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A probabilistic assessment for classification of bridges against fire hazard

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ABSTRACT

This paper presents the development of a simplified approach for classification of bridges based on fire hazard. Statistical data from recent fires in bridges is utilized to quantify the probable risk of fire in bridges and also probability of fire-induced collapse of structural members in bridges. An importance factor is derived for identifying the vulnerability of bridges to fire hazard. The proposed importance factor, developed using weighted factor approach, takes into account the degree of vulnerability of different bridge components, critical nature of a bridge from traffic functionality point and fire mitigation strategies present in a specific bridge. 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.

1. Introduction

Fire is considered to be one of the severe hazards that can significantly damage built-infrastructure, including bridges, during their service life. In recent years, due to urbanization, ground shipping have increased demand on fuel transportation (flammable and combustible materials). Any collision of such fuel tankers near the vicinity of bridges can initiate huge fires. These bridge fires are characterized by high intensity fires with peak temperatures reaching as high as 1000 °C within first few minutes of fire [1–5]. Such high intense fires, referred to as hydrocarbon fires, can cause significant economic and public losses. These losses include maintenance/reconstruction costs of fire induced minor/major/collapse of a bridge and costs of detouring traffic to nearby routes. In 2002, Battelle estimated bridge fire losses to be $1.28 billion [6].

New York state department of transportation conducted a survey over a 15 year period (1990-2005) that shows fire-induced collapse in bridges to be three times higher than that due to earthquake events. However, in current practice, structural members in bridges are to be designed for earthquake loading but not for fire hazard [7]. In addition, Wardhaua and Hadipriono [8] as well as Scheer [9] showed that 3.2% and 4.9% of total bridge population experienced some level of collapse due to fire, respectively. Similarly, Kodur et al. [1,10] reviewed recent bridge fire incidents and concluded that bridge fires can lead to major structural damage or collapse of bridges. However, no structural fire design provision for bridges currently exists in codes and standards.

There have been several bridge fire incidents in recent years. One such fire incident occurred at the I-20/I-59/I-65 interchange in Birmingham, AL, where on January 5, 2002 a gasoline fuel tanker carrying 37,000 l of gasoline caught on fire. The bridge was made of 36.6 m long steel girders. 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 of steel girders causing them to sag 3 m prior to collapse of the bridge [11]. After the fire incident, the bridge had to be shut down and commuters were detoured through nearby routes. Due to critical location of this bridge, the damaged bridge had to undergo inspection and rehabilitation process before re-opening for traffic which took 54 days [11].

Another fire broke out below the 9-mile road overpass at the I-75 expressway near Hazel Park, MI. This fire incident occurred on July 15, 2009, when a fuel tanker transporting 50,000 l of flammable fuel crashed into a passing truck. This collision initiated severe burning with temperatures exceeding 1000 °C. These high temperatures resulted in degradation of strength and stiffness properties of the unprotected steel girders. Within 20 min of fire exposure, the overpass steel girders lost much of their capacity

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Nomenclature

ρ	mean of Poisson's distribution
P	probability of an event
t	number of years
φ	parameter weight
ψ	class factor
ψ_g	geometrical features, material properties and design characteristics class factor
ψ_h	hazard (fire) likelihood class factor
ψ_t	traffic demand class factor
ψ_e	economic impact class factor
ψ_f	expected fire losses class factor
ψ_{fms}	fire mitigation strategies class factor
$\varphi_{x(max)}$	maximum weightages factors of each parameter in class (x)
$\varphi_{i,x}$	weightage factor of sub-parameter (i) in class (x)
φ_{total}	summation of maximum weightages factors of all parameters
Δ	class coefficient
$\varphi_{i,x}$	score value in an individual parameter of class (x)
λ	overall class coefficient
λ_u	updated overall class coefficient
IF	importance factor

and collapsed. The collapse of these girders significantly affected traffic conditions in the region and also resulted in high costs for maintenance and repair [3].

From previous bridge fire incidents, it is clear that fire represents a significant hazard to bridges during their lifetime. However, occurrence of a fire on a bridge is still a rare event, and even in such cases, only few grow into larger size fires that can affect the structural members of a bridge. Thus, designing all bridges to withstand the adverse effects of fire may not be economical or practical. Only critical bridges, from the point of fire hazard, may have to be designed for fire safety. Identification of such critical bridges can be done through the use of fire-based importance factor similar to that used for evaluating snow or wind loading in the design of buildings [10].

This paper presents the development of weightage factor approach to derive an importance factor for fire design of bridges. In a previous study, Kodur and Naser proposed an importance factor for classification of bridge girders based on fire hazard [10]. The proposed importance factor considers only bridge girders to be vulnerable to fire, and does not take into consideration possible weakness of other super and sub-structural components of bridges to fire. To overcome this limitation, the weighted factors approach is extended to derive an importance factor for super and sub-structural components (elements) such as, decks, abutments, girders and piers of a bridge taking into account different characteristics of these structural members. In addition, the revised importance factor accounts for the effect of “service features”, such as gas pipelines and high-voltage transmission lines on fire hazard, as well as the impact of fire mitigation strategies in evaluating relative fire risk on a bridge.

2. Probabilistic risk of fire in bridges

Fire incidents are random events that follow a stochastic (probabilistic) approach. The probabilistic nature of such events is best described as a series of independent events that occur over time. The nature of these events can be quantified using Poisson distribution. Poisson distribution has been used in previous studies to investigate probability of ignition and occurrence of fire incidents in buildings [12–16].

A review of literature was conducted on bridge fires to collect statistical data on number of bridge fires, fire causes, state of traffic at break out of fire, fire incident features (fire intensity, fuel type, duration of fire), bridge characteristics and overall bridge population. The literature review clearly indicate that there is a lack of reliable data on some of this information specific to bridge fires. For instance, only major fire incidents on bridges are well documented. Data related to traffic state and fire conditions vary significantly from one source to another. Even in cases where data on some parameters are available, there is a lack of mathematical (statistical) models to represent interaction of different parameters. For instance, no mathematical model to link fire severity, bridge characteristics and probability of fire induced collapse is yet available. Thus, it is clear that there is a need to develop mathematical (statistical) models that integrate these various parameters and better comprehend their complex relations.

However, based on the available statistical data, an estimate of fire to breaking out in a bridge and chances of inducing fire-induced collapse of structural members can be developed. This estimation is obtained with the aid of few assumptions. These assumptions simplify the aforementioned complex relation between various parameters, but uses reliable information on the number of fire incidents and associated fire losses. The approach used here utilizes similar set of assumptions as that used by other researchers to estimate probability of fires in buildings [3,12–16].

According to National Fire Protection Association (NFPA) [17], there have been a total of 195,600 vehicle fire incidents that occurred on all U.S. roadways in 2011. Out of these fire incidents, 53,700 occurred on highways, 13,800 occurred on commercial roads and 22,500 burned on streets with the remaining incidents occurring on rural and residential driveways. As discussed earlier, and for the sake of this study, it is assumed that all vehicle fires have similar intensity [12–16]. Fire intensity measures the destructive impact of fire and is a function of fire temperature, type and availability of fuel, ventilation etc. This fire intensity can also be expressed as the mean of Poisson distribution (ρ). Using the principles of Poisson distribution, the estimated fire intensity of highway vehicle fires reported by NFPA is equal to $\rho = \frac{53,700+13,800+22,500}{195,600} = 0.46\ \text{year}^{-1}$. Then, applying Poisson distribution principles, the probability (P) of one vehicle fire occurring every year is estimated as:$P = 1 - e^{-\rho t} = 1 - e^{-0.46(1)} = 0.37$ (37%), where (t) is the number of years.

Since there is no available statistical information on the total number of fire incidents on bridges, a reasonable fraction of the total highway fire incidents can be assumed to occur in the vicinity of bridges. Herein, 5% of total highway fire incidents is assumed to occur on/underneath bridges. Following the same approach described above, the probability of a fire breaking out on a bridge is 2.27%, ($\rho = \frac{0.05\times(53,700+13,800+22,500)}{195,600} = 0.023\ \text{year}^{-1}$, and $P = 1 - e^{-\rho t} = 1 - e^{-0.023(1)} = 0.0227$). According to NFPA 551 [18] provisions, a risk having a probability ranging between 0.1% and 10% is considered a probable risk. Probable risks are those which can occur several times during a life span of a system (50–75 years for highway bridges) [18]. Given the annual increase in number of vehicles, fuel shipping, and number of collisions, the roughly estimated probability of fire occurrence on a bridge seems realistic.

Further, Wardhana and Hadipriono [8] recently published statistical data on total number of highway bridges and number of collapsed bridges in the US over a period of 11 years (1989–2000).