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Strategies for enhancing fire performance of steel bridges

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ABSTRACT

This paper presents an approach for developing strategies to mitigate fire hazard in critical bridges. The proposed approach comprises of two steps; namely estimating fire risk in a bridge, and then developing strategies for minimizing fire hazard on a critical bridge. As part of the first step, an analytical procedure is employed to derive a fire-based importance factor to assess the vulnerability of a bridge to fire. When the bridge is susceptible to likely fire damage, the second step involves a sequential finite element analysis to develop alternate strategies for minimizing the consequences of fire hazard on that bridge. The applicability of this approach is demonstrated through case studies on three major steel bridges that experienced failure due to fire incidents in recent years. It is shown that the proposed approach can be used as a practical tool for identifying critical bridges from the point of fire hazard and then developing solutions to overcome fire hazard in such critical bridges.

1. Introduction

In recent years, bridge fires are becoming a growing concern due to rapid urbanization and increased ground transportation of hazardous materials (flammable and spontaneously combustible materials). The most common cause of bridge fires is attributed to collision of fuel tankers with bridge components (such as piers and abutments) or other vehicles which results in burning of fuel (gasoline) in the vicinity of a bridge. The resulting fires, referred to as hydrocarbon fires, are characterized by rapid rise of temperature that can reach 1000 °C within the first few minutes of ignition [1,2]. The high intensity of these fires can cause substantial structural damage and, in some incidents, collapse of the bridge which often lead to large public and property losses. These losses include post-fire inspection, maintenance or reconstruction of fire damaged bridge, in addition to indirect costs arising from delays resulting from traffic detouring to nearby routes.

In current practice, steel is widely used in bridge construction due to its high strength, ductility properties, ease of installation and cost considerations. However, due to its high thermal conductivity, low specific heat, and lower sectional mass (slenderness) 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 strength and modulus properties of steel to degrade at a fast pace. Thus, steel structural members can lose much of their load carrying capacity in the first few minutes of fire. 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. Therefore, steel bridges can be more vulnerable to fire-induced collapse than that of concrete bridges (made of conventional concretes).

Fire hazard in steel structural members in buildings is minimized through the provisions of active and passive fire protection systems prescribed in codes and standards. These provisions may not be directly applicable to bridges due to major differences in key factors such as fire intensity, design objectives and member characteristics [3]. To date, there are no specific requirements in codes and standards for designing bridges to withstand fire hazard. This is due to the common presumption that probability of fire-induced collapse of a bridge is rare and hence it is not practical to design all bridges for fire hazard [2]. Further, only few of the bridge fires grow into large fires that can jeopardize integrity of bridge structural members. In addition, unlike in buildings, life safety of commuters is not severely at risk as bridges are often open structures with readily available egress paths.

There have been several bridge fire incidents in recent years [1–5]. The adverse consequences of fire on a bridge can be

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Nomenclature

ψ	class factor
Δ_g	geometrical features, material properties and design characteristics class factor
Δ_h	hazard (fire) likelihood class factor
Δ_t	traffic demand class factor
Δ_e	economic impact class factor
Δ_f	expected fire losses class factor
Δ_{fms}	fire mitigation strategies
$\varphi_{x(max)}$	maximum weightages factors of each parameter in class (x)
$\varphi_{i,x}$	weightage factor of sub-parameter (i) in class (x)
Δ	class coefficient
λ	overall class coefficient
λ_u	updated overall class coefficient
IF	importance factor

illustrated by looking at one such bridge fire incident which occurred on 9-mile road overpass located at the I-75 expressway near Hazel Park, MI, USA and occurred on July 15, 2009. This bridge fire broke out when a fuel tanker (transporting 50,000 l of flammable fuel) crashed into a passing truck close to the bridge. This collision initiated severe fire, which burned rapidly with temperatures exceeding 1000 °C. These high temperatures lead to rapid degradation of strength and modulus properties in unprotected steel girders, leading to loss of capacity; which in turn induced collapse of these girders within 22 min into fire. The collapse of this overpass caused large monetary losses as well as major traffic delays. The losses were estimated at 2 million US dollars and it took several weeks to repair the fire-damaged bridge [3,6].

Due to the increasing number of bridge fires, there is a need to develop practical approaches for evaluating vulnerability of critical bridges to fire hazard. Currently, there are lack of approaches and strategies for overcoming fire hazard in bridges. This paper presents a practical approach for mitigating fire hazards in bridges. The approach comprises of application of a fire-based importance factor for classification of a bridge based on fire risk and then undertaking detailed finite element analysis to develop relevant strategies for enhancing fire resistance of structural members, thereby minimizing vulnerability of a bridge to fire.

2. Proposed approach for mitigating fire hazard in bridges

Although fire represents a significant hazard to bridges, it is still of a rare occurrence in the life span of a typical bridge. As a result, it is not economical or practical to design all bridges for fire hazard and only bridges that are vulnerable (at high risk) to fire should be designed for fire safety. Enhancing fire resistance of structural members is key to mitigate such fire hazard on bridges. Of all the different structural members, steel girders are more vulnerable since they are made of steel unlike bridge piers or abutments that are made of reinforced concrete [1–3].

2.1. General approach

The proposed approach for mitigating fire hazard in a bridge comprises of two main steps. In the first step, magnitude of fire hazard on a selected bridge is quantified analytically through the application of a fire-based importance factor. If the analysis indicate that fire risk to the bridge under consideration is high, then relevant strategies for mitigating fire hazard in that bridge is developed. For this purpose, in the second step, structural members of the selected bridge are analyzed under thermal and structural loading effects to evaluate inherent fire resistance. If the structural members (such as girders) have low fire resistance and cannot withstand adverse effects of fire, then the configuration of bridge structural members is to be modified, through measures such as providing fire insulation, to enhance fire resistance. The modified structure is reanalyzed till bridge structural members can withstand a design fire hazard. The analysis is carried out under various scenarios to develop optimum strategy for enhancing fire resistance of structural members. The associated steps in this approach are illustrated through a flow chart shown in Fig. 1.

2.2. Evaluating fire risk (Step 1)

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 [2,4]. Relevant data on characteristics of the selected bridge is to be collected and analyzed. These characteristics take into account the 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.

For instance, geometrical feature of the bridge is one of the main factors used in evaluating vulnerability of a bridge to fire. This factor accounts for various influencing parameters i.e., material type, structural configuration, etc., and each parameter further accounts for a wide range of sub-parameters. Each of these sub-parameters is assigned an ascending (numerical) order (1–5) where the largest value indicates the highest risk to fire hazard as shown in Table 1. These weightage 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. For instance, a steel bridge (from material consideration) is more vulnerable to fire than that of a concrete bridge. Thus, steel bridges are assigned a higher weightage factor (of 5) than concrete bridges (of 2). It should be noted that detailed rationale for assigning weightage factors for each sub-parameter is given in [2,4].

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. The limiting values for grouping a bridge under a risk grade is 0.8, 1.0, 1.2 and 1.5, respectively. If the bridge falls under "low" or "medium" risk grade, such as a concrete bridge located in rural area that serve a low volume of traffic, then the bridge is considered to be less susceptible to fire damage or collapse, and thus no additional measures may be needed to enhance fire safety of such a bridge. However, if the bridge falls under "high" or "critical" risk grade, as in the case of a suspension steel bridge that serve large volume of traffic and located above a water body (i.e., river), then the bridge is deemed to be somewhat or highly susceptible to fire induced damage/collapse, and thus additional measures are needed to minimize fire hazard on that bridge.

In general, structural members in steel bridges that fall under "high" or "critical" risk grade often have inherent fire resistance