AN APPROACH FOR EVALUATING VULNERABILITY OF BRIDGES AGAINST FIRE HAZARD

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Abstract
In recent years, bridge fires are becoming a growing concern, however there is no specific requirements in codes and standards for design of bridge structural members against fire hazard. This paper presents an approach for developing an importance factor for design of bridges against fire hazard. The proposed importance factor takes into account the degree of vulnerability of a bridge to fire and also the critical nature of a bridge from traffic functionality point. The proposed importance factor for fire design, which is similar to the one currently used for evaluating wind, and snow loading in buildings, is validated against previous bridge fire incidents. It is shown through this validation that the proposed method for importance factor can be used as a practical tool for identifying critical bridges from the point of fire hazard and also to develop relevant design strategies for mitigating fire hazard in bridges.

Keywords: fire hazard, importance factor, bridges, fire protection, bridge collapse.

1 INTRODUCTION

There have been numerous fire incidents in bridges in recent years and in some cases these fires lead to significant damage or collapse of bridges (Kodur et al, 2010). The majority of these bridge fires are caused by collision of vehicle with other automobiles or bridge structural members(Garlock et al, 2012; Bai et al, 2006; Guthrie et al, 2012), hence fires in bridges can be explosive in nature. This has been attributed to the fact that collisions occur at high speeds leading to burning of highly flammable hydrocarbon based fuels. Thus, bridge fires can reach extremely high temperatures (in the range of 1000˚C or more) in the first thirty minutes. In some cases, fires can induce significant capacity degradation in structural members, due to loss of strength and stiffness properties of constituent materials, which often lead to partial or full collapse of bridges (Bai et al, 2006; Guthrie et al, 2012). Even in the case of minor fire incidents, where no collapse occurs, proper investigation, inspection and maintenance,in the aftermath of a fire incident, is required before the bridge is opened to traffic. Shutting down a bridge for maintenance would require traffic detouring to nearby routes which can impose significant traffic delays in the affected region.

Bridges during their servicelife are exposed to multiple loadings and various risks. In recent years, there is an increase in shipping of hazardous materials; spontaneously combustible materials and dangerous materials (U.S. Department of Transportation, 2012). Further, bridges are open to general population and easily accessible to public; with minimum or no security at all, hence they are susceptible to vandalism which can often lead to fires (SAIC, 2002).

Although fire represents a significant hazard to bridges, it is still of a rare occurrence and in many cases these fires may burn-out quickly or are extinguished through firefighting. As a result, it is not economical or practical to design all bridges for fire hazard. Only bridges that are at high risk from the point of fire hazard are to be designed for fire safety. Fire hazard in bridges can be overcome to a certain extent through provisions of appropriate fire resistance to structural members, such as girders, piers, etc. (Garlock et al, 2012). For evaluating fire risk, an importance factor similar to that used for evaluating snow or wind loading in the design of buildings, can be quite useful.In general, fire resistance is achieved via proper design, selection of materials and detailing of the structural members. Unfortunately, at present, there are no specific requirements in codes and standards for fire resistance of structural members in bridges. Hence, this paper presents the development of an importance factor for fire design of bridges.

2 FACTORS INFLUENCING FIREPERFORMANCE OF BRIDGES

The importance factor for assessing fire risk in a bridge is mainly a function of fire performance of structural members in a bridge and impact of fire on traffic flow. The fire performance of a bridge is influenced by the degree of vulnerability of structural members to a fire. On the other hand, the impact of fire on a bridge is dependent on the critical nature of the bridge from the point of traffic functionality. Some of the key factors that influence the fire performance of bridges are discussed below.

2.1 Vulnerability of bridges to fire

The key factors that contribute to vulnerability of bridges to fire hazard are geometrical features, materials used in construction, loading and restraint conditionsand fire intensity.For instance, slenderness and lateral restraint to structural members used in steel bridgescan significantly affect local or torsional buckling of girders under fire conditions. On the other hand, concrete cover thickness to internal steel reinforcement has a direct bearing on the fire response of reinforced concrete structural members in concrete bridges. Further, the thermo-physical and mechanical properties of constituent materials significantly affect the response of structural members under fire. In general, all materials experience loss of strength and elastic modulus properties at high temperatures and rate of loss varydepending on thecomposition of these materials. The type and intensity of loading, as well as restraint conditions, can influence the fire performance of structural members. High load levels subject the members to additional stresses;hence rapid degradation of available capacity occursunder fire. Restrained support conditions can significantly enhance fire resistance of flexural members due to development of fire induced restraint forces that can counter balance the load induced moments. Further, fire intensity in a bridge fire and its duration depend mostly on the fuel type and quantity.Presence of highly flammable hydrocarbon products, unlimited oxygen supply and lack of active and passive fire protection measurescan accelerate the rate of growth of fires, producing high intensity fires.

2.2 Critical nature of bridges

The second major factor that is to be considered in evaluating the importance of a bridge, from the point of fire hazard, is the critical nature of the bridge whichis mainly influenced by the bridge locationand traffic density.If the bridge is located in a route connecting natural obstacles (such as valleys or rivers) and if there are no alternative routes for traffic detours, then any closure of that bridge due to fire damage will significantly slow down or shut down the traffic in the region. Similarly, traffic densitycan determine the critical nature of the bridge. If a bridge is located on a condense highway or in the surroundings of urban area that serves large number of vehicles daily, loss of operation of such a bridge due to fire will cause significant traffic disruptions in the region.

3 APPROACH TO EVALUATE IMPORTANCE FACTOR

The proposed approach for importance factor isderived by takinginto account the vulnerability of bridge structural members to fire, as well as the critical nature of the bridge to the traffic flow. The steps associated in the development of importance factor of bridges are explained below.

3.1 Calculation of the importance factor

In order to evaluate the importance factor of a given bridge, several factors and parameters are to be considered. The parameters are based on the vulnerability of bridge structural members to fire,as well as the critical nature of the bridge from traffic flow consideration.The vulnerability of a bridge to firearises fromgeometric dimensions and design features of its structural members and likelihood of fire occurrence in the vicinity of that bridge. Based on the previous fire incidents in bridges, those factors were found to be the major contributing factors to the bridge's state of vulnerability(Kodur et al, 2010).

On the other hand, traffic demand, economic consequences in the aftermathof a fire incidentand expected fire lossesdefine the critical nature of a bridge.Bridges with high traffic volumes are more prone to higherlossesand traffic disruptiondue to fire. Further, closure of a fire damaged bridge due to post-fire inspection or maintenancewould require detouring traffic to nearby routes. Such detouring would amplify traffic intensity in the nearby highways and affect the traffic flow in the region.

For deriving an importance factor, the key characteristics that definethe importance of a bridge; vulnerability to fire and critical nature to traffic flow,are grouped into five classes(Kodur and Naser, 2013). Each class is comprised of different parameters that contribute to the importance factor. Within each parameter, there are various sub-parameters that determine the conditions of a specific bridge. Based on engineering judgment and recommendations of previous studies(Garlock et al, 2012; Elhagand Wang, 2007;Wardhana andHadipriono, 2003; Scheer, 2010), weightage factorsare assigned to different sub-parameters.The weightage factors ($\varphi_{i,x}$), on a scale from 1 to 5, are shown in Table 1.

Table 1 Weightage factors based on the different features of a bridge

Class I: Geometrical properties and design features			
Param.	*Sub-parameters*	*($\varphi_{i,x}$)*	*$\varphi_{i,x(ma}$*
Structural system	Truss/Arch	1	5
	Girder - continuous	2	
	Girder - simply supported	3	
	Cable-stayed	4	
	Suspension	5	
Material type	Reinforced concrete	1	5
	High strength/(pre-stressed) concrete	2	
	Steel-concrete composite	3	
	Concrete members strengthened with FRP	4	
	Steel and timber	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	

Class II: Hazard (fire) likelihood			
Param.	*Sub-parameters*	*($\varphi_{i,x}$)*	*$\varphi_{i,x}$*
Response time (min)	<5	1	5
	5-10	2	
	10-20	3	
	20-30	4	
	>30	5	
Hist./arch. 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 and fire with other vehicles	2	
	A fuel tanker collision and fire with bridge sub-structure	3	
	Major fuel tanker collision and fire with multiple vehicles and against bridge sub-structure	4	
	Fire due to fuel freight ship collision with a bridge pier	5	

Param.	Sub-parameters	$(\varphi_{i,x})$	$\varphi_{i,x(ma}$
Additional service features	1 deck	1	5
	2 decks + pedestrians	2	
	Accommodates railroad	3	
	Multi-level	4	
	Above water	5	
Class III: Traffic demand			
Param.	*Sub-parameters*	$(\varphi_{i,x})$	$\varphi_{i,x(ma}$
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
	Sub-urban	2	
	Urban	3	

Class IV: Economic impact			
Param.	*Sub-parameters*	$(\varphi_{i,x})$	$\varphi_{i,x}$
Closeness to alt. routes	<10 km	1	3
	10-20 km	2	
	>20 km	3	
Time expected for repair	<3 months	1	3
	3-9 months	2	
	>9 months	3	
Cost expected for repair	< 1 million	1	3
	1-3 million	2	
	>3 million	3	
Class V: Expected fire losses			
Param.	*Sub-parameters*	$(\varphi_{i,x})$	$\varphi_{i,x}$
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	

Knowing the maximum weightage factors for various parameters in a bridge(from Table 1), aclass factor (ψ_x)is calculated as:

$$\psi_x = \frac{\sum \varphi_{x(\max)}}{\varphi_{total}} \qquad (1)$$

where $\varphi_{x(max)}$is the maximum weightage factorof each parameter in class (x)

$\varphi_{total}$is the summation of maximum weightagefactors of all parameters in all five classes

Then, a class coefficient (Δ_x) is calculated as the ratio of the summation of the weightage factors of all sub-parameters in class(x) to the summation of the maximum weightage factorsofall the parametersinthe same class:

$$\Delta_x = \frac{\sum \varphi_{i,x}}{\sum \varphi_{x(\max)}} \qquad (2)$$

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)

Finally, an overall class coefficient (λ) is evaluated as the summation of the product of class coefficient (Δ_x) and corresponding class factor (ψ_x).

$$\lambda = \sum \Delta_x \psi_x \qquad (3)$$

The overall class coefficient *(λ)* is then utilized to assign fire risk grade for a bridge. This is done by comparing the value of the overall class coefficient *(λ)* with numerical scores given in Table 2 and arrive at a risk grade and importance factor (*IF*). The risk grades and related overall class coefficient *(λ)*scores are given in Table 2. It should be noted that, about 5% of bridges fall under "critical" risk category and appropriate fire protection to structural members in "critical" bridges can minimize the adverse effects of fire hazard to a great extent. Further information on the classes, parameters, rationale for assigning weightage factors and risk grades can be found elsewhere (Kodur and Naser, 2013).

Tab.2 Risk grades and 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

3.2Validation of the proposed approach

The abovedeveloped approach was validated by evaluatingimportance factor for several bridges that experienced major fire incidents. One such incident is the bridge fire that occurred at the I-95 Howard Avenue Overpass in Bridgeport, CT. Full details of validation and additional case studies are provided else where (Kodur and Naser, 2013).

In Bridgeport, CT, fire a car crashed into a fuel tanker transporting 50,000 liters of heating oil on the I-95 Howard Avenue Overpass on March 23, 2003. The bridge was supported by 30-inch deep steel girders that had a span of 22 meters. The truck slipped along the overpass's concrete barrier and hit two light poles after an unsuccessful maneuvering attempt. The heating oil spilled over a length of 100 meters and ignited. The fire broke and lasted for two hours with peak temperatures of about 1100˚C. The high intensity of fire initiated significant buckling in steel girders carrying the overpass. This resulted in partial collapse of steel girders causing both northbound and southbound lanes to collapse. Following the fire, traffic in both directions had to be detoured. The refurbishment of this fire damaged bridge costed about $11.2 million (Van Horn, 2012).

The above developed approach is applied to evaluate the importance factor for this bridge against fire hazard. The importance factor was found to be 0.64. Using Table 2, the risk grade for fire hazard is determined to be high and thus the importance factor is 1.2. Since the bridge falls under high risk category, fire proofing of steel structural members would enhance the fire performance of the bridge. Hypothetically, the bridge could have survived if the steel girders were protected with 1-hour fire insulation.

4 DESIGN IMPLICATIONS

The vulnerability of a bridge to firehazard can be assessed using the proposed importance factor. The proposed importance factor is similar to the one used for evaluating wind and snow loading in buildings and can be applied in the design of new bridges or in retrofitting of existing bridges. If a bridge is found to be in "critical" or "high"fire risk category, the vulnerability of such a bridge to fire hazard can be minimizedby providing fire protection to structural members based on conventional prescriptive approaches. Alternatively, advanced approached such as performance based fire design methods can be applied to develop unique solutions to overcome fire risk in critical bridges.Hence, the above developed fire-based importance factor can provide a mean to identify critical bridges from fire hazard risk and develop appropriate strategiesto enhance fire safety of such bridges.

SUMMARY

Based on the information presented in the paper, the following conclusions can be drawn.

- Fire represents a severe hazard in bridges and can induce significant damage or collapse of structural members.
- Amethodology for evaluating importance factor for fire design of bridges is presented.The approach takes into account the level of vulnerability and critical nature of the bridge from the point of traffic functionality.

- The importance factorcan be used as a benchmark to assess relative fire risk in bridges and also develop appropriatestrategies for mitigating fire hazard in bridges.

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