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Designing Steel Bridges against Fire Hazard

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Abstract

Bridge fires can lead to significant economic and public losses; however, no provisions are specified for fire resistance of bridge structural members in current codes and standards. This paper presents an approach for mitigating fire hazard in steel bridges. The approach comprises of two steps, estimating fire risk in a bridge, and then developing strategies for enhancing fire resistance of a critical bridge. An analytical procedure is employed to derive a fire-based importance factor to estimate the vulnerability of a bridge to fire, and then a sequential finite element analysis is carried out to develop strategies for mitigating fire hazard in that bridge. The validity and applicability of this approach is demonstrated through a case study on a steel bridge that experienced fire recently.

Keywords: Fire hazard; Bridges; Fire; Mitigation strategies; Finite element analysis

Introduction

Fire represents a significant hazard to built infrastructure and can induce significant damage during the service life of a structure [1]. Thu fire hazard in buildings is minimized through provisions of active and fire protection systems, as prescribed in codes and standards. These provisions may not be applicable for bridges due to major differences in key factors such as fire severity, member characteristics and design objectives. Unfortunately, there are no specific requirements in codes and standards for designing bridges to withstand fire hazard. This is due to the common assumptions that probability of fire occurring on a bridge is rare and hence it is not practical to design all bridges for fire hazard. Further, only few of these bridge fires grow into larger size fires that can affect the structural members of a bridge. Still, bridge fires are a growing concern due to rapid urbanization and increased transportation of flammable materials. Such bridge fires are characterized by high intensity burning with peak temperatures reaching as high as 1100 °C within few minutes of ignition [2].

Such intense fires are referred to as hydrocarbon fires and can cause significant structural damage, as well as large economic and public losses specifically to steel bridges [2,3]. In current practice, steel is widely used in bridge construction due to its high strength and ductility properties, ease of installation and cost considerations. However, due to its high thermal conductivity, low specific heat, and lower sectional (and thermal) mass of steel, temperature rises rapidly in fire-exposed steel members. Since strength and modulus properties of steel are highly sensitive to elevated-temperatures, rapid rise in steel temperature causes fast degradation in strength and modulus properties of steel. Hence, steel structural members exhibit lower fire resistance than concrete members which experience slower rise in cross-sectional temperature (due to its low thermal conductivity and high specific heat) as well as slower loss of strength and modulus properties of concrete with elevated temperatures. Thus, such damage is amplified in steel girders, more so than that in concrete piers or abutments [2,3].

In fact, recent fire incidents have shown that bridge steel girders can fail and collapse in 20-30min of fire exposure which leaves little room for firefighting activities given that average response time of firefighters is 15-20 minutes [4-7]. It can be inferred from above discussion that there is a need to develop practical approaches for evaluating vulnerability of critical "steel" bridges to fire hazard. This paper presents a novel approach that can be used for mitigating fire hazards in bridges.

Proposed Approach for Mitigating Fire Hazard in Bridges

The proposed approach for mitigating fire hazard in a bridge comprises of two main steps. In the first step, the risk of fire hazard to a given bridge is quantified analytically through the application of a fire-based importance factor derived in an earlier study [2]. If the fire risk for the bridge under consideration is high, then relevant strategies for mitigating fire hazard in that bridge is developed. In the second step, structural members of the selected bridge are analyzed through a nonlinear finite element analysis to evaluate inherent fire resistance of structural system. If the structural members do not have sufficient fire resistance then relevant strategies to enhance fire resistance are developed through series of analysis. These steps along with number of sub-steps are illustrated through a flow chart in Figure 1.

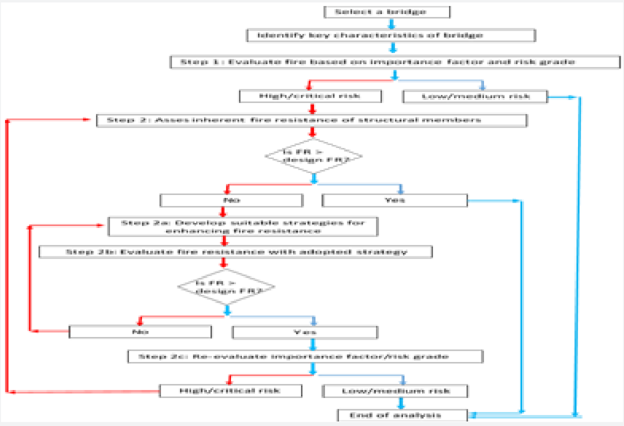

Figure 1: Flow chart of the proposed approach for mitigating fire hazard in bridges.

Identifying critical bridges

Table 1: Risk grades and associated importance factors for fire design of bridges.

Risk grade	Importance factor (IF)
Critical	1.5
High	1.2
Medium	1.0
Low	0.8

As part of the first step, the magnitude of fire risk to a bridge is to be quantified. This can be done by calculating a fire based importance factor for a given bridge [2,3]. Relevant data on characteristics of the selected bridge in terms of degree of vulnerability of a bridge to fire, the critical nature of a bridge from the point of traffic functionality, and fire mitigation strategies adopted for that bridge is to be collected and analyzed. For instance, such characteristics may include material type, structural configuration etc. Each of these characteristics is assigned an ascending numerical (from 1 to 5) where the largest value indicates the highest risk to fire hazard. These weight age factors, which indicate significance of an influencing factor to fire performance of a bridge, are assigned based on engineering judgment and recommendations in previous studies. Using this data, a fire based importance factor for selected bridge is determined through an approach recently proposed in literature [2]. Based on the value of this fire-based importance factor, the fire risk associated with bridges is grouped under four risk grades. These risk grades are defined as low, medium, high and critical and are listed in Table 1. In general, bridges that fall under "high" or "critical" risk grade often have fire resistance of much less than 60min [2,3]. Thus, suitable strategies are to be developed to enhance the fire risk of these bridges to "low" or "medium" risk grade. This can be done through developing relevant strategies to enhance fire resistance (FR) of main structural members in the bridge.

Developing strategies through finite element simulation

Kodur et al. have shown that one practical strategy is the application of fire protection to main structural members through conducting finite element simulation [5]. This applied fire protection is provided to enhance fire resistance to main structural members (to 60-90min) since previous bridge fire incidents have shown that bridge steel girders can fail and collapse in 20-30min of fire exposure [4-7]. Thus, enhancing the fire resistance of structural members through fire insulation can significantly lower the risk of collapse/damage to bridge. The viability of fire protection is then verified through finite element simulation. If fire resistance of insulated structural members is higher than required fire resistance (of 60 to 90 minutes), then no additional measures may be needed to enhance fire safety of such a bridge. However, if fire resistance of structural members is less than the required fire resistance, then the use of suitable fire mitigation strategies is needed.

Case Study

The applicability of the above discussed approach to a practical situation is illustrated by selecting a bridge that experienced fire damage due to fire hazard.

Selection of a bridge and description of bridge fire incident

I-65 interchange in Birmingham, Alabama, USA is selected for this case study. This bridge is comprised of steel girders spanning 36.6 m on top of reinforced concrete piers. This bridge caught fire on January 5, 2002 when a fuel tanker carrying 37,000 liters of gasoline overturned near the bridge. The fire resulted in an intense heat producing temperatures in the range of 1100 °C. This rapid rise in steel temperature degraded strength and stiffness properties of steel girders causing the girders to sag about 3m [7]. After this fire incident, the bridge had to be shut down and commuters were detoured to alternative highway routes.

Evaluating fire risk importance factor and inherent fire resistance of steel members

The above approach is applied to evaluate vulnerability of this bridge to fire. Following the outlined procedure proposed by Kodur & Naser [4], the fire-based importance factor for this bridge works out to be 1.2, which places the bridge under "high" risk grade. In order to evaluate the fire resistance of I-65 steel bridge girder, a nonlinear thermo-mechanical finite element model was developed to evaluate the fire resistance of steel bridge girder under hydrocarbon-based fire exposure (Figure 2 (a))[5]. It can be seen from (Figures 2 b & c) that the uninsulated

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girder experiences rapid rise in sectional temperature which leads to significant deflection at the early stage of fire and premature failure within 11min of fire.

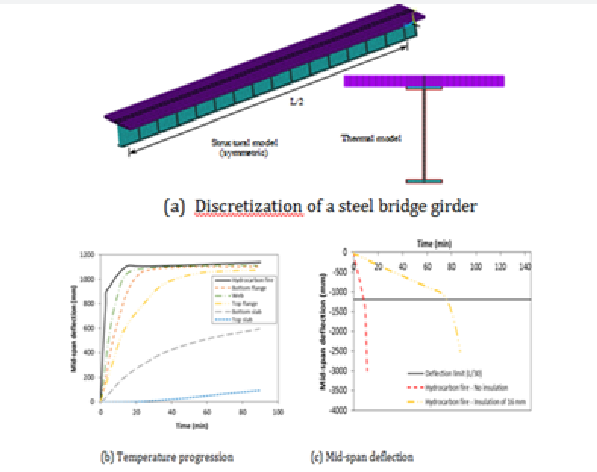

Figure 2: (a) Discretization of a steel bridge girder for thermal and structural analysis in Ansys [8]. Thermal and structural response in I-65 steel girder exposed to hydrocarbon fire.

Developing strategies to enhancing fire resistance

Since the uninsulated steel girder fails early into fire exposure, the fire performance of this girder is deemed poor and can lead to substantial damage of this bridge in the event of fire (as reported in actual fire incident [7]). The strategy to overcome such damage scenario in the event of fires is to enhance fire resistance of steel girders [5]. This can be achieved through provision of appropriate fire protection to girders. In order to arrive at optimum insulation scheme (thickness), a series of finite element simulations are carried out. Outcome of this analysis indicate that using16mm thick insulation can enhance fire resistance of steel girder to 75min (Figure 2 (b)). As discussed above, 60-90 minutes of fire resistance can significantly lower the risk of collapse to bridge since steel girders can fail within 20-30 of fire.

Re-assessing fire risk based importance factor

To take the application of fire protection into account, the fire-based importance factor is re-evaluated and was found to be 1.0. Thus, this bridge falls under "medium" fire risk category to be less susceptible to fire damage/collapse and no additional measures may be needed to enhance fire safety of this bridge.

Conclusions

Based on the information presented, the following conclusions can be drawn:

i. Fire represents a severe hazard to structural members in bridges and can induce significant damage or collapse in certain adverse fire scenarios.

ii. The proposed approach for mitigating fire hazard comprises of estimation of fire risk in a bridge and then undertaking detailed finite element analysis to develop optimum solutions for evaluating fire resistance of structural members in bridges.

iii. Steel structural members in a bridge can experience failure in 20-30 minutes under severe fire conditions. Provisions of60-90 minutes of fire resistance to critical structural members, through external fire insulation, can mitigate fire hazard in most bridges.

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