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REVIEW

# Fire hazard in transportation infrastructure: Review, assessment, and mitigation strategies

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**ABSTRACT** This paper reviews the fire problem in critical transportation infrastructures such as bridges and tunnels. The magnitude of the fire problem is illustrated, and the recent increase in fire problems in bridges and tunnels is highlighted. Recent research undertaken to address fire problems in transportation structures is reviewed, as well as critical factors governing the performance of those structures. Furthermore, key strategies recommended for mitigating fire hazards in bridges and tunnels are presented, and their applicability to practical situations is demonstrated through a practical case study. Furthermore, research needs and emerging trends for enhancing the "state-of-the-art" in this area are discussed.

**KEYWORDS** fire hazard, bridges, tunnels, fire resistance, mitigation strategies, transportation infrastructure

## 1 Introduction

Transportation structures, such as bridges, tunnels, and metro stations, are often built to serve for a number of decades and for various modes of transportation. During their long service life, bridges and tunnels are exposed to various loading scenarios and hazards. Because any damage to these structures (e.g., collapse of bridge and closure of tunnel) can adversely affect the overall performance of the transportation network (and ultimately the economy/society), transportation structures must be designed to withstand risks arising from natural (e.g., earthquakes and tsunamis) or man-made disasters (e.g., fire, blast, and impact) [1–4].

In the past two decades, the number of fire incidents in transportation structures has increased, some of which have resulted in destructive damage and prolonged interruptions to traffic flow [3,5]. Although fire is a growing concern in transportation structures, current codes of practice do not necessitate explicit fire safety provisions to be implemented in bridges and only limited active fire protection measures are recommended for tunnels [6]. In fact, most of these transportation structures (e.g., bridges and tunnels) are often designed without any specific fire resistance provisions. Hence, in the case of fire, transportation structures may be extremely susceptible to fire-induced damages, possible resulting in a partial or complete collapse of the structure. Based on recent surveys compiled by Battelle [3] and Schütz [5], the average annual fire losses in bridges (in the US alone) and tunnels (worldwide) are estimated to be $1.28 billion and $1.06 billion, respectively.

A number of recent studies have documented fire incidents and associated losses in transportation structures [7–10]. The findings of these studies indicate that most fires are triggered by the blazing of combustibles resulting from vehicle collision, e.g., fuel tankers colliding with vehicles/structural components. Another typical cause of fires on bridges (or in tunnels) is wildfires or lightning. Owing to the nature of transportation infrastructure, i.e., an unlimited supply of oxygen combined with large flammable fuels (such as that transported by fuel tankers), fires in transportation infrastructure can be "explosive" and "intense". For example, temperatures in bridge and tunnel fires can reach 700°C–1000°C within the initial stage of fire breakout, and such high temperature levels can be maintained for an hour or two [7,11]. This rapid increase in fire temperature can induce high thermal gradients, which

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often result in temperature-induced instabilities in steel girders [12–15]. Such thermal gradients along with high moisture conditions can result in ideal conditions for the spalling of concrete in tunnel linings, concrete girders, or piers/columns.

Fire problems in bridges and tunnels can be overcome by implementing appropriate fire resistance provisions for critical elements such as girders and linings. Fire resistance is defined as the duration during which a structural member exhibits adequate performance in terms of load carrying capacity, structural integrity, stability, and insulation functionality. Fire resistance, in general, is attained through suitable material selection, design, and detailing of structural members. However, no explicit requirements or provisions of minimum fire resistance to structural members in bridges or tunnels exist. Although such provisions are specified for dwellings, they may not be applicable to transportation infrastructure because of variations in fire severity, member attributes, and design objectives [9,16].

Despite the increasing awareness regarding the potential of fire in damaging the structural integrity of bridges or tunnels and hence unexpected delays and substantial monetary losses, comprehensive guidelines for overcoming fire hazards in transportation infrastructures are still insufficient. Even in some critical scenarios, where fire protection to transportation structures is considered, designers tend to extend the prescriptive fire requirement used in buildings to transportation structures despite major differences in key factors. Consequently, these prescriptive fire provisions may not yield optimum fire safety measures in transportation structures [1]. To narrow this knowledge gap, this review highlights the extent of fire in bridges and tunnels and identifies critical factors affecting the fire performances of transportation structures. The key strategies and emerging trends for mitigating fire hazards are discussed, and research needs for advancing this critical area are outlined.

## 2 Fire problem in bridges and tunnels

Literature review reveals that the number of fires in bridges and tunnels has increased significantly in recent years [2,17]. Most transportation fires occur because of fuel leakage resulting from collision or spillage. Consequently, fires in transportation structures are typically high in intensity. This is credited to collisions, which results in the quick ignition of highly flammable materials, which have a relatively low flash point. This burning of fuel initially results in extremely high temperatures (~700°C–900°C) with peak temperatures exceeding 1200°C.

Whereas the common perception among structural designers (and the general public) is that a bridge or tunnel is highly unlikely to collapse because of fire, intense fires can cause major degradation in the load-bearing capacity of main structural members. Such degradation can result in major damages to structural members, and in some cases, the collapse of fire-damaged bridges or tunnels. Some notable fire incidents on bridges and tunnels are listed in Tables 1 and 2, respectively. For each fire incident, the cause of fire and the damage type are summarized in these tables. A closer analysis into the fire incidents summarized reveals that fire hazard is a universal problem that can occur due to various causes. Whereas the majority of severe fires occur because of the collision of fuel tankers, e.g., the I-75 bridge near Hazel Park in Michigan and the Gudvanga tunnel in Norway, few fires occurred because of arson (I-85 in Atlanta, GA, USA) and natural effects such as wildfires (Green Spot Bridge, CA, USA) and lightening (Rio-Antirrio bridge, Greece).

Fire-induced damages and collapse in bridges have been documented in a current survey by the New York State Department of Transportation. The results of this survey revealed that in time period 1990–2005, nearly three times more bridges have collapsed because of fire than earthquakes [2]. In the case of tunnels, Schütz [5] performed a worldwide survey on fires in tunnels. This survey indicated that 177 fire incidents had occurred in 29 countries since 1866. Among these 177 tunnel fire incidents, 28 major fires were recorded between 1949 and 2008. Furthermore, these tunnel fires resulted in more than 700 deaths, 1000 injuries, and loss of more than 500 vehicles.

However, it is noteworthy that the breakout of a fire on a bridge or in a tunnel is rare, and even in such cases, only a few fires become large fires that adversely affect the integrity and performance of the main structural members. For example, through a statistical analysis on US bridges, tunnels, and buildings, Naser and Kodur [10] demonstrated that the annual prospect of fire occurring in a bridge was approximately 5%, which was slightly higher than that in tunnels (approximately 3%) but much lower than that in buildings (approximately 12%). Despite this small probability of fire occurrence, the fire incidents listed above clearly indicate the devastating effect of high intensity fires in terms of structural damage, traffic detouring, and economical losses. Even in the case of lower-intensity fires, a rapid temperature increase can generate thermal gradients. Such gradients can result in "unconventional" failures, such as spalling or temperature-induced buckling [13,37,38]. To demonstrate typical fires in bridges and tunnels, four recent fire incidents are presented herein.

On April 29, 2007, a large fire occurred in the vicinity of a major bridge connecting the I-580 MacArthur Maze interchange in Oakland, CA. This bridge was built in the mid-1990s and comprised two spans of six 25.6 m bare steel girders (without any fire protection). The fire started when a fuel tanker transporting 32500 litters of fuel overturned, resulting in a sudden conflagration that yielded intense temperatures that were approximately 1100°C [39]. Consequently, the strength and stiffness of the bare steel girders weakened due to a rapid increase in the

**Table 1** Noteworthy bridge fires

| location | date | cause | material type used in structural members | damage |
|---|---|---|---|---|
| I-85 bridge, GA, USA [18] | March 30, 2017 | vandalism led to burning of large Polyvinyl chloride (PVC) pipes stored under the bridge | concrete bridge | one span collapsed after 30 min of fire break out |
| I-375 bridge, MI, USA [19] | May 24, 2015 | gasoline tanker carrying 9000 gallons crashed | composite bridge | concrete deck was significantly damaged by fire |
| I-15 at Cajon, CA, USA [20] | May 5, 2014 | construction Workers cutting rebar with blowtorches spread the fire into the “falsework” of the bridge | composite bridge | collapse |
| Bridge over freeway 60, Los Angeles, CA, USA [21] | December 14, 2011 | a tanker carrying 33814 gallons of gasoline caught fire | precast prestressed I girders and cast in place reinforced concrete slab | concrete girders were significantly damaged and bridge was demolished and replaced |
| Zhuoshui Fengyu Bridge, China [22] | November 29, 2013 | unknown | wood girders on top of brick piers | bridge collapsed after burning of wooden superstructure. |
| I-75 Bridge, MI, USA [1] | July 15, 2009 | gasoline tanker collision | composite bridge | collapse |
| Big Four Bridge, KY, USA [1] | May 7, 2008 | electrical problem of the lighting system | steel truss bridge | minor structural damage resulting in large amount of debris on the bridge |
| Bill Williams River Bridge, AZ, USA [23] | June 20, 2007 | gasoline tanker over-turned | precast prestressed I girders and cast in place reinforced concrete slab | concrete girders were severely damaged |
| Rio–Antirrio bridge, Greece [24] | January 25, 2005 | lightning strike caused one of the cable links snapped | cable stay composite bridge | cable failed after 40 min into fire |
| Wiehltalbrücke Bridge, Germany [1] | August 26, 2004 | collision of fuel tanker transporting 33000 litters of fuel | steel bridge | major damages that costed €7.2 million |
| I-95 CT, USA [25] | March 26, 2003 | a car struck a truck carrying 8000 gallons of heating oil near the bridge | composite bridge | collapse |

temperature, which resulted in large overstressed fire-damaged bolted connections and hence a collapse within 22 min. The fire resulted in significant traffic disruptions and detours for weeks in one of the busiest traffic routes in the United States. Additionally, the associated fire losses were estimated to be $10 million.

Most recently, on March 30, 2017, a fire occurred on a bridge located on the I-85 route near Atlanta, GA [40]. This bridge, which was built in 1953 and reconstructed in 1985, achieved a “sufficiency rating” of 94.6 on a scale of 100 in a recent inspection in 2015. The I-85 bridge comprised ten prestressed concrete girders resting on top of three reinforced concrete piers; furthermore, it served 243000 vehicles per day. On March 30, a fire started underneath the bridge because of the burning of large polyvinyl chloride (PVC) pipes stored under the bridge, and this fire was initiated from vandalism. Because of the burning of these plastic pipes, the temperature increased rapidly to 900°C–1100°C, as reported by the Georgia Department of transportation (DoT). During firefighting operations, firefighters reported hearing “explosive sounds” attributed to concrete spalling, and they were advised to evacuate the fire scene. Thirty minutes into the intense heat arising from the burning of plastics and composite materials, a span measuring 30.3 m long collapsed, whereas adjacent piers and spans underwent significant damages, as shown in Fig. 1. Post-fire investigation revealed major spalling in the concrete piers and girders within (and near) the collapsed portion of the bridge. The aftermath fire losses were estimated to be $10 million, and several weeks were required to repair the damage [40].

In the case of tunnels, a number of fires have occurred recently; some of these fire incidents are listed in Table 2. To illustrate the devastating effect of fire, two fire incents are discussed. The first fire incident occurred in the 16.9-km-long Gotthard Road Tunnel pass in Switzerland. This tunnel, which was open for traffic since 1980, was affected by a major fire on October 24, 2001 because of a collision between two heavy goods vehicles (HGVs) [41]. This collision resulted in the ignition of gasoline fuel in one of the HGVs that spread rapidly to the second HGV involved in the accident along with five other vehicles. However, at the time of the accident, the active fire protection system

**Table 2** Notable fire incidents in tunnels

| location | date | cause | material type used in structural members | damage |
|---|---|---|---|---|
| Weihai city tunnel, China [26] | May 9, 2017 | bus collision | concrete lining | 12 deaths (11 children) |
| Hachihonmatsu tunnel, Japan [27] | March 17, 2016 | a truck crashed into several vehicles stopped in a pile up, fire burned for three hours | concrete lining | 2 deaths and 70 injuries |
| Sangju tunnel, South Korea [28] | October 26, 2015 | truck carrying flammable paint thinner exploded after crashing into tunnel siding | concrete tiles | 21 injuries |
| Shanxi tunnel, China [29] | March 1, 2014 | two methanol tanker trucks collided | NA | 31 deaths and major damages to tunnel (which did not have any ventilation facilities) |
| Gudvanga tunnel, Norway [28] | August 5, 2013 | HGV on fire due to engine break down duration | concrete lining | 67 severe injuries |
| Melbourne Burnley road tunnel, Australia [30] | March 23, 2007 | collision of truck and car | concrete lining | 3 deaths and minor structural damage |
| Howard Street tunnel, Mary-land, USA [31] | July 18, 2001 | derailment of the train car | concrete lining | losses estimated at $12 million |
| Tauern road tunnel, Austria [32] | May 29, 1999 | collision of cars and HGVs and lasted to 53 h | concrete lining | losses estimated $32 million (and 12 deaths) |
| Channel rail tunnel, France-UK [33] | November 18, 1996 | HGV caught fire and fire burned for 10 h | concrete lining | $278 million in losses |
| Summit Tunnel fire, UK [34] | December 20, 1984 | train carrying more than 260000 gallons of gasoline derailed, the fire lasted 3 days | brick lining | tunnel was shut down for nine months for repairs |
| Salang Tunnel fire, Afghanistan [33] | November, 3 1982 | two military convoys of Soviet Army collided causing a traffic jam | concrete lining | 176 deaths |
| Caldecott tunnel, California, USA [34,35] | April 7, 1982 | collision between gasoline tanker, car and bus, fire lasted for 2 h | concrete lining | losses estimated $3 million (and 7 deaths) |
| Holland Tunnel fire, NY, USA [36] | May 13, 1949 | truck carrying 4400 gallons of carbon disulfide malfunctioned | tiles | 66 people were injured, tunnel walls spalled and concrete ceiling collapsed |

installed in the tunnel included fire detection systems, which were ineffective in detecting fire breakouts. Consequently, seven vehicles were burned, causing the tunnel to be filled with intense heat and toxic smoke. The fire in the tunnel lasted for more than 24 h and high temperatures were reached [41,42]. Such conditions prevented firefighting activities, resulting in 11 deaths and a number of injuries. The heat arising from the severe fire also resulted in the explosive spalling of the concrete linings and the collapse of a portion of the tunnel ceiling measuring 250 m long. As a result of this damage, the tunnel had to be closed for two months for repair works.

The second fire incident described below represents one of the worst recorded tunnel fires in Europe. This fire occurred in the Mont Blanc Tunnel in Italy. This tunnel, which was opened for traffic since 1965, was 11.6 km long and 8.6 m wide. The fire occurred on March 24, 1999, when a Belgian truck with a refrigerated trailer carrying significant quantities of margarine and flour (equivalent to a 6100 gallons of oil) caught fire. This fire quickly spread to other vehicles, and because of the intense heat generated, smoke filled the entire tunnel section, preventing emergency evacuation and firefighting operations. This fire lasted for 53 h and reached temperatures exceeding 1000°C, killing 39 people, including a commanding firefighter officer. In addition, 14 other firefighters who were trapped in two of the emergency fire cubicles suffered from serious injuries. This fire destroyed more than 30 vehicles and caused losses exceeding $390 million, including severe spalling exceeding 900 m of concrete linings and roofs [5].

## 3 Complexities in applying conventional fire design methods

In the current practice, fire threats in dwellings and buildings are overcome through the provision of active and


**Fig. 1** Post fire damage in I-85 bridge in Atlanta, GA, USA (courtesy of GDoT).

passive fire protection systems detailed in building codes and standards [43]. Although the implementation of such provisions in other structures can result in undesirable fire effects, these fire safety provisions may not be pertinent to transportation structures owing to significant variations arising from fuel characteristics, ventilation conditions, and geometrical features. Table 3 highlights the key differences in characteristics between buildings, bridges, and tunnels from the fire performance perspective. It is noteworthy that the comparative features listed in this table for buildings, bridges, and tunnels are based on predominant factors that contribute to fire performance.

The fire growth characteristics in a bridge or tunnel are dissimilar to those in a building. In the latter, cellulose-based fuels comprising combustible materials are typically ignited; these fuels burn gradually and hence produce less intense fires. However, gasoline- or chemical-based fuels generally correlate with bridge or tunnel fires ignited at rapid rates, generating high intense heating rates. Cellulose-based fuels can be represented through a standard fire curve (with the fire temperature increasing from 20°C to 548°C after the first 5 min and reaching 1000°C over a period of 120 min). Meanwhile, gasoline fires resulting from the burning of combustibles and chemicals can be described through a hydrocarbon fire curve (such as ASTM E1529) or tunnel fires. These hydrocarbon fires can reach 1050°C within 5–10 min of ignition and can generate high levels of toxins and smoke [44].

Ventilation characteristics are another difference among buildings, bridges, and tunnels. Buildings are typically designed to be compartmentalized; consequently, each compartment contains limited fuel and oxygen. Meanwhile, bridges and tunnels are much larger and open spaces with an unlimited supply of oxygen, and when mixed with large fuels (i.e., chemical spills), they provide ideal conditions for intense fire burning and spread. This effect is amplified during a tunnel fire, as smoke spread and radiative heat transfer from tunnel linings can produce ideal conditions for a rapid increase in temperature. Another complexity that is associated with tunnels is the enclosed nature of tunnels, which limits the availability of escape routes and restricts evacuation and firefighting activities [45].

Fire hazards in buildings can be overcome using active fire protection systems, e.g., alert and suppression systems such as smoke detectors. Such systems help detect and control fire spread during the early stages of ignition. Although such systems (specifically ventilation/air circulation-related systems) are being used in tunnels, bridges still lack active fire protection systems owing primarily to from installation challenges and cost implications. Meanwhile, active fire protection systems in tunnels are primarily installed to control the spread of smoke and facilitate commuter evacuation. Recently, concerns have been raised regarding activation time and system reliability, particularly under fast-developing fires. In one study, Li and Ingason [11] indicated some of these concerns raised by the Swedish Transport Administration, which is planning to construct a new highway connection known as the Stockholm Bypass.

In addition to the above, other differences in structural features exist between buildings and transportation structures. For example, structural shapes in buildings (used for beams and columns) are often compact, whereas those in bridges are slender (i.e., plate girders). This selection of shapes arises from differences in performance requirements and aims to satisfy cost constraints. Whereas slender members can be designed optimally to satisfy load

**Table 3** Variation between key characteristics of buildings, bridges, and tunnels

| scenario | building | bridge | tunnel |
|---|---|---|---|
| fuel source | wood/plastics | hydrocarbon[a)] flammables | hydrocarbon [a)] based |
| ventilation | restricted supply of oxygen | unlimited supply of oxygen | unlimited supply of oxygen [b)] |
| fire severity | ISO 834/Natural fires | hydrocarbon fire/ ASTM E1529/pool fires | hydrocarbon fire/ ASTM E1529 |
| enclosure | compartmentation | open | large space |
| fire protection features | active and passive systems | – | some features (such as smoke control systems) [c)] |
| structural members | | | |
| failure limit state | mainly flexural | flexural/shear | lining materials |
| typical connections | web and/or the flange | bearing of the bottom flange | – |
| typical sectional slenderness | web slenderness [50] | web slenderness (150 with no stiffeners) | – |
| loading | dead load + % of live load | dead load + (very little live load) | dead load |
| exposure conditions | interior environment | outdoor environment (i.e., high humidity/ moisture content etc.) | outdoor environment (i.e., high humidity/moisture content etc.) |

Note: a) Predominantly hydrocarbon fuels, and other fuels (wood etc.) is also possible. b) In open tunnels; can be limited if the tunnel is partially or fully closed. c) These are general features provided in most tunnels; additional fire protection features can be present in certain tunnels.

capacity requirements under ambient conditions, they can be susceptible to temperature-induced instabilities [46,47]. From a construction material perspective, newer concrete types have been demonstrated to exhibit poor fire-resistance properties compared with conventional concretes. For example, high-strength concrete (used in bridge and tunnel construction) is prone to a faster degradation in mechanical properties and can undergo spalling, particularly under severe (intense) fire conditions, as those encountered in tunnels and bridges. To mitigate spalling and rapid loss in strength and modulus properties, a number of solutions have been proposed [48,49]. These solutions include the addition of special fiber reinforcements to concrete (i.e., polypropylene fiber) and enhanced lateral confinements.

Despite the adverse effects of fire, design provisions for transportation structures do not specifically entail installing passive fire protection measures [50,51]. This is primarily owing to the popular belief that the likelihood of fire occurrence in bridges and tunnels is low and hence does not justify the cost associated with passive fire resistance provisions. Other issues related to the durability of fire protection under harsher weather conditions (e.g., freezing/thawing cycles and high humidity) contribute to the complexity in installing and maintaining fire insulation. The lack of effective protection systems may result in bridges and tunnels becoming highly vulnerable to adverse effects of fire. (It is noteworthy that future editions of NFPA 502 [50], American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Technical Committee 5.06 will include new guidance directed toward the installation of passive fire protection systems to transportation structures.)

## 4 Strategies for enhancing fire safety

Recently, a few studies have addressed the problem of fire hazards in bridges and tunnels [6,17]. In these studies, limited fire tests and numerical studies were performed on specific bridges or tunnel structures exposed to fire. However, no general approach exists for addressing fire safety in bridges and tunnels. Hence, a broad approach for enhancing fire safety in transportation structures is proposed. Additionally, a number of innovative strategies that can be adopted to assess and improve the fire resistance of bridges and tunnels are presented in this section.

### 4.1 Overall approach

Although fire is a substantial threat to transportation structures, the probability of its occurrence in a bridge or tunnel is low. This implies that it may not be economical or practical to design all bridges and tunnels with fire safety. Only "critical" transportation structures with elevated risks of fire should be designed or upgraded to ensure fire safety.

The overall strategy for mitigating fire hazard in a bridge or tunnel comprises five main steps, as shown in Fig. 2. In the first step, susceptible transportation structures susceptible to fire risk are identified. This identification process requires the consideration of various critical parameters, such as the type of construction materials, structural features, facility location, and possible fire scenarios. In this step, the magnitude and risk of fire hazard on a bridge or tunnel are quantified by analyzing a fire-based importance factor. When such an analysis indicates a

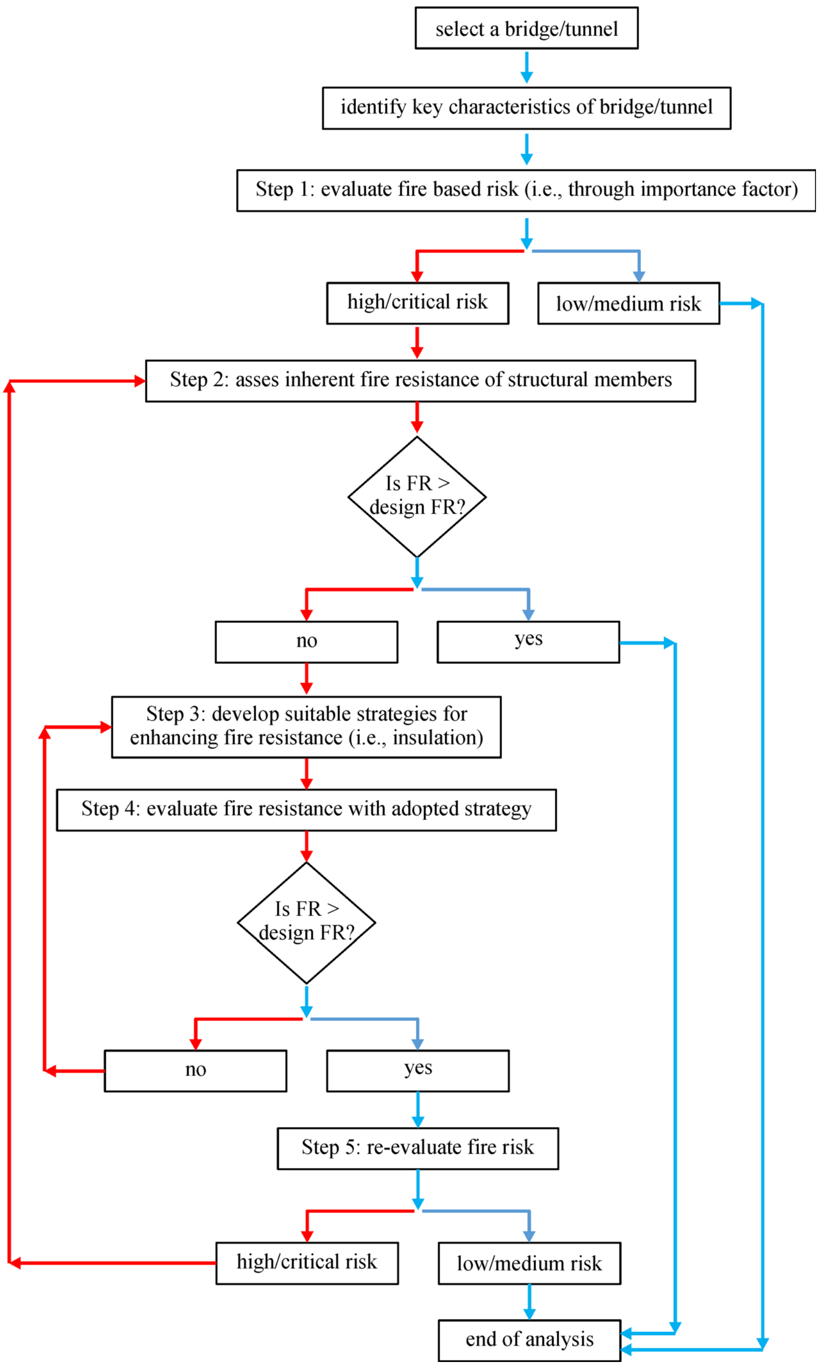


**Fig. 2** Flow chart of the proposed approach for mitigating fire hazard in transportation structures (FR: Fire resistance).

high fire risk to the transportation structure, then relevant mitigation strategies should be developed.

If the selected bridge or tunnel is identified to be susceptible to fire, then the fire performance of this structure will be assessed through qualitative approaches (engineering judgment based on previous fire incidents) and/or quantitative measures (through numerical simulations). Hence, in the second step, the selected structure is analyzed under possible thermal (fire scenarios) and structural loading effects to evaluate its inherent fire resistance. If that analysis indicates that a particular structural member (i.e., a girder or pier) possesses low fire resistance, then carefully designed strategies will be implemented, as part of the third step, to mitigate the adverse effects of such fires and to enhance structural fire safety. Such strategies include the installation of automatic flooding agents or water curtains in tunnels and configuration modifications by providing fire insulation to improve the fire resistance of main structural members in bridges. Subsequently, in the fourth step, the modified structure is reanalyzed iteratively until structural members with sufficient load-bearing capacity that can withstand fire hazards are obtained. In the final (fifth) step, the numerical analysis is performed under various scenarios until the fire risk of the structure is minimized.

### 4.2 Identification of critical structure for fire hazard

As discussed earlier, the first step in the proposed approach is to identify fire-critical transportation structures. Such identification can be performed based on a fire-based importance factor similar to the importance factor for wind loading. However, unlike the other factors, statistical data pertaining to fires in transportation structures are scarce and not widely available. Moreover, the associated frequency, random nature of fire, and lack of relevant mathematical models further challenges and the development of such importance factors. However, many of these limitations can be overcome if an importance factor is derived based on rational engineering judgment.

A fire-based importance factor was recently developed for classifying bridges based on fire hazard risk [52]. This derived factor accounts for the vulnerability of structural members to fire as well as adverse consequences resulting from fire on transportation networks and local economies. The key characteristics that determine the critical nature and vulnerability of a bridge to fire hazard are categorized into six classes: geometrical properties and design features, hazard (fire) likelihood, traffic demand, economic impact, expected fire losses, and availability of fire mitigation strategies. Each of the aforementioned classes includes various influencing features that collectively contribute to the derived fire importance factor, which is evaluated through a weighted factor approach. Although this importance factor has been specifically developed for bridges, the principles utilized in this approach can be extended for classifying fire risk in tunnels and other transportation structures.

### 4.3 Risk assessment

The main goal of enhancing the fire safety of transportation structures is to minimize adverse consequences of fire hazards, including life loss, property damage, interruption to traffic, and economical shortfalls. To enhance fire safety in a typical bridge or tunnel to a certain level, the fire risk must be assessed first. Such an assessment involves quantifying the probability (likelihood) of fire breakout and estimating the magnitude of potential losses resulting from a fire incident. Hence, an appropriate risk assessment measures the vulnerability of a bridge or a tunnel in terms of structural performance, number of vehicles served daily, availability of alternative routes, etc. Such an assessment also identifies the characteristics of probable fire incidents and the potential consequences on transportation networks when a fire occurs. In general, the risk assessment comprises three components: hazard identification, vulnerability analysis, and risk analysis. The first component aims to identify the magnitude of fire to which the infrastructure is susceptible. By performing a vulnerability analysis, potential losses can be estimated in bridges and tunnels. Finally, risk analysis includes a further analysis of fire characteristics, such as the severity and frequency of occurrence.

### 4.4 Enhancing fire resistance

One of the most effective and practical strategies to overcome the adverse effects of fire hazards on transportation structures is by enhancing the inherent fire resistance. In general, fire resistance is highly affected by the type of construction material (i.e., concrete structural members can be provided with sufficient concrete cover thickness, whereas fire proofing to steel members is required to achieve 1 to 2 h of fire resistance). In some cases, the use of composite construction has been shown to enhance fire resistance owing to the positive effect of composite action. This enhancement can significantly improve structural performance under ambient conditions and has been shown to significantly enhance structural performance under fire conditions, even without the use of fire insulation [53].

Furthermore, fire resistance is affected by the structural configuration and design parameters. For example, circular concrete piers in bridges provide better fire performances than rectangular piers. This is because the temperature propagation in circular sections is slower than that in rectangular sections (owing to lack of edges and bi-dimensional heat transmission). In the case of steel structural members, the use of thicker steel sections (specifically with thicker webs) prevents the rapid loss in shear capacity and the development of temperature-induced local buckling, both of which occur when using slender sections in bridges. In general, fire resistance can be enhanced by appropriate detailing and accounting for fire-induced forces [53]. Furthermore, fire resistance can be enhanced through the installation of suppression systems [33]. Such systems may include sprinklers, foam systems, water spray systems, and water mist systems and may differ in the operating pressure and droplet size [11,54].

### 4.5 Appropriate selection of construction materials

Recent technological advancements have enhanced the key performance characteristics of construction materials used in transportation infrastructure. For example, newer types of high-performance concrete (HPC) are more durable and exhibit improved strength characteristics compared with conventional concrete. Despite such improved properties, HPC is still more vulnerable to fire because of its rapid temperature-induced degradation in strength compared with normal strength concrete. Furthermore, HPC is susceptible to fire-induced spalling arising from its dense mix and low permeability. Fire-induced spalling can decrease the cross-sectional area of concrete members, thereby increasing heat transmission to steel reinforcements. This accelerates the loss in the load-bearing capacity and promotes premature failure in the main structural members of bridges and tunnels.

To overcome spalling in concrete members, a number of novel solutions have been developed in recent studies [55]. One such solution is the addition of polypropylene fiber to the concrete mix. Polypropylene fibers melt at a relatively low temperature of 170°C, and once melted, these fibers create "channels" for vapor to escape, thereby preventing pressure buildup within concrete members. This can be a feasible solution because only a small amount of polypropylene fibers (approximately 0.1%–0.15% by volume) is required to minimize spalling [56]. The use of such fibers can be beneficial particularly in tunnels where concrete is highly prone to spalling because of high moisture conditions. Another strategy to improve the resistance of concrete to spalling is by adding steel fibers [57,58]. These fibers significantly enhance the tensile strength of concrete; consequently, tensile stresses generated by the increase in pore pressure are overcome and spalling is minimized.

### 4.6 Use of rational approaches for fire design

Transportation structures, particularly bridges, are currently not designed to withstand fire hazards. In rare cases, such as tunnels, some fire mitigation measures (primarily active systems) are applied, and these measures are often based on the extension of the prescriptive provisions used in building design. As discussed earlier, this approach of extending current prescriptive provisions used in buildings to transportation structures may not yield optimum fire performances because of significant differences between buildings and bridges or tunnels. Hence, it is acknowledged that conventional "prescriptive" approaches present numerous disadvantages. However, these disadvantages can be overcome by applying rational approaches for fire design. The rational approaches are based on engineering principles and can account for unique features of transportation structures based on sophisticated analysis. Through these approaches, innovative solutions can be customized to achieve the required fire performance in transportation structures.

### 4.7 Incorporating cognitive features in critical structure

One of the modern strategies for enhancing fire safety in critical infrastructures is by adopting a coupled sensing-structural framework that utilizes "Internet of Things" technology [16,59]. This framework involves incorporating cognitive abilities in bridges and tunnels through various sensing devices. Such a framework allows a newly designed (or upgraded) transportation structure to collect observations and measurements during fire and to independently analyze the data to predict structural performances and commuter behaviors in real time. This cognitive ability can significantly improve the fire response in bridges/tunnels by facilitating disaster response and management operations.

## 5 Case study

The aforementioned strategies are applied to overcome fire hazards in critical transportation structures. To illustrate this, an actual bridge that experienced fire was selected for analysis as part of a case study, and the steps discussed above were applied to minimize the adverse effects of fire hazard. The I-65 overpass in Birmingham, USA, which had experienced fire-induced structural damage, was selected for this case study.

### 5.1 Description of incident

A fuel tanker transporting 9900 gallons of diesel collided with a pier belonging to the I-65 overpass near Birmingham, Alabama, on January 5, 2002. This collision resulted in a fire with intense heat reaching approximately 1100°C, causing significant degradation to steel girder number 7 and hence deforming 3 m within 20 min. After the fire was extinguished, the bridge had to be shut down. The repair required 54 days and incurred $1.33 million before the bridge was reopened for traffic [60].

### 5.2 Characteristics of I-65 bridge

The I-65 bridge was erected with three simply supported spans (25 m-36 m-25 m). Each span carried seven girders equally spaced at 2.15 m. The girders comprised 350 MPa built-up sections with flange plates (457 mm × 28 mm) and a web plate (1344 mm × 12 mm), and they were stiffened with 12-mm-thick stiffeners spaced 1.1 m and 25 mm at the support locations. The steel girders supported a concrete slab (170 mm × 2150 mm) with a compressive strength of 40 MPa [60].

### 5.3 Evaluating fire-based importance factor

Following the steps outlined in Fig. 2, the "fire-based importance factor" was evaluated to assess the susceptibility of the I-65 bridge to fire. Through an analysis of the bridge characteristics conducted previously [19], it was clear that the fire performance of this bridge was dominated by the fire performance of steel girders; furthermore, the importance factor of the bridge was evaluated to be 1.2 ("high" risk category implying the bridge is susceptible to collapse during severe fires). A detailed calculation of the importance factor for this bridge is presented elsewhere [52].

### 5.4 Evaluating fire resistance of steel girders

To cross-validate the actual fire resistance of this bridge, finite element simulations on steel girders were conducted [52]. The layout of the girder as well as its cross section are shown in Fig. 3, where a 36, simply supported steel girder was selected for analysis in ANSYS. A fire analysis on the I-65 bridge girder was performed under a hydrocarbon fire scenario, and the structural loading was assigned to a full dead load and 20% of live load, which were estimated as per the AASHTO provision. The temperature-dependent material properties used in this analysis were based on Eurocode 2 and Eurocode 3 recommendations.

The temperature distribution in the steel girder and concrete slab as a function of fire exposure time, as obtained from the analysis, is shown in Fig. 4. An analysis of the plotted results indicates that the temperature increased rapidly in both the bottom flange and web and reached 1000°C within 20 min of fire exposure. As concrete possesses high thermal capacity, the temperature increase in the slab remained low (360°C), and the slab attracted most of the heat from the top flange. This translates into a large thermal gradient and hence thermal bowing.

The mid-span deflection of this bridge girder is illustrated in Fig. 5. As shown, at the early stage of fire, the mid-span deflection increased linearly owing to thermal bowing resulting from the development of thermal gradients. Subsequently, the rapid increase in temperature resulted in the further weakening of the mechanical properties of steel, wherein the steel web began to exhibit instability. During the later stages of fire, the rate of deflection increased rapidly as the creep effects amplified. Finally, the steel girder failed as a result of the flexural capacity loss, and the bridge girder failed 9 min after being exposed to severe hydrocarbon fire (see Fig. 5).

### 5.5 Developing strategies for enhancing fire resistance

A gypsum-based spray fire insulation (SFRM) was applied to minimize fire damage. Hence, a series of finite element

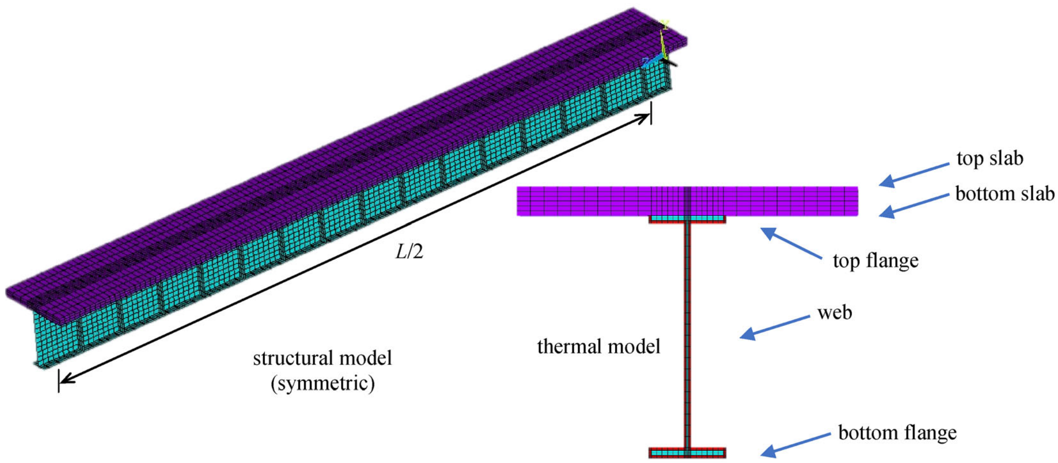


**Fig. 3** Discretization of a steel bridge girder for thermal and structural analysis.

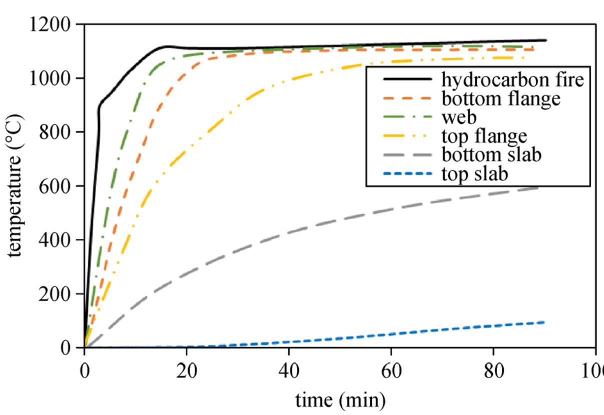


**Fig. 4** Temperatures progression in bare I-65 Birmingham Bridge.

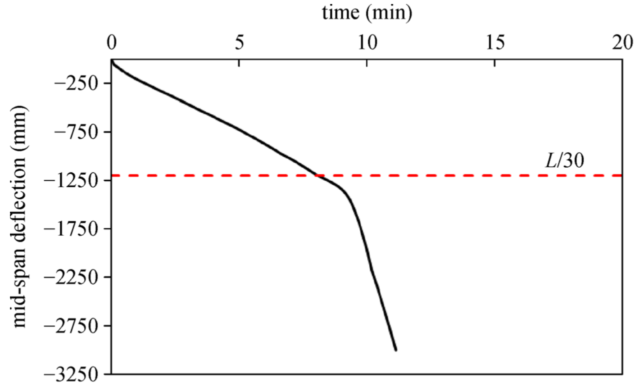


**Fig. 5** Mid-span deflection in bare I-65 Birmingham Bridge girder.

analyses was performed using various thicknesses of the SFRM to obtain an optimum fire insulation thickness. At the end of each analysis, the corresponding fire resistance was evaluated until the fire resistance requirement was satisfied.

To illustrate this procedure, two insulation thicknesses of 16 and 30 mm were selected for analysis. Figure 6, which presents the outcome of this analysis, shows that the addition of 16- and 30-mm thick fire protection increased the fire resistance of the steel girder from 9 to 76 and 125 min, respectively. This enhanced fire resistance can significantly lower the risk of fire-induced damages or collapse. Using the same approach, the designer can achieve any level of fire resistance based on the specific requirements of a bridge.

### 5.6 Re-evaluating fire-risk-based importance factor

To confirm that the vulnerability of the bridge to fire risk is reduced, the fire-risk-based importance factor was re-evaluated by considering the modified characteristics of the girder, including the newly added fire protection to the steel girders. Hence, the importance factor evaluated for the reconfigured bridge decreased to 1.0 (from 1.2), indicating a “medium” (from “high”) importance factor. This implies that using insulating steel girders, the fire risk on a bridge can be reduced and the risk of fire damage is minimized (see Table 4).

## 6 Research needs

Although research and development have been performed in recent years to enhance the fire safety of transportation structures, it can be inferred from the discussion above that design guidelines pertaining to fire safety assessment and the development of relevant strategies for enhancing fire performance in transportation structures are still insufficient. Hence, further developments are necessitated to mitigate fire hazards in transportation structures. A few of these research needs are highlighted herein.

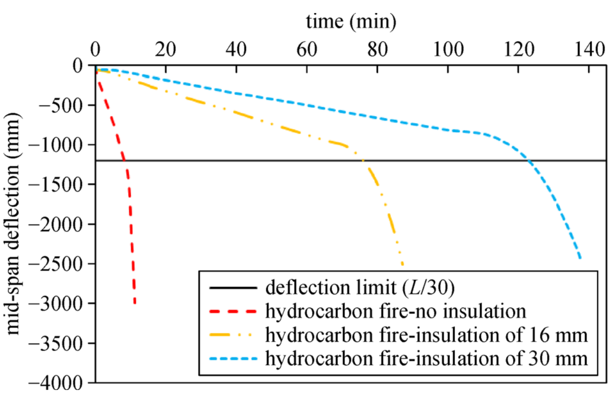


**Fig. 6** Comparison between mid-span deflection in uninsulated and insulated I-65 Birmingham Bridge girder.

**Table 4** Summary of simulation analyses on I-65 Birmingham Bridge

| case | girder condition | insulation thickness (mm) | risk grade (importance factor) | failure time (min) |
|---|---|---|---|---|
| I-65 Birmingham Bridge | bare girder | – | high (1.2) | 9 |
| | insulated girder | 16 | medium (1.0) | 76 |
| | insulated girder | 30 | medium (1.0) | 125 |

### 6.1 Classification of transportation structures based on fire risk

Because approaches for identifying vulnerable transportation structures to fire hazards do not exist, a comprehensive approach for evaluating fire risk in bridges and tunnels must be developed. Such an approach can be developed similarly as that of the importance factor used in building design. This importance factor can be developed based on a deterministic basis (such as checklists, engineering judgment, and weightage factors) or can be derived through probabilistic analysis from statistics and surveys collected on recent fire incidents and past performances of fire-damaged bridges and tunnels. In either case, the developed importance factor must be unified and applicable to a various transportation structures. Furthermore, this importance factor must account for the vulnerability of structural members to fire as well as the contribution of bridges (or tunnels) to traffic and network functionality. This can be achieved by considering key characteristics that determine bridge or tunnel performances under fire, such as geometrical configuration, construction material, fire likelihood, traffic demand, and economic impact. Hence, the recently developed importance factor for bridges can form the basis for extending the same concept to tunnels, metro stations, and other transportation structures.

### 6.2 High-temperature properties of materials

The thermal, mechanical, and material-specific temperature-dependent properties of construction and fire protection materials are critical for establishing an accurate prediction of the fire response of transportation structures. However, consistent high-temperature constitutive relationships are non-existent for new types of materials used in bridges and tunnels, such as HPC, high-strength concrete, high-strength low alloy steel, fiber-reinforced composites (FRPs), and more specifically, insulation materials. Hence, further research is warranted, particularly in regard to the development of high-temperature material properties under conditions encountered in transportation structures. This is because most standardized tests and material properties currently available in the literature are based on tests relevant to exposure conditions in buildings. Because fires occurring in transportation structures are much higher in intensity, relevant material models (and tests) that represent actual fire exposure in transportation structures are required [61].

### 6.3 Development of validated models

Numerical models currently used for evaluating the fire performance of structures, including bridges, only consider the degradation of material properties at elevated temperatures. These models disregard the effects of critical factors such as concrete spalling and creep, temperature-induced buckling in steel sections, degree of composite action in composite construction, and bond action in FRP-strengthened concrete members. Although these models only aim to evaluate the performance of structures under fire conditions, other aspects such as the modeling of fire spread and smoke movement as well as commuter behavior and evacuation are equally important; as such, they must be integrated into the development of such models. In general, numerical models that capture fire–structure interactions at the "member" level as well as fire-structure-human interactions at the global "system" level are required. Such numerical models should be validated to ensure their applicability to transportation structures subjected to fire; this may necessitate full-scale experiments.

### 6.4 Performance-based fire design approaches

Rational approaches based on performance-based fire design are currently being used in building design to a limited extent. The implementation of these methods has been shown to provide innovative solutions for enhancing fire safety in buildings. A performance-based design delivers a set of designs that satisfy performance criteria through a quantitative fire risk assessment using engineering and rational methodologies. Such approaches, which depend significantly on numerical analysis, are still being developed and require additional calibration and validation. Hence, to successfully extend these methodologies to evaluate fire performances in bridges and tunnels, performance-based design approaches must account for complex features of transportation structures, including severe fire scenarios and various failure limit states. Owing to the unique characteristics of performance-based approaches, guidelines must be defined to ensure the appropriate application of performance-based design methods to transportation structures.

### 6.5 Development of codal provisions

Codal provisions not only stipulate the fire performance for different transportation structures, but also provide guidance regarding applicable strategies for achieving the required fire performance. As appropriate provisions for the fire design of bridges and tunnels do not exist, specific guidelines must be developed for the fire design of such structures. These guidelines must address various aspects such as fire safety (e.g., active/passive systems and evacuation means), fire design (e.g., detailing of structural members and appropriate selection of construction materials), and fire analysis tools (e.g., validated models and analytical methods). Such guidelines can be developed through cooperation among governmental organizations, academics, professional societies, industry partners, and trade organizations.

### 6.6 Development of fragility functions

Because fire is a random incident, probabilistic frameworks have been gradually being adopted in fire design methods. Fragility analysis is one such framework that provides valuable information regarding the reliability of structural systems [62]. This framework recognizes the role of uncertainty in evaluating the fire response of structural systems by relating the intensity of fire hazard to the probability of exceeding a certain level of fire damage in a bridge or a tunnel. As such, fragility analysis incorporates the demand uncertainties (load event) and resistance (i.e., load-carrying capacity), which affect the transportation structure. The development of fragility functions associated with fire incidents in transportation structures can improve the current state of fire design and facilitate the identification of critical structures and transportation networks.

### 6.7 Assessment of post-fire residual capacity

In a severe fire, a bridge or a tunnel may experience significant structural damage or collapse, and exposure to moderate fires may not result in noticeable damage. However, localized damage can still occur, such as spalling in concrete linings (and girders) or local buckling in the web in the case of steel girders. Nevertheless, a fire-weakened transportation structure cannot be reopened for commuters, even after the fire is fully extinguished, until its residual capacity is evaluated appropriately [63]. Hence, it is imperative to develop approaches that can accurately evaluate the post-fire residual capacity of structural members/systems to facilitate the rapid recovery of services and to develop retrofitting solutions to repair bridges and tunnels.

### 6.8 Development of fire mitigation/preventative systems

The development of appropriate fire mitigation/preventative systems is critical to enable firefighting activities and evacuation. Fixed or movable smoke curtains (or smoke barriers) must be developed such that a platform region can be separated from a track tunnel when a fire occurs in train or carriages [11]. Furthermore, self-activating modern ventilation systems must be developed to extract smoke and toxic gases. Such systems must be installed in conjunction with normal tunnel and forced ventilation systems (i.e., natural opening or with shafts) and operated once a fire occurs. Additionally, fire-resistant cross passages and refuge areas may need to be developed.

### 6.9 Alternative fuel vehicles

Modern and smart vehicles utilize hybrid fuels or electric batteries. Hence, fire hazards associated with the use of such fuels must be understood. For example, the susceptibility of these vehicles to malfunctions and explosion near a bridge or in a tunnel must be considered [64].

## 7 Conclusions

The conclusions obtained from the review presented are as follows.

1) Fire is a severe hazard to transportation structures and can induce significant damages or collapse. Therefore, critical transportation structures must be designed appropriately to mitigate fire hazards.

2) Owing to significant differences in characteristics and structural members between buildings and transportation structures, current fire mitigation strategies applied in buildings may not be applicable to bridges or tunnels.

3) Estimating fire risk in a transportation structure and then performing a detailed finite element analysis to evaluate its inherent fire resistance is a general approach to evaluate its fire vulnerability. If the analyzed bridge or tunnel exhibits poor fire resistance, then appropriate strategies for enhancing fire resistance, such as the use of fire insulation, should be applied.

4) One of the most effective strategies for enhancing fire safety is to ensure appropriate fire resistance to structural members.

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