{y,T}-f_{u,T}$
$0.04 \leq \varepsilon \leq 0.15$	$\sigma_s=f_{u,T}$
$0.15 < \varepsilon < 0.20$	$\sigma_s=f_{u,T}[1-20(\varepsilon-0.15)]$

  - **Concrete model →** The stress-strain relationships for concrete in compression is obtained using Eurocode2 model.



Eurocode2 stress-strain model for concrete used in analysis

Strain range	Stress σ(T)
$\varepsilon \leq \varepsilon_{c,T}$	$3\varepsilon f_{c,T}/[\varepsilon_{c,T}(2+(\varepsilon/\varepsilon_{c,T})^3]$
$\varepsilon_{c,T} < \varepsilon \leq \varepsilon_{cu,T}$	Linear or nonlinear models are permitted

$\sigma_{tru} = \sigma_{nom}(1+\varepsilon_{nom})$ and $\varepsilon_{tru} = \ln(1+\varepsilon_{nom})$

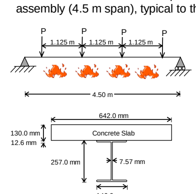
Fire Resistance Evaluation – Failure Limit States

- **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 occur once shear force due to applied loading exceed the shear capacity at a critical section.**
    - **Deflection limit states:**
      - **L/20**
      - **Rate of deflection reaches (L2/9000d).**
    - **Temperature limit state:**
      - **Unexposed temp. exceeding certain Temp.** (139°C)

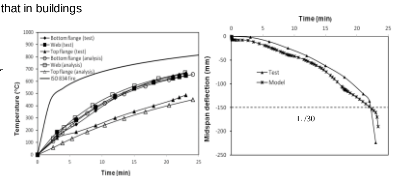
Fire Resistance Evaluation - Validation

- **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

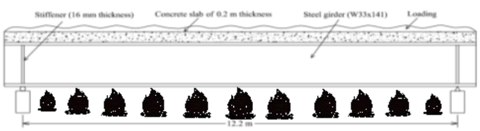


Comparison of predicted and measured response parameters in fire exposed beam-slab assembly

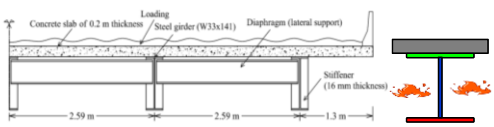
Validated against test data from girders with varying parameters

Parametric Studies

Typical steel bridge selected for analysis (FHWA)



(a) Longitudinal section



(b) Traverse section near supports

Longitudinal and transverse sections of the typical steel bridge

Parametric Studies – Factors Varied

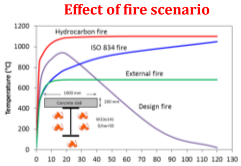
Summary of parametric Studies

Case	Varied Parameter	Parameters variation and scenarios	Constant parameters
Case 1	Fire scenario	Hydrocarbon fire	Load level=30%, D/tw=50
Case 2		Design fire	
Case 3		ISO 834 fire	
Case 4		External fire	
Case 5	Load level	20%	Hydrocarbon fire, D/tw =50
Case 6		30%	
Case 7		40%	
Case 8		50%	
Case 9	Exposure scenario	Entire span (12.2m)	Load level=30%, Hydrocarbon fire, D/tw =50
Case 10		Mid-span zone (4.2m)	
Case 11		Support zone (4.0m)	
Case 12	Web slenderness (D/tw)	30	Load level=30%, Hydrocarbon fire
Case 13		40	
Case 14		50	
Case 15		70	
Case 16		100	
Case 17	Stiffeners spacing (a/D)	No stiffeners	Load level=30%, Hydrocarbon fire, D/tw =80
Case 18		1	
Case 19		1.5	
Case 20	Span length (L)	12.2 m	Load level=30%, Hydrocarbon fire, D/tw =50
Case 21		17.0 m	
Case 22		22.0 m	

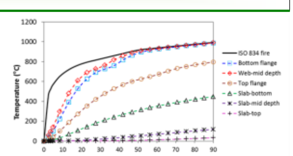
Case 23	Axial restraint	0%	Load level=30%, Hydrocarbon fire, D/tw =50
Case 24		10%	
Case 25		30%	
Case 26		50%	
Case 27		100%	
Case 28		200%	
Case 29		Fully restraint	
Case 30	Rotational restraint	0%	Load level=30%, Hydrocarbon fire, D/tw =50
Case 31		30%	
Case 32		50%	
Case 33		100%	
Case 34		200%	
Case 35	Axial and Rotational restraint	0%	Load level=30%, Hydrocarbon fire, D/tw =50
Case 36		30%	
Case 37		50%	
Case 38		100%	
Case 39		200%	

Parametric Studies – Fire Scenario

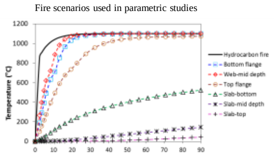
Effect of fire scenario



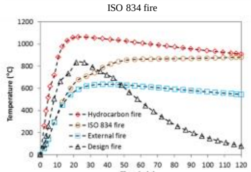
Fire scenarios used in parametric studies



ISO 834 fire

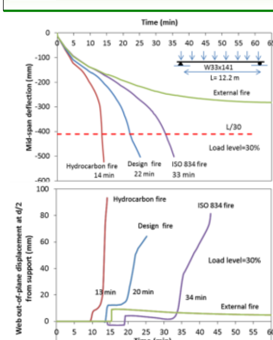


Hydrocarbon fire

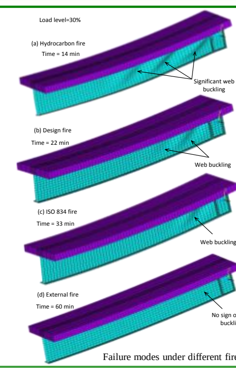


Thermal gradients along the depth of bridge girder section

Parametric Studies – Fire Scenario

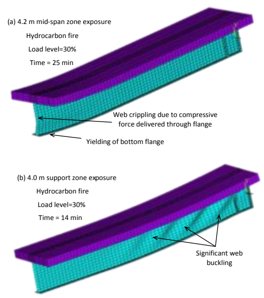


Effect of fire scenario on the fire response of steel bridge girder



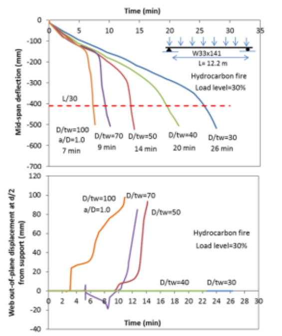
Failure modes under different fire scenarios

Parametric Studies – Web Slenderness



Failure modes under different exposure scenarios

Effect of web slenderness



Effect of web slenderness on the fire response of steel bridge girder

Fire Resistance Evaluation – Different Fire Scenarios

Summary of Test Parameters and Results from Case Study

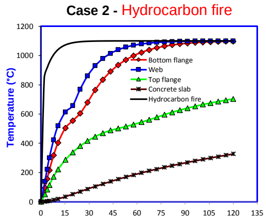
Loading under fire = DL+0.3LL

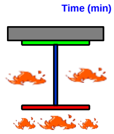
Case	Parameter	Fire Scenario
Case 1	No composite action	Hydro. fire
Case 2	Full composite action	Hydro. fire
Case 3	Fire scenario	External fire
Case 4	Fire insulation (12.5mm)	Hydro. fire
Case 5	Fire insulation (25mm)	Hydro. fire

Esam A. and Kodur, V.K.R., "An approach for evaluating the residual strength of fire exposed bridge girders", Journal of Constructional Steel Research, 88, pp. 34-42, 2013.

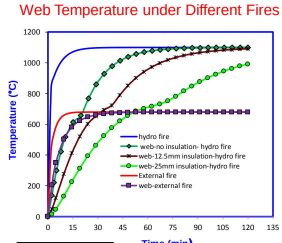
Fire Resistance of Bridge Girders: Thermal Response

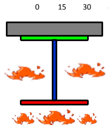
Case 2 - Hydrocarbon fire





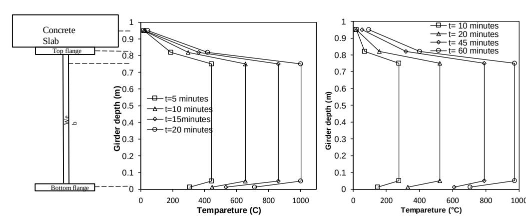
Web Temperature under Different Fires





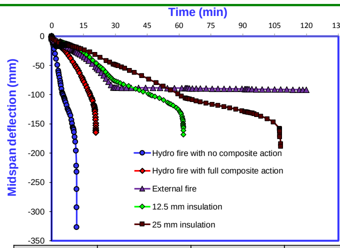
Fire Resistance of Bridge Girders: Thermal Response

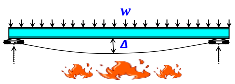
- At 20 minutes, the thermal gradients is 880 °C in Case 2, as opposed to 420 °C in Case 4
- In Case 2 (hydrocarbon fire scenario) at 60 minutes the thermal gradient is 950 °C as opposed to 520 °C in the Case 3 (external fire scenario)



(a) Cross section (b) Case 2 (bare girder) (c) Case 4 (12.5mm insulation)

Fire Resistance of Bridge Girders: Structural Response under Different Scenarios

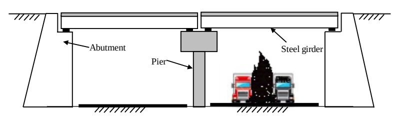




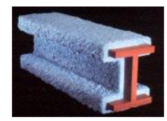
Case	Parameter	Fire Scenario	Time to failure (minutes)	Max. mid-span deflection (mm)	Max. axial displacement (mm)
Case 1	No composite action	Hydro. fire	12	-326.6	167.7
Case 2	Full composite action	Hydro. fire	21	-164.6	110.2
Case 3	Fire scenario	External fire	No failure	-91.7	113.4
Case 4	Fire insulation (12.5mm)	Hydro. fire	61	-191.6	112.1
Case 5	Fire insulation (25mm)	Hydro. fire	107	-185.2	119

Strategies for Enhancing Fire Performance of Steel Bridges

- Fire performcane 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



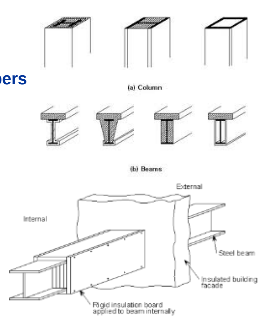
(a) Layout of typical steel bridge



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

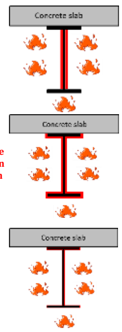
- Innovations
- Fire Insulation to steel members
  - Cementitious based
  - Enhanced adhesion & cohesion
  - Improved spray-on techniques
- Connections:
  - Protection of connections for fire
  - Accounting for fire induced forces
- Composite construction
  - Concrete filling/encasing to steel abutments/piers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

Design Strategies

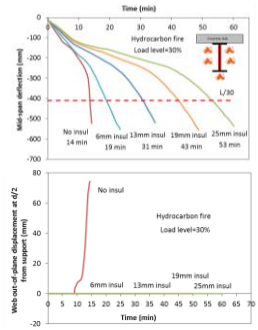
Strategies for enhancing fire resistance in steel bridge girders

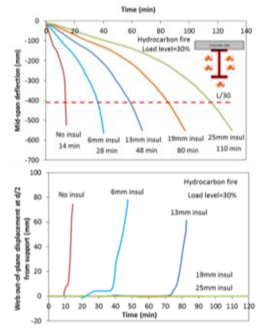
Case	Insulation type/configauration	Thickness	Constant parameters
Case 40	Insulation thickness (only on web-2 sides)	6.4 mm	Load level=30%, Hydrocarbon fire, D/tw =50
Case 41		12.7 mm	
Case 42		19 mm	
Case 43		25.4 mm	
Case 44	Insulation thickness (steel section-3 sides)	6.4 mm	Load level=30%, Hydrocarbon fire, D/tw =50
Case 45		12.7 mm	
Case 46		19 mm	
Case 47		25.4 mm	
Case 48	Intumescent coating thickness (steel section-3 sides)	1 mm	Load level=30%, Hydrocarbon fire, D/tw =50
Case 49		2 mm	
Case 50		3 mm	
Case 51		5 mm	

Carry out a series of fire resistance analysis



Practical Implication





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 approached such as performance based fire design methods can be applied to develop unique solutions to tackle fire risk.

Thank You

Questions ?????