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Framework for fire risk assessment of bridges

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Abstract

Bridge fires are a major concern because of their social and economic consequences when bridges have to be closed to traffic. The concern for life safety is not significant as there are minimum reported fatalities during a bridge fire but can result in a huge economic and social consequence. Despite the frequency and consequences of bridge fires, they have been the subject of very few studies and are neglected in the different international bridge design standards. This paper presents a framework for evaluating the fire risk to the bridges. Fire risk is estimated by considering various criteria such as the social and economic impact of fire, the vulnerability of bridge structures to fire and the likelihood of a bridge fire. In this framework, each criterion, sub-criteria and alternative which can influence the fire risk of a bridge are assigned with a weighting value depending upon their importance. Analytical hierarchy process (AHP) is utilised to estimate the weightings for different factors. The proposed framework is implemented and validated using previous fire accident data. Six bridge fire incidents are considered in this study and the damage level experienced by them is found in compliance with the damage level associated with the fire risk estimated by the proposed framework. This framework presents an important methodology for the highway department and bridge engineers to estimate the fire risk for a particular bridge or entire bridge network in a region. An accurate estimation of fire risk helps the highway engineers to calculate the amount of fire protection required for bridge structures.

Keywords: Fire risk assessment, bridges, analytical hierarchy process, damage level, fire protection

1. Introduction

Generally, fire resistance to any structure is provided by an adequate structural design, installing active fire protection measures and providing suitable passive fire protection to the structural members. Design codes and standards are quite mature in addressing the issues related to fire safety and providing fire protection to the building infrastructure or closed spaces [1–3]. Whereas, bridge structures which are an integral part of the transportation system are ignored and unfortunately, at present, there are no specific requirements in codes and standards for fire resistance design of bridges or providing fire protection measure to the structural members in bridges.

In bridge design codes, although the impact of earthquake, wind and floods are incorporated, however, the equivalent provisions for fire hazard are generally ignored. This ideology is supported by the fact that bridges are open structures and fire safety measures might not require for this type of structures. However, it has also been reported in a survey [4] that the number of bridges damaged due to fire is significantly more than the number of bridges damaged due to earthquake. In the survey, 1062 bridge failures were investigated, 65% of the bridges were made of steel, 22% were concrete bridges, and 12% were timber bridges. Out of all the surveyed bridges, the facility type was known only for 799 bridges and it was reported that out of these 799 bridge failures, 91% were on roadways, 6% were on highways, 2% on railways, and 1% on pedestrian bridges. Lee et al. [4] have published a statistical report for bridge failure based on the causes of failure. It was reported that 3.2 % of bridges failed due to fire in comparison to 1.8% and 2.1 % bridge failure due to wind and earthquake, respectively. They opine the behaviour of bridge structures in earthquake and wind is relatively well understood compared to fire. Besides, the fire protection measures provided in buildings may not be applicable for bridge infrastructure due to large differences in key factors such as fire load, ventilation, structural member design objectives [5]. So, it is imperative to understand the behaviour of bridge structures under fire situations and develop suitable design methods. Nevertheless, to design all bridge structure in accordance with the fire requirement may be quite uneconomical. To decide whether a bridge is required to be designed for fire loads or it has to be provided with sufficient fire protection measures, a framework to assess the level of fire risk to bridge infrastructure needs to be developed. This framework would identify the bridges that are at high fire risk and only those bridges can be designed following suitable fire design methods. Moreover, according to the level of fire risk estimated by the framework, the necessary fire protection could also be estimated.

The cause of fire in most of the bridges that collapsed or failed due to fire was typically the crash of a tanker truck carrying a large amount of highly flammable substance such as gasoline [6]. The crash triggers an explosion and the subsequent heat release from the fire is so intense that it substantially reduces the material properties and load-carrying capacity of the bridge. Eventually, the softened steel, cracked concrete can no longer hold up the structure, and the bridge falls. The event of a bridge fire can be dreadful for the population living in that region in terms of the social and economic impact of the event. Due to a fire incident that affects the bridge structurally, the impact on the traffic flow of the region is devastating and it can lead to the complete closure of the bridge especially if it results in significant damage to structural members.

In the past, the risk to bridges due to fire and their structural behaviour has been studied by Kodur et al. [7,8], Kim et al. [9], Joo et al. [10] and Giuliani et al. [11]. Giuliani et al. [11] focused on the occurrence and consequence of bridge fires, considering both the economic and social impact and structural vulnerability factors. Important cases of recent bridge fire were also presented in detail and major structural damage were highlighted. The paper advocated the development of fire safety design for bridge structures whereas the fire risk assessment of bridges was not addressed. Joo et al. [10] proposed a method for assessing bridge fire risk by conducting field surveys. The underneath condition of the bridge was used to evaluate the fire risk and the fires over the bridge were not included in their study. In their field survey, it was found that the damage in special bridges such as cable-stayed and suspension bridges only occurred due to fire in the upper surface and the damage due to fire in the lower surface was negligible. Since their study was concentrated on bridge network in Korea and due to the low percentage of special bridges (1%) of the total bridges in Korea the fire risk assessment was carried out only on the general bridges.

Kodur et al. [8] developed an approach based on the calculation of weighting factors for various classes for estimating fire risk in bridges. The classes examined in their study consider the structural vulnerability of a bridge, traffic demand and economic impact of a bridge fire, etc. A bottom to down approach was used to calculate the weightings for various classes. The weighting factors calculated for each class were mainly dependent on the number of parameters considered in that particular class. If a greater number of parameters are assumed in a particular class, this would result in a very high weighting factor whereas a smaller number of parameters under a class would result in a very low weighting factor. For example, a weighting factor of 0.13 was estimated for the economic impact class and it is found to be very low when studying previous fire accidents where tremendous economic loss due to damage and closure of bridge occurred [12,13]. As observed in previous fire incidents, the concern for life safety is minimum, whereas, the economic impact of a bridge fire is one of the most important class while assessing bridge fire risk and should be assigned with a high weighting factor.

A methodology to estimate the fire risk of bridges present in Korea was proposed by Kim et al. [9]. This methodology estimated the qualitative risk to a bridge such as low risk, medium risk and high risk. The framework developed in the current paper estimates the bridge fire risk on a numerical scale. A numerical risk value provides a clear idea about the absolute fire risk to a bridge and relative fire risk within a bridge network. It would be helpful for highway engineers in estimating the requirement of fire protection for a bridge. The current paper uses a top to down approach for estimating the weighting factors and assessing fire risk to the bridges. A statistical method "Analytical Hierarchy Process" (AHP) combined with engineering judgement based on previous bridge fires is used to estimate the weightings for various parameters.

2. Fire risk assessment of bridges

In this paper, a framework has been developed by considering various factors which are responsible for a fire hazard to a bridge. The proposed method for evaluating the fire risk to a bridge takes into account the social and economic importance of the bridge, structural vulnerability to fire and also the likelihood of a fire incident on the bridge. Bridges are one of the most important parts of the transportation system of any region. The economical loss due to a fire-affected bridge is not only limited to the direct cost in repairing and rebuilding the damaged structure but also the indirect cost due to the closure of the bridge, which is sometimes multiple times the direct cost [12–14]. Due to the closure of the bridge that had undergone a fire, a huge loss incurred to the businesses which were using the bridge as the main transportation route [12]. The indirect cost due to the loss of operation of the bridge also includes the costs to the administration for providing an alternative transportation route and also the loss of revenue through toll tax.

For example, in 1995, a fuel tanker fire caused the collapse of two spans of the MacArthur Maze interchange in Oakland, California. This incident leads to the closure of the route for 26 days during which the damaged spans were reconstructed. Since this interchange was serving various major cities in California, it was estimated that the overall economic impact due to the closure was more than \$150 million with an average daily cost of \$6 million approximately [12,13]. In this case, the overall economic loss due to the suspension of the bridge was estimated as high as 17 times the direct cost of rebuilding the damaged part [13]. There are numerous other incidents where the economic impact due to the closure of the bridge was many times more than the direct cost of reconstruction of the bridge. In 2012, a similar fire broke out on one of the busiest bridges “Mathilde Bridge” in France. In this incident, the bridge structure did not fail but was massively damaged and cannot be repaired. Therefore, the damaged part was rebuilt which took more than 22 months for reconstruction [14]. The economic impact ($11 million) was not as high as the MacArthur Maze accident but it was still higher than the direct cost ($9 million) to repair the bridge [14]. The magnitude of the indirect cost was not many times compared to direct cost because it was one of six bridges over the Seine River in that city and the traffic was diverted to other bridges. However, if there were fewer number of bridges for the traffic to be diverted, the economic loss would have been more. Nevertheless, due to the divergence of the high volume of traffic to other bridges, a lot of inconveniences might have caused the people of that city. Therefore, in this study, the social impact of a bridge fire accident is also considered as one of the most important factors when assessing the fire risk.

Furthermore, even a temporary closure may have a huge social impact as in the case of the Mathilde Bridge fire. The overall sustainability of the entire region’s transportation system gets affected and it reduces the resilience of the network. Closure of the main transportation route may cause social inconvenience and unrest to the people of the affected region. Despite so many consequences of bridge fire incidents, there are rare guidelines available to assess the fire risk for bridge structures. One of the few guidelines related to this aspect of bridge development is NFPA 502 [15], Standard for Road Tunnels, Bridges and Other Limited Access Highways. NFPA 502 was published by the National Fire Protection Association and offers general recommendations for bridges that are approximately 1,000 feet long or more. To develop and implement fire design to all type of bridge structures, bridges at high fire risk need to be identified. The framework developed in this paper considers various important factors to assess the fire risk to bridge structures. The weighting factors to various fire risk affecting criteria have been assigned using a statistical process, AHP. The details of the AHP process are explained in the next section.

3. AHP Process

The analytic hierarchy process (AHP) was proposed by Saaty [16,17] in the early 1970s. It is a powerful multicriteria decision-making method that has been used in various economical, scientific and engineering applications. This method is based on the idea of pairwise comparisons of alternatives to achieve the desired goal. This is achieved by assessing the relative importance of one alternative over another by comparing them in pairs. The alternatives are compared in relative terms to their importance or contribution to the desired goal.

The AHP method enables the user to assign a value representing the preference degree of a criterion to each additional criteria [18]. These values help to establish a hierarchical structure and are used to select the appropriate alternative. In the field of construction management, such as project management, AHP is being widely used for selecting the technology, equipment, and materials [19,20]. Also, AHP is one of the most popular methods for evaluating software [21] [22].

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In this method, all criteria are arranged in the form of an inverted tree as shown in Fig. 1. The arrangement of criteria is made relative to their importance, where the main goal is placed at the top. Criteria which contribute to achieve the main goal are placed at the second level. Each criterion can be decomposed at the third-level into sub-criteria, and each set at each level meets the objective of the level to which they are subordinate. These sub-criteria are further decomposed into various alternatives as shown in Fig. 1. At each level, the criteria, sub-criteria and alternatives are listed and compared pairwise according to their contribution to reaching the main goal, criterion and sub-criteria, respectively.

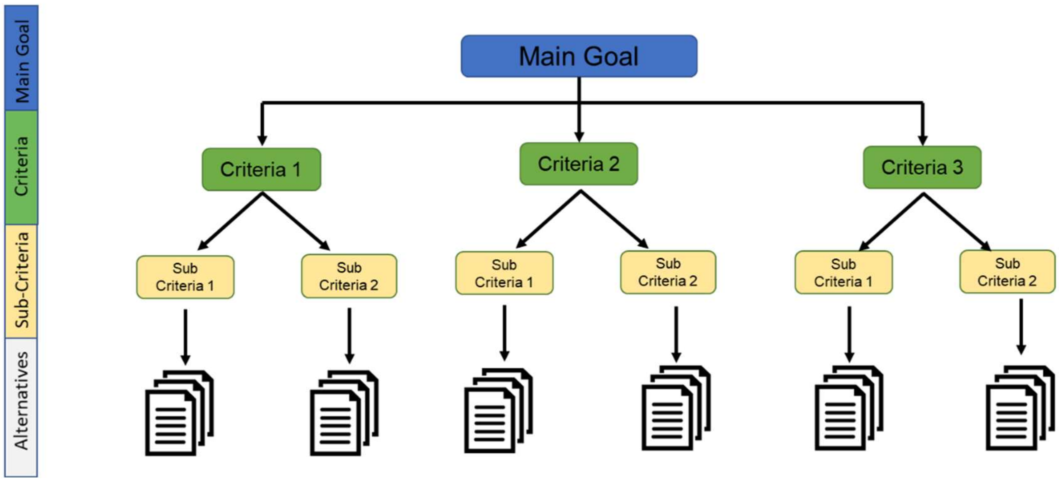

Figure 1 Hierarchical diagram used for in Analytical Hierarchy Process (AHP)

A square matrix (judgement matrix) is composed at each level using a pairwise comparison of criteria, sub-criteria and alternatives. The rows and columns represent different criteria that are being compared. The entries in each cell represent the ranking of the two criteria that are being compared. The judgement matrix A is an m×m real matrix, where, 'm' is the number of criteria being compared. Each element (a_{ij}) of matrix A represents the importance of the i^{th} criterion relative to the j^{th} criterion. If $a_{ij} > 1$, then the i^{th} criterion is more important than the j^{th} criterion, while if $a_{ij} < 1$, then the i^{th} criterion is less important than the j^{th} criterion. If two criteria have the same importance, then the entry a_{ij} is 1 and follow the Eq 1.

$$a_{ji} = 1/a_{ij} \qquad \text{Eq 1}$$

The entries a_{ij} and a_{ji} satisfy the following constraint:

$$\mathbf{A} = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{pmatrix} = \begin{pmatrix} \frac{w_1}{w_1} & \frac{w_1}{w_2} & \cdots & \frac{w_1}{w_n} \\ \frac{w_2}{w_1} & \frac{w_2}{w_2} & \cdots & \frac{w_2}{w_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{w_n}{w_1} & \frac{w_n}{w_2} & \cdots & \frac{w_n}{w_n} \end{pmatrix} = \begin{pmatrix} 1 & \frac{w_1}{w_2} & \cdots & \frac{w_1}{w_n} \\ \frac{w_2}{w_1} & 1 & \cdots & \frac{w_2}{w_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{w_n}{w_1} & \frac{w_n}{w_2} & \cdots & 1 \end{pmatrix}$$

In the above matrix,
w_i/w_j is the relative importance of i^{th} criteria relative to j^{th} criteria.

$$a_{ij} = w_i / w_j \qquad \text{Eq 2}$$

To make the pairwise comparisons, a fundamental scale as presented in Table 1 was proposed by Saaty [16].

Table 1 Fundamental scale of Saaty [16].

Intensity of importance	Definition
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance

According to this scale, the relative importance of the i_{th} criterion is estimated in comparison to j_{th} criterion. The phrases used in the definition column of Table 1 are only suggestive and can be modified depending upon the user's qualitative estimation of the difference in the importance of the two criteria. It is also possible to use other intensities of importance such as 1.1, 1.2, and, 1.3 for criteria that have a close importance level. According to Eq 1, the values in the construction of matrix *A* follows a pairwise consistency.

After the construction of the matrix, *A*, a normalized pairwise judgement matrix A_{norm} is derived using Eq. 3. Using Eq 3, the sum of the entries of each column becomes equal to 1. The entries of the normalized matrix are computed as below.

$$\bar{a}_{ij} = \frac{a_{ij}}{\sum_{l=1}^{m} a_{lj}} \qquad \text{Eq 3}$$

Finally, the weightings of each criterion are evaluated by averaging the entries on each row of the normalized judgement matrix (A_{norm}) using Eq. 4.

$$w_j = \frac{\sum_{l=1}^{m} \bar{a}_{il}}{m} \qquad \text{Eq 4}$$

4. Criteria, Sub criteria and alternatives

An inverted tree of various factors that contribute to the fire risk is shown in Fig 2. In this study, three main criteria are considered which contribute to fire risk of a bridge which are the social and economic importance of the bridge, structural vulnerability and likelihood of a fire. Each criterion is decomposed into various sub-criteria as shown in Fig. 2. Other sub-criteria are shown using a dotted line in Fig 2. These sub-criteria are further decomposed into alternatives as shown in Fig. 2. The individual weighting factors associated with each criterion, sub-criteria and alternative are calculated using the AHP process which will be explained in the later section. Various tables are presented later in section 5 which provide detailed checklists and values for alternatives which are being used for evaluating bridge fire risk based on recommendations of previous studies [5,8–10,13] and similar to the seismic risk and steel details included in New York State Department of Transportation vulnerability manuals [23,24].

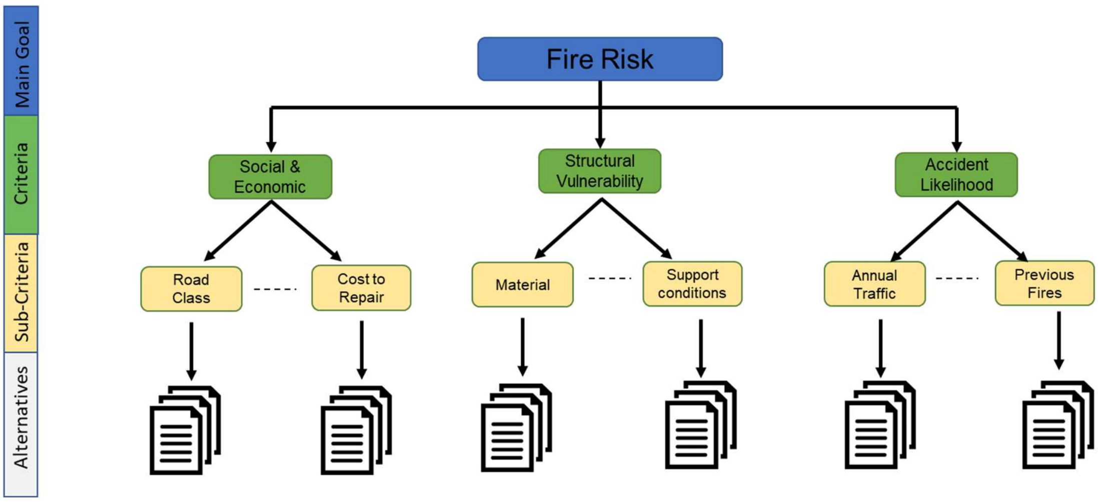

Figure 2 Hierarchical diagram for bridge fire risk assessment in AHP

4.1. Sub criteria under social and economic impact criterion

4.1.1. Bridge Location

The location of the bridge is crucial in estimating the social and economic impact when a bridge is affected due to a fire incident. If the affected bridge is the only route to connect two important places that are connected socially or economically, then the disruption in the bridge services to allow traffic flow can cause a social disconnect in the region and the resulting financial loss could also be very high. In such situations, any closure of a bridge due to a fire accident will drastically affect the social and economic activities in the region.

In a transportation network, the location of bridges can be broadly classified into three major categories referred herein as rural, suburban and urban. In this study, the social and economic impact of the bridges present in a rural area is considered as minimum as they connect fewer people and businesses compared to the bridges present in suburban and urban regions. The social and economic importance of the bridges present in urban region is assumed to be the highest because they generally connect big cities with relatively high population and the presence of large businesses. The weighting factors for all three different locations of bridges is calculated using the AHP process and listed in the relevant Tables later in section 5.

4.1.2. Time and cost to repair the bridge

The time required to repair a bridge is an important factor that affects the social and economic life in the region of the affected bridge. In previous research, it has been observed that the indirect cost incurred due to the traffic closure may be many times the direct cost to repair the bridge [12,13]. Generally, a fire accident causes damages to the bridge which ultimately affect traffic movement due to the closure of the bridge. The time required to repair a damaged bridge is directly related to the extent of the damage and the extent of the damage may depend on various factors such as the source of fire (tanker, car etc.) and type of bridge material (steel, concrete and timber). The extent of the bridge damage due to a fire accident can be evaluated using information from previous fire accidents. In this manuscript, the indirect cost factor has been incorporated in terms of time to repair or rebuild the bridge because the longer it takes for the repair, the greater is the economic losses (indirect cost) due to the long suspension of the traffic movement. Three levels of repair time are assumed in this study depending upon different damage levels such as less than 1 month, 1 to 3 months and more than 3 months.

The direct cost to repair or retrofit the bridge is also an important factor and can have a considerable economic impact. In this framework, the direct cost to repair a bridge is classified into three levels such as less than 3 million USD, 3 to 9 million USD and more than 9 million USD. These different levels for repair cost have been selected based on the information available in the literature [8]. More is the time and cost required to repair a bridge more is their contribution towards fire risk in the framework.

4.1.3. Closeness to a major city

The distance to a major city of a bridge greatly influences its social and economic importance. A bridge connected to a major city deals with a very high traffic volume and rerouting of which might cause huge inconvenience to the social and economic activities related to the city. Generally, major cities serve as an industrial hub of the region and a disruption in the transport facilities results in a halt of many industrial operations. Other activities related to the service sector such as head offices of companies are also located within major cities and they also get badly affected as employees are unable to commute to the workplace due to the closure of the bridge. Due to the above reasons, the distance of a bridge from a major city is considered an important factor for the fire risk assessment of the bridge. Bridges that are more than 50 km away from the major cities are assumed at the lowest risk whereas bridges between 20 to 50 km are assumed at medium risk, and bridges within 20 km radius contribute the highest to fire risk.

4.2. Sub criteria under structural vulnerability

4.2.1. Material

The most common materials which are being used for bridge construction are steel, concrete, composite, prestressed, and timber. Each type of material has unique behaviour when exposed to fire. The reduction in the strength and modulus of elasticity is different for all material types when they are exposed to elevated temperature. Moreover, the stress-strain relationship of materials such as concrete, steel and timber are entirely different from each other. The behaviour of a bridge under fire exposure is highly dependent on the thermomechanical behaviour of its constitutive materials.

For example, a reduction in the physical properties of concrete is less compared to steel when exposed to a fire. Since timber is a combustible material so the reduction to its physical properties is also very high whereas concrete does not show a significant reduction in the material properties. Whereas, spalling of concrete is one of the most important phenomena which is responsible for the deterioration of concrete structures when exposed to fire. The evaporation of moisture in the concrete due to the heat may also lead to progressive spalling [25]. It has been observed that the extent of spalling in high strength concrete structures is significantly higher compared to low strength concrete structures and this extensive spalling may directly expose the reinforcement to the flames. The loss of concrete cover due to spalling weakens the whole structure and may lead to poor fire performance. Pre-stressed concrete is also highly vulnerable when exposed to fire and apart from the factors which are common to normal concrete such as spalling, strength reduction of concrete and steel, the prestress tension can also be lost within the steel tendons due to decreasing modulus of elasticity. It has been observed that approximately 20 % of prestressing tension is lost at 300°C [26]. Other factors which are responsible for the losses of tension with increases of temperature arise from the relaxation of steel due to creep at elevated temperature. Therefore, the structural fire response of bridges is highly dependent on the type of material used in the construction. When bridges made up of these materials exposed to fire, they have various levels of vulnerability. Therefore, different weighting factors should be assigned for different material type.

It has been observed in previous fire accidents that steel and timber bridges are the most vulnerable type of bridges in fire conditions [27]. In this study, bridges with steel and timber material are considered at the highest risk to fire and the corresponding weighting factor is calculated. Bridges that are constructed using reinforced concrete and prestressed concrete are kept under one category and a single weighting factor has been calculated for these bridges. Composite bridges made with steel girder and concrete deck are considered the least vulnerable when exposed to fire. Due to the composite action of the steel girder and concrete deck, an enhanced performance has been observed in fire conditions [28]. So, composite bridges that are constructed using steel girder and concrete deck are at the least risk to fire and the corresponding weighting factor is also calculated using the AHP process.

4.2.2. Age

The age of the bridge is an important factor when analyzing its vulnerability to fire. Generally, it is assumed that an older structure loses some of its strength such as in a reinforced concrete structural member, the bond between concrete and steel gets deteriorate over time due to corrosion. In the case of prestressed concrete bridges, relaxation of prestressing force can also occur due to creep. Due to multiple loading and unloading cycles, fatigue is also observed as one of the most critical phenomena which get magnified with time [27]. With a reduction in strength, the ability to withstand designed fire loads also gets reduced with the increasing age of the bridge.

It has been observed in the literature that the damage caused due to fire is more to older bridges [29,30]. Therefore, the age of the bridge is considered a critical factor when assessing its vulnerability to fire. In this study, the age of bridges is divided into three categories such as less than 30 years, 30 to 60 years and more than 60 years.

4.2.3. Distance from a fire station

Once a fire gets started due to an accident, it gets magnified with time until fully developed and produce intense heat until all the fuel is burned out as oxygen is available in abundance (fuel-controlled fire) [31,32]. The high magnitude of heat release rate (HRR) can result in massive damage or collapse of a bridge. The HRR which gets developed due to a tanker fire in a typical bridge accident is in the range of 50 – 100 MW [33,34]. Such a large amount of heat can cause significant damages to the bridge. In such situations, if a fire station is located in the vicinity of the bridge, the fire could be suppressed or controlled in early stages and the resulting damage to the bridge can also be minimized. It is interesting to note that a shorter distance may not always permit a quick arrival and the time to arrive at the fire location may be a more meaningful parameter for risk assessment. The time required by firefighters to arrive at the fire location is entirely dependent upon the distance of the bridge from the fire station and the traffic density on the route. The time to arrive at the fire location must be estimated under a specific traffic conditions to maintain the uniformity in the process because traffic density varies at all instant during the day and it would result in different arrival time. In this manuscript, the traffic density is assumed as constant and the time for fire fighters to arrive at the bridge fire location is considered entirely dependent on the distance between the fire station and the bridge. Hence, the distance of a fire station from the bridge is also considered one of the important factors while estimating the bridge fire risk. The distance of a fire station from a bridge is categorized into three major ranges such as less than 6 km, 6 to 18 km and more than 18 km. In case of bridges present in urban regions, the fire station may be located as close as within 5 km, whereas bridges present in rural or remote location the fire station may not be present until 15 km or more.

4.2.4. Fire Protection

Generally, most of the bridges does not have any provision of fire protection in terms of insulation coating and active fire suppression systems such as sprinkler systems etc. However, in the most recent construction of bridges, fire protection is being provided such as protective coating is applied to the cables of a cable-stayed and suspension bridges up to a certain height to avoid the damage to the cables due to fire flame [35]. A protective coating on RC and prestressed bridges can also be applied to reduce the effect of fire and allow more time for firefighters to stop the fire before it damages the bridge substantially. The provision of a fire protection system provides a general fire rating to the bridge and depending on the level of fire protection applied, the fire protection level has been classified into three major categories such as 1-hour fire rating, 2-hour fire rating and no fire protection.

4.2.5. Structural system

A wide range of structural systems is being used for bridge construction depending upon various factors such as availability of local skills and materials, easiness for future inspection and maintenance, and aesthetic and environmental aspects. The various structural system has a different level of fire risk. The choice of the structural system for bridges is also dependent on the length of the span and traffic volume to be served by the bridge. The average span length for arch and truss type bridges is very low (100 to 150 meter) and they are generally designed for a lower traffic volume. Whereas the average span for a suspension bridge is very high (1200 meter) and they are being used to serve high traffic volume. In this study, due to low traffic volume and smaller span length, truss and arch bridges are considered at the lowest fire risk followed by girder bridges [36]. Whereas cable-stayed and suspension bridges are kept under the highest fire risk as they can handle the high traffic volume. Abundant research is available that addresses the high level of damage caused to suspension and cable-stayed bridges in case of fire [37,38].

4.2.6. Support Conditions

Support condition for a bridge also influences its performance during the event of a fire. Various support conditions are possible for bridges such as simply supported, continuous, and partially restrained. The ultimate moment capacity of the continuous bridge deck is greater than that of simply supported decks due to the phenomenon of redistribution of moments in continuous structures. It has been observed that the performance of a structural member during a fire is enhanced due to the presence of axial restraints [39]. Initially, the load is carried by flexural action but in the later stages of fire, the load-carrying mechanism changes to tensile catenary action. This tensile catenary action develops only if the axial restraints are present [40]. Therefore, simply supported bridges are kept under the highest fire risk followed by restrained bridges and continuous support bridges.

4.3. Sub criteria under the likelihood of fire criterion

4.3.1. Annual Traffic

Annual average daily traffic (AADT) is considered as the most crucial factor for the likelihood of fire [9]. AADT is defined as the total volume of vehicle traffic of a highway or road for a year divided by 365 days. It provides the average daily traffic volume on a road. The probability of a fire accident is highly influenced by the AADT count. It has been observed that bridges with high AADT had suffered from a severe and high number of fire accidents [36]. Moreover, apart from physical damage to the bridge, the economic and social impact is also very high due to the interruption of this high volume of traffic (as discussed in section 2). A fire on a bridge, serving an enormous volume of daily traffic, causes inconvenience to a large number of travellers by traffic jams and subsequent rerouting to an alternative route. In this study, fire risk due to AADT count is divided into three subcategories. Fire risk to the bridges with traffic count less than 50000 AADT is considered as least. Whereas, bridges with traffic count between 50000 to 175000 are in medium level fire risk, and bridges with a traffic count of more than 175000 are assumed at the highest fire risk. These traffic count ranges are similar to the seismic risk and steel details included in New York State Department of Transportation vulnerability manuals [23,24].

4.3.2. Distance to Chemical Plant/Oil Refinery

In most of the severe fire accidents on the bridges, it has been observed that an oil refinery/chemical plant was located in the vicinity of the bridge. Generally, there could be any source of fire on a bridge such as a car accident, scaffolding and oil tanker, however, in the case of an oil tanker as a source of fire, bridges are damaged to the highest degree [36]. In various bridge fires which were caused due to an oil tanker, the location of the chemical plant, oil refinery or gas station was within the radius of 10 km from the bridge. Therefore, the distance to an oil refinery/chemical plant from a bridge is considered an important factor contributing to bridge fire risk. The bridges that are located within a radius of 10 km from the oil refinery are considered at the highest fire risk. And, the bridges which are located between 10 to 50 km from the oil refinery are at medium fire risk whereas the bridges that are more than 50 km away are at the least fire risk or have the least probability of fire due to an oil tanker.

4.3.3. Previous Fires

A record of previous fire accidents on a bridge also helps in estimating the likelihood of a fire. Bridges with a high number of fire accidents in the past have a high probability of experience a fire accident compared to a bridge with a lesser number of fire accidents or no fire accidents. It has also been observed that some of the bridges have experienced multiple fire accidents whereas others have none [36]. Due to this reason, the likelihood of a fire on bridges with fire accidents of more than 3 is considered as the highest. Whereas bridges having a fire history of 1 to 3 times in their lifespan are assumed to have a medium probability of experiencing a fire again and bridges with no previous fire accident record are considered at the least fire risk.

5. Weight Factor calculation

In this section, weighting factors to all criteria, sub-criteria and alternatives which contribute to fire risk for bridges are calculated. In this example, weightings are calculated for three main criteria of fire risk i.e., Social and Economic, Structural vulnerability and Likelihood of fire. Similarly, weighting factors for sub-criteria and alternatives are also calculated. If the intensities of importance are spaced at a large interval, it shows that difference in the contribution of two factors with adjacent intensities is very high. Therefore, the fundamental Saaty scale [16] is modified with values that represents a closeness in the importance of factors contributing to fire risk as shown in Table 2.

Table 2 Modified Saaty Scale [16]

Intensity of importance	Definition
1.0	Equal importance
1.5	Moderate importance
2.0	Strong importance
2.5	Very strong importance
3.0	Extreme importance

Using the modified scale and Eq 1, firstly, a matrix of relative importance (judgement matrix) is built as follows (Table 3).

Table 3 Judgement matrix for fire risk assessment criteria

	Social and Economic importance	Structural Vulnerability	Likelihood of fire
Social and Economic importance	1	1.5	2
Structural Vulnerability	0.67	1	1.5
Likelihood of fire	0.50	0.67	1
	Σ 2.17	Σ 3.17	Σ 4.5

Secondly, the normalized matrix for the above matrix is developed using Eq 2. The normalized matrix for this example is presented in Table 4.

Table 4 Normalised matrix for fire risk assessment criteria

	Social and Economic importance	Structural Vulnerability	Likelihood of fire
Social and Economic importance	0.46	0.47	0.44
Structural Vulnerability	0.31	0.32	0.33
Likelihood of fire	0.23	0.21	0.22

Once the normalized matrix is built, the weighting factors for each criterion are calculated by averaging the values of each row of the normalized matrix (Eq 4). The calculated weighting factors for all three criteria are listed in Table 5. It is noteworthy that the sum of all the weighting factors is unity.

Table 5 Weighting factors calculated for fire risk assessment criteria

Social and Economic importance	0.46
Structural Vulnerability	0.32
Likelihood of fire	0.22

Similarly, the weighting factors for sub-criteria under each criterion are also calculated. The weighting factors for all sub-criteria are shown in Table 6, 7 and 8. Finally, as each sub-criterion is decomposed into various alternatives, the weighting factors for the alternatives under each sub-criteria are also calculated using the same process and their values are listed in tables (Table 6 to Table 8). The final weighting factors for each alternative are calculated by multiplying the weighting factor of that alternative with weighting factors of corresponding sub-criteria and criteria as shown in table 6, 7 and 8.

Table 6 Weight factors for social and economic importance criteria, sub-criteria and alternatives used to assess fire risk

Criteria	Sub criteria	Alternatives	Final weighting factors
Social and Economic importance (0.460)	Road Class (0.308)		
		Rural (0.164)	0.023
		Sub Urban (0.297)	0.042
		Urban (0.539)	0.076
	Time to Repair (0.308)		
		0 to 1 Months (0.164)	0.023
		1 to 3 months (0.297)	0.042
		> 3 months (0.539)	0.076
	Nearby city (Km) (0.235)		
		0 to 20 (0.539)	0.058
		20 to 50 (0.297)	0.032
		> 50 (0.164)	0.018
	Cost to Repair (USD) (0.149)		
		3 million (0.164)	0.011
		3 to 9 million (0.297)	0.020
		> 9 million (0.539)	0.037

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Table 7 Weighting factors for structural vulnerability criteria, sub-criteria and alternatives used to assess fire risk

Criteria	Sub criteria	Alternatives	Final weighting factors
Structural Vulnerability (0.319)	Material (0.285)		
		Composite (0.164)	0.015
		RC/Prestressed (0.297)	0.027
		Steel/Timber (0.539)	0.049
	Age (0.210)		
		0 to 30 Years (0.564)	0.011
		30 to 60 years (0.297)	0.020
		> 60 Years (0.539)	0.036
	Distance from fire station (0.148)		
		< 6 Km (0.164)	0.008
		6 to 18 Km (0.297)	0.014
		> 18 Km (0.539)	0.026
	Fire Protection (0.148)		
		2 hr (0.164)	0.008
		1 hr (0.297)	0.014
		No (0.539)	0.026
	Structural System (0.104)		
		Truss/ Arch (0.164)	0.005
		Girders (0.297)	0.010
		Cable stayed/ Suspension (0.539)	0.018
	Support Conditions (0.104)		
		Continuous (0.164)	0.005
		Restrained (0.297)	0.010
		Simply Supported (0.539)	0.018

Table 8 Weighting factors for likelihood of fire criteria, sub-criteria and alternatives used to assess fire risk

Criteria	Sub criteria	Alternatives	Final weighting factors
Likelihood of fire (0.221)	Annual Traffic (AADT) (0.429)		
		50000 (0.164)	0.016
		50000 to 175000 (0.297)	0.028
		> 175000 (0.539)	0.051
	Distance to Chemical Plant/Oil Refinery (0.286)		
		10 km (0.539)	0.034
		10 to 50 km (0.297)	0.019
		> 50 km (0.164)	0.010
	Previous Fires (0.286)		
		None (0.164)	0.010
		0 to 3 (0.297)	0.019
		> 3 (0.539)	0.034

6. Checking the consistency

To achieve reliable and rational results by using the AHP process, it is necessary to have consistency when making various pairwise comparisons. An AHP process is said to be consistent if all the pairwise comparisons are consistent with each other and do not contradict each other. However, an inconsistency may occur in the AHP process, when many pairwise comparisons are made. It may be explained using the following example. For instance, if the weighting factors of the three criteria are to be evaluated using a pairwise comparison of the AHP process. According to their importance level, it is assumed that criterion 1 is slightly more important than criterion 2, while criterion 2 is slightly more important than criterion 3. An obvious inconsistency will arise if the user mistakenly assumes that criterion 3 is equally important as criterion 1. In this case, a consistent evaluation would be that criterion 3 is less important than criterion 1. In another situation, there can be some cases where the inconsistency level will not be high and a low inconsistency will arise if the user makes a mistake in the assumption that criterion 1 is also slightly important than criterion 3. In this case, a consistent evaluation would be that criterion 1 is more important than the criterion 3.

In the AHP process, the pairwise comparisons in a judgment matrix are considered to be adequately consistent if the corresponding consistency ratio (CR) is less than 10% [41]. The AHP process provides an effective way to check the consistency of the evaluated weighting factors. The CR is calculated as follows. To check the consistency of the process, a consistency index (CI) is required to be calculated. For calculating CI, a factor "λ_{max}" (maximum eigenvalue of the judgement matrix) is required to be calculated first. This is done by multiplying the columns in the judgment matrix by the weighting vector and adding the resulting vector (weighted sum), as shown in Table 9. This results in an approximation of the maximum eigenvalue, denoted by λ_{max}. Once λ_{max} is estimated, the CI value can be calculated by using Eq. 6.

$$CI = (\lambda_{max} - m)/(m - 1). \qquad \text{Eq 6}$$

Where m is the order of judgement matrix. The following is the consistency ratio example calculation for the judgement matrix presented in Table 3.

Table 9 Consistency ratio calculation

	Social and Economic importance	**Structural Vulnerability**	**Likelihood of fire**	**Weighted Sum Σ**	**λ= Weighted Sum/ criteria weight**
Social and Economic importance	1×0.46	1.5×0.32	2×0.22	1.38	3.0
Structural Vulnerability	0.67×0.46	1×0.32	1.5×0.22	0.956	2.98
Likelihood of fire	0.50×0.46	0.67×0.32	1×0.22	0.663	3.01

$$\lambda_{max} = (3.0 + 2.98 + 3.01)/3 = 3.001$$

$$CI = (3.001 - 3)/(3 - 1) = 0.00078$$

Finally, the CR can be calculated by dividing the CI value by the Random Index (RI), as shown in Table 10 [16].

Table 10 Values of the Random Index (RI)

m	2	3	4	5	6	7	8	9	10
RI	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.51

$$CR = 0.00078/0.58 = 0.0013$$

A perfectly consistent decision-maker should always obtain CI=0, but small values of inconsistency may be tolerated. In particular, if CI/RI< 0.1 [41], the inconsistencies are tolerable, and a reliable result may be expected from the AHP. In this study, the consistency has been checked at all levels such as for criterion, sub-criteria and alternatives. The example presented above shows a CR of 0.0013 which is under the specified limit (0.01) and the results at each level were also found well within consistency limits.

7. Implementation of the Proposed framework

The above framework is implemented by estimating the fire risk to six bridges that have experienced fire accidents in the past. Out of six bridges considered in this study, four were composite and two were prestressed concrete. All the bridges considered in this study experienced fire due to an oil tanker. Details on the selected fire incidents are presented in Table 12. Fire risk has been calculated using the weightings assigned for various factors in previous sections. According to the weighting calculated for different factors, the minimum value on the risk scale is 0.20 (if minimum weighting is assumed for all alternatives). Whereas, if the maximum weighting for all alternatives is assumed then the maximum risk value obtained is 0.50. Therefore, the risk estimation scale is divided into different levels to estimate the fire risk, as shown in Table 11. Each risk level is associated with a specific damage level, the definitions of various damage levels have been provided as follows. A similar definition of damage level was also provided by Sayol et al.[36].

Table 11 Risk values and corresponding risk levels and damage levels

Value on Risk Scale	Risk Level	Damage Level
<= 0.16	No fire Risk	Superficial Damage
0.16 to 0.25	Low Fire Risk	Minor Damage
0.26 to 0.35	Medium Fire Risk	Partial Damage
0.36 to 0.4	High Fire Risk	Massive Damage
>= 0.4	Catastrophe	Catastrophic Damage

Superficial Damage: In this case, no structural damage occurs to the bridge and only the superficial damage which does not require immediate repair such as damage to the deck surface, equipment damage, etc. occur to the bridge.

Minor Damage: In this level of damage, minor damage at the structural level occurs to the bridge which is required to be repaired but a replacement of the whole structural member is not needed. For example, minor spalling is not able to expose reinforcement and can be repaired.

Partial Damage: In this category of damage, a replacement of whole structural member is required. For example, exposing of reinforcement due to substantial spalling, local buckling of steel members, etc.

Massive Damage: In massive damage level, the bridge experiences significant damage to the main structural members or may experience a partial collapse (collapse of a part of the structure i.e., single span). Due to the permanent reduction in the capacity to withstand service loads and partial collapse of the structure, a repair is not enough and the damaged or collapsed structural member is required to be rebuilt. For example, large permanent displacements in steel bridges that violets the limit state of serviceability, a significant reduction in the load-carrying capacity of bridges on account of being exposed to high temperature and high amount of spalling which exposes the reinforcement.

Catastrophic damage: This is the highest level of damage where the whole bridge collapsed and requires to be rebuilt.

The data related to these bridges have been collected from various literature [8,12,15,21,22,41–45] as shown in Table 12. The calculated risk level and corresponding damage estimated using the proposed framework for all these bridges are presented in Table 13. The actual damage caused to these bridges in previous fire accidents is in close agreement with the damage level estimated using the framework as shown in Table 13. This close agreement of predicted risk level and damage with bridges under real fire accidents shows the efficacy of the framework.

Table 12 Alternative's information for six bridge fire incidents from literature

Factor/Bridge	**Chester Creek, PA, USA**	**Denville, NJ, USA**	**MacArthur Maze, USA**	**Sweetwater, Texas, USA**	**I 75 Hazel Park, USA**	**Birmingham 2002, USA**
Social and Economic importance						
Road Class	Urban	Sub Urban	Urban	Rural	Urban	Urban
Time to repair	42 days	62 days	26 days	7 days	9 months	38 days
Closeness to the nearby city	28 km to Philadelphia	30 km to Newark NJ	5 km to Oakland	185km to Lubbock	20 to Detroit	5 km to Birmingham
Repair Cost (USD)	4 million	30 million	9 million	Minimal	3 million	3 million
Structural Vulnerability						
Material	Steel concrete composite	Prestressed Concrete	Steel concrete composite	Prestressed Concrete	Steel concrete composite	Steel concrete composite
Age (Years)	33	40	68	7	45	32
Distance from fire station	4.5 km	5.5 km	6 km	4.5 km	8 kms	17.6 km
Fire Protection	No fire protection	No fire protection	No fire protection	No fire protection	2 hr	No fire protection
Structural System	I girders	Box Girders	I Girders	I Girders	I Girders	I Girders
Support Conditions	Simply Supported	Continuous	Simply Supported	Continuous	Continuous	Simply Supported

Likelihood of fire						
Annual Traffic	80000	130000	280000	27600	12000	140000
Distance to Chemical Plant/Oil Refinery	6.4 Km	8 km	16 km	5 km	5 km	6 km
Number of previous accidents	3	1	1	None	1	None

Table 13 Validation of the framework by comparing risk level and associated damage level with actual damage

Bridge	Calculated Risk	Estimated Risk Level	Actual Damage level
Chester Creek, PA, USA	0.34	Medium Fire Risk	Partial Damage: The bridge carrying I-95 over Chester Creek buckled because of the fire and needed major structural repair [42]
Denville, NJ, USA	0.33	Medium Fire Risk	Partial Damage: The bridge structure was badly damaged during this fiery crash. The span was declared unsafe and was replaced using the same design as per the state transportation department [43].
MacArthur Maze	0.38	High Fire Risk	Massive Damage: The fire resulted in the collapse of two spans of the MacArthur Maze. Some of the steel plate girders of the I-580 were collapsed. The Mac Arthur Maze was repaired by replacing the 12 longitudinal girders on I-580 and the single box girder supporting them [11,46,47].
Sweetwater, Texas	0.22	Low Fire Risk	Minor Damage: Minor damage was made to the westbound structure, but it was open as there was still sufficient load capacity to handle the traffic. Temporary shoring was required for the eastbound structure of the bridge [48]

I 75 hazel Park	0.39	High Fire Risk	Massive Damage: Part of the overpass collapsed onto the interstate below as the spilled fuel burned. A two-mile stretch of I-75 was indefinitely closed and it took nearly 9 months to rebuild the collapsed part of the bridge [8,45].
Birmingham 2002	0.39	High Fire Risk	Massive Damage: The steel girders of the main span sagged off about 3 m. The damaged part was demolished and rebuilt in 38 days [8,44].

8. Conclusion

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

- The number of bridge failures due to fire hazard is significantly more than the number of bridge failures due to earthquakes. Therefore, fire is a more severe hazard for bridges than an earthquake, which can result in partial collapse and collapse of the bridges. To minimize the fire risk to a bridge, it is required to first quantify and estimate the fire risk.

- A comprehensive framework to quantify and estimate the fire risk to a bridge has been proposed. This framework considers a range of criteria i.e., the social and economic importance of the bridge, the structural vulnerability of a bridge to fire and the likelihood of fire for fire risk assessment. Weighting factors for each criterion, sub-criterion and alternative have been calculated using the AHP process depending upon their relative importance.

- The weighing factors in the proposed framework are similar to the ones used for estimating wind loads. These weighting factors can be used to estimate the level of fire risk to a bridge and it also identifies the probable level of damage that could occur in a bridge in case of a fire incident.

- When applied to a network of bridges, the framework is capable of identifying the number of bridges that are at high, moderate and low fire risk etc. Bridges at high fire risk can be provided with a higher level of fire protection and the adverse effects of fire hazard can be minimised. Moreover, by estimating the level of fire risk, a regional highway department can allocate funds for bridge fire protection in a systematic manner.

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