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REVIEW OF THE FIRE RISK, HAZARD, AND THERMO-MECHANICAL RESPONSE OF BRIDGES IN FIRE

Benjamin Nicoletta, S.M.ASCE[1], Panagiotis Kotsovinos[2], John Gales, A.M.ASCE[3]*

1 Graduate Student, York University. Toronto, Canada. E-mail: bnico@yorku.ca
2 Fire Engineer, ARUP. Manchester. E-mail: Panos.Kotsovinos@arup.com
3 Assistant Professor*, York University. Toronto, Canada. E-mail: jgales@yorku.ca
*Corresponding Author

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ABSTRACT

Resilient design requires information about a structure's response to a variety of exposures such that systems can be implemented to prevent unacceptable losses. For the case of critical infrastructure like bridges, losses associated with structural damage and traffic closures from fire events can be substantial. Despite this, there are no specific code requirements for bridge fire safety in different national jurisdictions, particularly in North America and Europe, and only minimal guidance available for establishing the fire resistance requirements of bridges. Research into the fire safety of bridges is ongoing but knowledge gaps persist that limit practitioners' ability to conduct performance-based fire-designs using the latest state of existing research. This paper provides a first-stage state of the art review of bridge fire research conducted to date in effort to summarize key findings and make available the most relevant information for researcher and practitioner use. The key research themes considered as subdivisions are fire hazard and risk assessment, bridge fire scenario modelling, and the structural response of steel and composite steel-concrete, cable-supported, concrete, and FRP-reinforced bridges to fire. The authors conclude the study with identified knowledge gaps and priority research areas.

Key Words: fire safety of bridges, fire hazard identification, thermo-mechanical response, structural materials, fire resilience, bridges.

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INTRODUCTION

Resilient fire-design aims to limit potential fire damage and ultimately ensure a return to peak operational capacity in a reduced timeframe following a fire. The acceptable period required for a bridge to return to its original operational capacity is highly dependent on the nature of the bridge and the requirements of the relevant stakeholders (Kotsovinos et al. 2016a). Resilient design requires information about a structure's response to a variety of exposures such that systems can be implemented to prevent limit unacceptable losses (Smith and Gales 2017). For the case of critical infrastructure like bridges, costs associated with operational time lost due to structural repairs structural damage and traffic closures can be substantial. There can often be economic incentive to develop the fire resilience of bridge infrastructure. For example, Chung et al. (2008) reported that the daily indirect traffic losses associated with the fire-induced MacArthur Maze overpass collapse in California were about $6 million USD. It took 26 days for the MacArthur Maze interchange to reopen to traffic (Chung et al. 2008). Despite this, there are no specific code requirements for bridge fire safety in different national jurisdictions, particularly in North America and Europe, and only minimal guidance available for establishing potential design fires for bridges which is provided by the National Fire Protection Association (NFPA) Standard 502 (NFPA 2014). Research into bridge fires is ongoing by the authors and others but knowledge gaps persist that limit the research user and practitioners' ability to conduct performance-based fire-designs that apply existing research.

This study provides a first-stage comprehensive review of research conducted on bridge fire risk and hazard assessment and the thermo-mechanical response of bridges to fires. The goal is to summarize key findings from research conducted to date and make the most relevant information available for researcher and practitioner use. Of specific note in the literature is the work of

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Garlock et al. (2012) which conducted the first major literature review in this field of study and reviewed past bridge fire events, summarized best-practice post-fire assessment and repair strategies for bridges, and identified potential research areas and knowledge gaps. The work herein could be considered an extension of the literature review by Garlock et al. (2012) but it is recommended by the authors that the interested reader should also review the work of Garlock et al. (2012) as it is still relevant and the key reference in the literature of bridge fire safety. This paper herein does not provide a comprehensive lessons learned through case studies as this has been performed by Garlock et al. (2012) and others before (Kodur et al. 2010; Peris-Sayol et al. 2017) and attempts to expand on the authors' previous efforts to address this topic (Nicoletta et al. 2018; Nicoletta et al. 2019).

The key research themes consider subdivisions as follows: bridge fire hazard and risk assessment, bridge fire scenario modelling, as well as the structural response of steel, concrete, composite steel-concrete, cable-supported, and FRP-reinforced bridges to fire. These topics have been determined by the authors as important areas in which research needs have been identified. Areas outside of these topics such as timber bridges are also briefly discussed. This paper concludes with a discussion of bridge fire experimentation and presents knowledge gaps the research community could consider targeting. The authors comprehensively tabulate research publications and include some discussion pertaining to major studies under each category when relevant. Only publications available in the English language are considered.

REVIEW OF BRIDGE FIRE LITERATURE

Fire Hazard and Risk Assessment Framework

Bridges can range in span and provide varying levels of service to the surrounding community, ranging from redundant (with no or limited impact associated with closure) to critical (with

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detrimental effects on traffic operations in the case of closure). Life safety due to fire-induced collapse could also be of relevance for certain type of bridges however the life safety of users or staff due to a fire that is not related to a fire-induced structural failure is outside the scope of this paper. It is not economic or feasible to provide fire resistance to all bridges against the threat of fire (Naser and Kodur 2015). Further, if a bridge is deemed to require fire resistance, care has to be taken to assess the possible fire hazards it may experience in its lifetime and the subsequent design must respond accordingly.

The literature studied in this section represents the initial considerations that are taken to consider the fire risk and hazards in bridge infrastructure. Table 1 presents a summary of past research efforts and the conclusions presented by each, followed by more detailed summaries of substantial studies.

It is well-cited in the literature and apparent after reviewing bridge design standards such as the CAN/CSA-S6-14, AASHTO LRFD Bridge Design Specifications, and Eurocode 1 Part 1-2 and Part 2 that there are no specific fire endurance requirements in contemporary bridge design (Kodur et al. 2010; Garlock et al. 2012; Peris-Sayol et al. 2017; CSA 2014; AASHTO 2015; CEN 2002; CEN 2003). In practice, fire resistance specifications are beginning to be considered on the basis of owner requirements that are driven by property protection and operational continuity goals rather than legislative requirements (see Kotsovinos et al. 2016a). The only guidance provided by a national standard is the National Fire Protection Association (NFPA) Standard 502 which specifies a high-level method to select design fires for highway bridges over 300 meters in length but does not provide procedures to undertake a computational fluid dynamics (CFD) model of a vehicle fire or the means to apply a fire in a thermo-structural model (NFPA 2014). Fire modelling and design of buildings vary significantly from bridges due to dissimilar and irredundant structural

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systems, well-ventilated potential fire scenarios in open air, and different consequences associated with structural failure (Kodur et al. 2010; Garlock et al. 2012; Giuliani et al. 2012; Wright et al. 2013). Therefore, a specific framework is needed to facilitate the design of bridges in the event of fires on or around the bridge. Research efforts discussed herein have established the base tools necessary to conduct fire hazard assessments, determine and characterize fire scenarios, apply thermal conditions to bridge structures and assess structural response.

Loss of bridge service is the primary factor in dictating fire risk and can be a result of moderate to severe fires which have mainly occurred due to vehicle collisions in previous fire incidents (Wright et al. 2013). Past experience has shown that more typically it is the most severe vehicle fires, such as fully loaded heavy goods vehicles (HGVs) and tanker trucks, which can cause permanent loss of bridge service. It is reasonable to expect one bridge in North America to permanently lose service as a result of a fire per year however this metric is based on survey data from the New York State Department of Transportation (NYDOT) cited in Garlock et al. (2012) and Wright et al. (2013) which considers also small and rural timber bridges that are more susceptible to fire. One of the most effective methods in reducing bridge fire hazards may be to increase highway safety near bridges which can reduce the number of vehicle fires from collisions (Woodworth 2013; Wright et al. 2013; Liu and Lou 2016). It is unlikely vehicle collisions could be completely prevented in any given highway segment but proper road safety design can be applied to reduce bridge fire risk. In cases where fire risk is greater than acceptable, bridge structural design coupled with active and passive fire protection systems can be relied on to protect assets. Kotsovinos et al. (2016b) have identified a lack of experimental data on the open-air fires of HGVs and petrol tankers and that the majority of cited data in bridge fire literature is based on tunnel fire experiments where the fire dynamics are different.

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Woodworth (2013) presents statistical data on the occurrence of bridge fires in the U.S. Of specific note is the rate of bridge-threatening hydrocarbon fires which is approximately one per year based on data from 1994-2013 (Woodworth 2013). Of bridge-threatening hydrocarbon truck fires from 1994-2013, the majority have been gasoline tanker fires (Woodworth 2013). However, for a given bridge, the most common fuel loads being transported in the region should be considered in a bridge fire-design. For example, in their study of a cable stayed bridge, Kotsovinos et al. (2016b) consider a liquefied natural gas (LNG) truck fire that could occur on the bridge due to the position of an LNG terminal in the surrounding area. To provide more context to the threat of bridge fires, Woodworth (2013) compares bridge failures due to fires to other sources of failure as reported in the NYDOT survey. The most prevalent categories of bridge collapse in descending order are: hydraulic events (assumed to refer to events like scour, debris flow, and flooding), collisions, overloading, deterioration, miscellaneous, fire, nature (assumed to refer to natural disasters outside of earthquakes and flooding), and earthquakes, among some other more minor categories (Woodworth 2013). Woodworth (2013) also reports that, of bridge collapses documented in the NYDOT survey, many of the fire-induced collapses were in small rural location bridges, most of which were timber bridges exposed to wildfires. Therefore, the risk posed by wildfires is largely directed to smaller timber bridge infrastructure and the risk to the non-timber bridge types considered in this document is not yet quantified in the literature.

Naser and Kodur (2015) provide a comprehensive framework for assessing the vulnerability of bridges to fire. Despite an overall increase in frequency in recent years (Garlock et al. 2012), bridge fires are low probability events and it is not economically reasonable to conduct intensive performance-based fire-designs for all bridges. The most critical bridges in terms of vulnerability to fire should be provided with adequate fire resistance on the basis of protecting life safety and

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minimizing potential economic disruptions. Using available statistical data (Wardhana and Hadipriono 2003; NFPA 2008; Scheer 2010), Naser and Kodur (2015) found the probability for a single bridge in the U.S to experience a vehicle fire in a given year to be 2.27% and the probability of one fire-induced bridge collapse to occur in a given year to be 3.1%. These values are low when compared to those for multi-storey buildings, for which the probability of one building in the U.S experiencing a fire is 29.5% and the probability of one fire-induced collapse occurring is 12.1% (Naser and Kodur 2015). Note that these values may be different in other jurisdiction such as those where there is less transport by heavy goods or fuel transport vehicles. Although the probability for fire occurrence and fire-induced collapse is much higher in multi-storey buildings, the likelihood of vehicle fires affecting bridges is still high enough to be classified as a probable risk by the National Fire Protection Association (NFPA) (NFPA 2007). This is because the consequence of structural failure in bridges can be high, in particular for long span bridges that are critical infrastructure. The low probability of bridge fire events compared to building fires is a main factor that has and continues to inhibit the development and implementation of fire resistance requirements for bridge infrastructure. This is contrary to other low probability accidental events such as ship impacts or explosion that are often considered in the design of long span bridges. Flint et al. (2017) have proposed the use of quantified risk assessment (QRA) to derive probabilities and consequences for the design of bridges as discussed. Moreover, since safe egress can be readily achieved in the majority of bridge infrastructure, life safety is not often a concern in bridge fire-design. It should be noted that for long-span infrastructure such as cable-supported bridges, life safety could also be a concern as evacuation times may be long and the fire may be difficult to reach by the fire service (Kotsovinos et al. 2016a). The value in protecting bridges against fire is in developing resilient transportation networks that are easily repairable in the event of a fire. As

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a note, literature on the growing concerns of wildfires is limited, however it is foreseeable that these transportation networks will play a critical role in community evacuation events which will ultimately rely on the existing fire resilience of bridge infrastructure.

Naser and Kodur (2015) consider two factors in determining the fire hazard level for a bridge: the structural vulnerability and critical nature with respect to the traffic network. Naser and Kodur (2015) propose importance factors that can be applied to each member type to account for fire scenarios. These importance factors consider bridge vulnerability and critical nature by giving a weight to five classes, considered briefly in Table 2 where the most critically vulnerable bridge will have a weighted score of unity.

Peris-Sayol et al. (2017) compile data from over 150 bridge fire events and present correlations between bridge damage levels and bridge and fire characteristics. Fires from tanker truck collisions are the most damaging events and gasoline is the most damaging (and common) type of hydrocarbon fuel; typical tanker fuel volumes were found to be between 30-35 m^3 (Peris-Sayol et al. 2017). From a strictly statistical perspective, the bridge site, structural system, and geometry do not have a significant effect on the bridge damage level (Peris-Sayol et al. 2017). It must be noted, however, that the observations made by Peris-Sayol et al. (2017) may be heavily skewed by the large number of steel girder highway bridges which represented the majority of collapsed bridges from tanker truck collisions. This may imply that, due to the severity of tanker truck fires, these factors make little difference on the bridge damage extent when faced with such extreme conditions. Peris-Sayol et al. (2017) identify the importance of the fire load position with respect to the structural elements of the bridge. For example, a tanker fire on the deck of a girder bridge may not pose a threat to the bridge structure unless significant fuel spills below and ignites. Conversely, a fire on the deck of a cable-supported bridge may be the most critical fire position

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based on the proximity to the cables. The potential fire load positions are critical in determining fire risk. If it isn't possible for a fuel load to accumulate in the worst-case scenario locations, it is less likely a fire that will cause major structural damage and the overall risk is reduced. The criticality of each fire scenario will depend on the type and use of the bridge and the surrounding site as discussed by Kotsovinos et al. (2016a). Peris-Sayol et al. (2017) recommend ensuring adequate fuel drainage from the bridge deck and limiting storing flammable materials below bridges to reduce fire risk. The database of bridge fire information used in the statistical analysis by Peris-Sayol et al. (2017) is openly accessible online and can be updated with contributions from the bridge fire community or downloaded by the interested reader (see Peris-Sayol and Payá-Zaforteza 2017).

For large and complicated structures, the fire hazards may be more complex to establish. Kotsovinos et al. (2016a) have carried out a qualitative assessment of the fire hazards beneath a cable-stayed bridge. A number of fire hazards were identified as posing a threat to the bridge and its users such as: 1) an HGV (including petrol tankers) fire on a road or in an industrial yard beneath the bridge; 2) a train (locomotive and/or cargo) fire under the bridge; 3) a ship fire (including fuel spill) on the river or in the docks below the bridge; 4) an industrial loading vehicle fire under the bridge; 5) a timber storage yard fire beneath the bridge; and 6) a wildfire under the bridge. The qualitative assessment by Kotsovinos et al. (2016a) for each of the fire hazards identified that the worst-case fires are unlikely and therefore the severity of the consequences requires that the likelihood of the event be considered. The probability/frequency of the identified fire hazards can be assessed so that the bridge owners can determine whether the risk is sufficiently great to require the implementation of restrictions or mitigating measures.

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Flint et al. (2017) continues the work from Kotsovinos et al. (2016a) and presents a risk-based methodology using quantified fire risk assessment as part of the decision-making process for the design of bridges. As a case study, all fire hazards identified by Kotsovinos et al. (2016a) are adopted to determine the probability of an event and its potential consequences. The study was based on relevant statistics collected from local authorities, national authorities, and international organisations.

Bridge Fire Scenario Modelling

If the fire risk for a given bridge is unacceptable, measures must be taken to decrease risk through sufficient design, see for example the restriction and mitigation measures suggested by Kotsovinos et al. (2016a). Where the potential of a fire cannot be mitigated, characterizing potential fire scenarios is an important step in creating fire-resistant bridges since subsequent structural design relies on the outputs generated by fire models. The majority of severe highway bridge fires are initiated through vehicle collisions but other circumstances such as construction materials being stored beneath a bridge must also be considered. Other fire hazards may also be likely such as those described in the previous section and Kotsovinos et al. (2016a). This section discusses the research efforts made in modelling various bridge fires as presented in Table 3.

Alos-Moya et al. (2014) apply a Fire Dynamics Simulator (FDS) model of a tanker truck fire compared with the Eurocode standard and hydrocarbon fires below a steel girder overpass to determine the influence of fire discretization, code-suggested fire curves, and live loading on the thermo-structural response. The Eurocode standard and hydrocarbon fires applied uniformly were found to not accurately represent realistic fires in medium and long-span bridges where significant longitudinal temperature variations are present (Alos-Moya et al. 2014). The Eurocode fires are

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better suited for short-span bridge fire models were longitudinal temperatures a relatively constant (Alos-Moya et al. 2014).

Quiel et al. (2015) propose four general steps to determine the structural response of bridge exposed to fire:

1. Determine fire characteristics like burning area, flame height, duration, and heat release rate;
2. Calculate the heat transfer to structural members;
3. Calculate structural member temperature increase based on heat exposure and duration; and
4. Apply material degradation factors at elevated temperatures and conduct a structural analysis.

Many bridge fire studies make use of simplified fire models like the standard hydrocarbon fire or parametric fires which are over-conservative and not representative of real fires resulting from large open-air hydrocarbon fires (Quiel et al. 2015). Detailed solutions involve CFD modelling of potential fire events which is intensive and often not practical due to a lack of input parameters, especially for forensic analyses where observations of a fire may not have been possible. Intermediate solutions are less intensive and can estimate a single fire parameter like temperature or heat release rate (HRR) for use in a thermo-structural model to determine a response. The framework proposed by Quiel et al. (2015) considers a pool fire as a solid shape which outputs calculated radiation values. This solid model is discretized into a luminous and a smoke obscured region (with varying emissivities) which is further discretized into individually modifiable rectangular elements (Quiel et al. 2015). This model can consider fire non-uniformity due to geometric or environmental factors and can efficiently approximate realistic bridge fire scenarios.

Elsewhere in the literature, efforts from Alos-Moya et al. (2019) have validated the use of simplified bridge fire models by comparing Heskestad and Hamada's (1993) analytical ceiling jet temperature correlation to experimental results from the gasoline pool fires used in bridge fire

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testing by Alos-Moya et al. (2017). Heskestad and Hamada's (1993) correlations were found to underpredict peak temperatures by just over 30% but were otherwise representative in reproducing temperature profiles in shape and magnitude along the soffit of the exposed bridge deck (Alos-Moya et al. 2019). The authors indicate this correlation has potential in conducting preliminary designs of future bridge fire experiments where medium-scale pool fires are applied (found accurate for HRRs of 361-1130 kW and flame-to-ceiling height ratios less than 2.0) (Alos-Moya et al. 2019). The authors also indicate the potential for Heskestad and Hamada's (1993) correlations to be used as a starting point for a simplified model to estimate full scale bridge fire temperatures.

Structural Fire Response of Steel and Composite Steel-Concrete Bridges

As discussed, steel bridges make up the largest portion of collapsed bridges due to fire (Peris-Sayol et al. 2017) and have been the key focus of the research community following the MacArthur Maze collapse in California. This section presents research detailing the fire response of steel and composite concrete-steel bridges in Table 4 with more detailed discussions following.

Paya-Zaforteza and Garlock (2012) examine the effect of varying deck axial restraint, constitutive relationships for carbon steel, live loading, and fire scenarios on the response of a steel girder bridge (both carbon and stainless-steel models are considered). The Eurocode standard and hydrocarbon fires (CEN 2002) as well as a large hydrocarbon fire proposed by Stoddard (2004) were applied uniformly to the bridge structure in ABAQUS (Paya-Zaforteza and Garlock 2012). Stainless steel structural models experienced lower temperatures than carbon steel models due to lower thermal conductivity and increased time to failure by over 80% which was attributed to superior high-temperature mechanical properties (as opposed to superior thermal properties) (Paya-Zaforteza and Garlock 2012). Thermal expansion was found to be greater than is permitted

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by typical expansion joints and should be accounted for in modelling (Paya-Zaforteza and Garlock 2012). This is corroborated by Alos-Moya et al. (2014) where it is noted that longitudinal thermal expansion routinely exceeds the width of expansion joints. Paya-Zaforteza and Garlock (2012) also conclude that the inclusion of live-loading has negligible influence on the bridge response to fire which was again confirmed by Alos-Moya et al. (2014). When considering axial restraint to replicate the effect of excessive thermal expansion, deflections were reduced and failure occurred through excessive strains due to buckling (Paya-Zaforteza and Garlock 2012). Conversely, in an axially unrestrained model, larger deflections were observed and failure occurred through excessive deflections (Paya-Zaforteza and Garlock 2012). The real fire scenario presented by Stoddard (2004) yielded a longer time to failure than the Eurocode hydrocarbon fire (Paya-Zaforteza and Garlock 2012). This indicates the Eurocode hydrocarbon fire may be too severe when uniform heating is considered.

Braxtan et al. (2015) conducted a preliminary analysis of a multi-span composite weathering steel box girder exposed to the Eurocode hydrocarbon fire. The weathering steel properties at elevated temperatures were taken from Labbouz (2014) with the largest noted difference between carbon and weathering steel being the loss of yield strength with temperature increase above 400°C for traditional steel and above ambient for weathering steel (Braxtan et al. 2015). The Eurocode hydrocarbon fire was considered in the midspan of the center span and adjacent to a pier in an outer span; the effects of localization were considered by applying the fire intensity gradient created by Alos-Moya et al. (2014) which decreased the fire intensity every five meters from the fire source (Braxtan et al. 2015). The midspan fire caused large deflections and stresses in the bottom flange while the fire close to the pier caused large stresses in the girder web and concrete slab (Braxtan et al. 2015).

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Based on the steel girders modelled by Paya-Zaforteza and Garlock (2012), Peris-Sayol et al. (2015) use FDS modelling of a gasoline tanker truck fire and a thermo-structural model in ABAQUS to consider the effects fire load position, structural boundary conditions, model scale (single element representation versus full bridge structure), vertical clearance, span configuration, and wind effects. It was found modelling the single most fire-exposed girder can approximate the full bridge response in terms of failure modes, critical temperatures, and time to failures (Peris-Sayol et al. 2015). Significant axial forces were developed in the girders when longitudinal restraint was applied (Peris-Sayol et al. 2015); this is representative of the typical bridge response when expansion joint width is exceeded. A fire load close in proximity to the abutment increased member temperatures and reduced failure time when compared to fire at midspan due to reduced ventilation (especially in single-span bridges with abutments than can retain hot gases) and the Coandă effect (Peris-Sayol et al. 2015). Wind was found to reduce the effect of the fire but can also direct flames onto structural members depending on the fire load location (Peris-Sayol et al. 2015).

Aziz (2015) experimentally and numerically characterizes the response of steel bridge girders exposed to the ASTM E119 standard fire. Three ASSHTO-compliant steel bridge girders were simultaneously heated in a furnace recreating ASTM E119 and loaded by an actuator (Aziz 2015). The girders were found to fail after 30-35 minutes of heating with a rolled steel girder with web slenderness near 50 failing in flexural yielding and a steel plate girder with web slenderness greater than 100 failing in web shear buckling (Aziz 2015). Material tests suggested reduction factors for the strength, modulus of elasticity, and post-heated strength are suggested and guidance for the high temperature creep is suggested (Aziz 2015). Aziz (2015) proposed a methodology to determine the residual capacity of steel bridge girders exposed to fire which consists of: 1)

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determining the ambient capacity of the girder using FEM modelling; 2) exposing the girder to a fire scenario under appropriate loading and boundary conditions with elevated-temperature material properties; and 3) allowing the girder to cool then loading incrementally until failure. A parametric study by Aziz (2015) found that steel girders fail in under 20 minutes during exposure to hydrocarbon fires where failure is in flexural yielding or web shear buckling for web slenderness ratios of less than 40 or greater than 50, respectively. The presence of stiffeners does not enhance the fire resistance however increasing axial restraint improves high-temperature flexural behaviour; including fire insulation is the most effective way to increase girder fire resistance (Aziz 2015).

Alos-Moya et al. (2017) present experimental results of a large-scale composite steel-concrete bridge with two abutments supporting a composite steel deck with girders on bearings exposed to a real open-air gasoline pool fire. Fire exposure was characterized through a series of preliminary test fires which measured temperatures at varying heights above the fire, measured the fuel mass loss rates, and concluded winds above two meters per second affected flame behaviour substantially (Alos-Moya et al. 2017). The bridge was exposed to varying fire sizes at the midspan and adjacent to an abutment (Alos-Moya et al. 2017). Although the fire load considered in this study is smaller than that of a tanker truck fire (upwards of 72 MW per Babrauskas 2016), Alos-Moya et al. (2017) report that the severity of fire is acceptable since: 1) the bridge was required to withstand multiple tests without significant damage; 2) the steel girder temperatures were found to be similar to those of real fire events; 3) the fire load was sufficient to impinge a flame on the bridge deck; and 4) safety concerns rendered a large fire unfeasible. The mass loss rate was similar to predicted values, however the effect of moving the fuel pan closer to the bridge deck increased the mass loss rate due to an increase of heat radiating back into the pan while moving the pan

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closer to the abutment decreased the mass loss rate (Alos-Moya et al. 2017). There was little difference between the web and bottom flange temperatures of the steel girders in any fire scenario, but the top flange was significantly cooler (Alos-Moya et al. 2017). Both gas and steel temperatures varied significantly in the longitudinal direction (Alos-Moya et al. 2017). Non-negligible wind speeds reduced observed deflections and decreasing the distance between the fire source and the bottom steel flange increased deflections (Alos-Moya et al. 2017).

Hu et al. (2018) using ABAQUS modelling of a two-span steel bridge to examine the effect of bridge skewness and abutment restraint of the fire response of the structure. A fire duration of 20 minutes was chosen on the basis that failure is typically induced within this period (Kodur et al. 2012) and it was assumed a fire under one span would not influence the adjacent span (Hu et al. 2018). In general, skew bridges yield a stiffer response to fire as a result of two-way action developed by the varying stiffness in girder members (Hu et al. 2018).

Whitney et al. (2018) conduct a two-dimensional parametric study of the girder properties in a steel bridge exposed to ASTM E119 in ABAQUS. The influence of global girder section factor, steel flange and web thicknesses, steel material properties, concrete slab width and thickness, applied intumescent paint, and spray-applied insulation thickness on the heat transfer through the bridge cross-section was studied (Whitney et al. 2018). Increasing girder web thickness and introducing either intumescent paint or spray-applied fire insulation were the most effective parameters in reducing cross-sectional temperature while the influence of alternative carbon steel material properties and increasing concrete slab thickness had little benefit (Whitney et al. 2018).

Structural Fire Response of Cable-Supported Bridges

Cable-supported bridges often have a primary function in the surrounding community and their stability can also have important life safety consequences to users and staff (Kotsovinos et al.

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2016a). Naturally the most susceptible to a fire on the deck of the bridge members for cable supported bridges are the pre-tensioned structural cables. Although the fire performance of cables would be similar to that of the cables used in other structures such as stadia or ferris wheels, limited research has been undertaken to date to describe their thermomechanical behaviour. This section presents relevant research on the topic of cable supported bridges in Table 5 followed by a more detailed discussion of significant literature. The detailed thermo-mechanical response of structural cables at component level (Atalioti et al. 2017) is outside the scope of this paper.

Bennetts and Moinuddin (2009) reviewed the potential fire scenarios a cable-stayed bridge may experience based on vehicle fires on the bridge deck. Three major fire cases are considered in their work:

1. Heavy goods vehicle (HGV) fire close to main support (towers) or cables;
2. Oil/flammable liquids tanker fire in same regions; and
3. Gas jet fire from a pipe fracture in a liquid natural gas (LNG) tanker impinging a cable.

Each fire case was applied in a 2-D thermal analysis of both a steel stay-cable and a welded steel box structure (representative a stay-cable tower). Fire properties from Pettersson et al. (1976), Shokri and Beyler (1989), and Beyler (2002), were used to model each fire scenario respectively. All fire scenarios consider radiation and convection and are two hours in duration. Stay-cables were modelled as a square configuration of two or three layers of lumped masses for both an uninsulated and insulated cases (Bennetts and Moinuddin 2009). The insulated strand case was protected by a 13 mm thick mineral fiber blanket which was modelled with and without an air gap to the adjacent cable surface. Cable geometric factors such as air gaps and contact areas between wires were not considered in the thermal analysis. Bennetts and Moinuddin (2009) concluded the presence of the insulation layer would likely protect the cables from severe temperatures in all

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cases until the fire is extinguished. The uninsulated cables experience rapid temperature rise and would experience severe material degradation.

There is limited literature related to the analysis of bridge cables under thermal loads. Bundled strand construction can be difficult to analyse especially when the inclusion of lubricants or stopping agents within cable voids can make thermal and structural analysis non-intuitive and continuum mechanics more challenging to apply (Wright et al. 2013). However, detailed analysis approaches have been presented in the literature (Atalioti et al. 2017). Furthermore, bridge cables can lose significant strength under thermal loads. Strength gain from the cold drawing process is lost typically when steel approaches 600°C (Wright et al. 2013). Wright et al. (2013) hypothesize that, despite the most exposed surface cables reaching critical temperatures first in a fire, the yield deformation will be delayed due to load shedding via differential thermal expansion; heated perimeter wires will tend to expand more than interior wires but some strain compatibility through friction will be present and result in a load transfer to the interior. Based on this, overall cable elongation is expected to be minimal until internal cable temperatures rise. Post-fire cable evaluation will be dependent on the temperatures reached in individual wires however the post-fire strength may be approximated by using the average post-fire strength of all individual wires in a cable cross-section (Wright et al. 2013).

Gong and Agrawal (2016) examine the effect of various fires on the response of cable-supported bridge decks. The main factors to consider with respect to bridge deck stability in fires are: 1) material degradation from heating; 2) additional loading due to thermal expansion; and 3) additional bending moment due to thermal bowing (Usmani et al. 2001). Three cable-supported bridges, a cable-stayed, anchored suspension, and self-anchored suspension, are considered in thermo-structural analysis. Of the three bridge types, the self-anchored suspension bridge deck has

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the largest pre-existing axial compression force which increases its susceptibility to thermal strains. Cable stayed bridges have a distributed axial force along the length of the deck but are usually less than half of the compression of a self-anchored suspension bridge (Gimsing and Georgakis 2011). FDS was used to model fire scenarios resulting from a ship fire below the deck and a truck fire above the deck. ABAQUS was applied for the thermo-structural analysis. Gong and Agrawal (2016) conclude the critical nature of pre-existing and thermally-induced axial forces in cable-supported bridge decks. Anchored suspension bridges were the least vulnerable of the cases studied due to having no existing axial compression. Fire scenarios near the tower involved critical P-delta effects, especially in self-anchored suspension bridges (Gong and Agrawal 2016).

Similar to Bennetts and Moinuddin (2009), Kotsovinos et al. (2016b) presents a number of potential fire scenarios on a bridge deck that could affect the thermal and structural response of a cable stayed bridge; namely:

1. An HGV fire;
2. A petrol tanker fire arising from the early ignition of the fuel at the release location following puncture of the tank containing the fuel;
3. A pool fire on the deck of the bridge arising from the delayed ignition of the fuel spilled from the location of the localised failure/puncture of the envelope of the tank of a petrol tanker; and
4. A tanker transporting LNG resulting in pool/jet fires.

The potential for structural collapse of the cable stayed bridge is simply estimated by considering the potential severity of the fire scenarios in terms of peak heat release rate and duration which can affect metrics such as flame length and structural member temperatures. A similar methodology is followed by Kotsovinos et al. (2016a) for potential fire scenarios below the deck of a cable stayed bridge that could affect the steel girders and structural cables.

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Structural Fire Response of Concrete Bridges

The fire response of concrete bridge structural members is a relatively under-researched topic likely due to concrete's assumed inherent fire resistance capacity. This section presents relevant literature on the response of concrete bridge members exposed to fire in Table 6.

Gales et al. (2016) review contemporary issues with post-tensioned concrete in fire and specifically the behaviour of pre-stressing steel at elevated temperatures. Gales et al. (2016) introduce a test program for analyzing the fire behaviour of prestressing steel which is influenced from results of tests on girders used for informing bridge performance. Guidelines for practitioners in assessing post-tensioned concrete after fires are discussed. Although experiments were not specifically for bridge girder structures, they provide insight into load-induced thermal straining (LITS) and tendon performance. Robertson and Gales (2016) follow this with a comprehensive literature review of bridge fires of prestressed concrete and post-fire mechanical testing of prestressing wires exposed to a range of fire severities, noting spalling and current methodologies for post fire material evaluation being insufficient and in need of further study.

Zhang et al. (2017) conducted modelling of a prestressed concrete box girder exposed to the ASTM E1529-14a large hydrocarbon pool fire (ASTM 2014) uniformly along its length in ANYSYS. Web and bottom flange elements were shown to have approximately the same temperatures for all fire durations considered and after 120 minutes of exposure web and bottom flange temperatures (included prestressing steel) exceed 450°C (Zhang et al. 2017). Zhang et al. (2017) found the vertical deflections of box girders take place in four distinct stages:

1. Linear increase in deflections due to thermal expansion (independent of applied loads);
2. Slight decrease in deflections as prestressing strands resist thermal expansion of bottom concrete flange;

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3. Non-linear increase in deflections as material properties degrade; and
4. Rapid increase in deflections due to further material degradation and high-temperature creep in the prestressing strands.

The degree of prestressing has a significant role in high-temperature response. Zhang et al. (2017) associated lower prestressing with a more rapid deflection increase in the first stage, a longer duration for which downward deflection is reversed and reduced hogging rates in the second stage, more significant creep and more rapid deflection increase in the third stage, and larger and more rapid deflections in the fourth stage.

Structural Fire Response of FRP-Reinforced Bridges

Elevated temperatures are known to have severe effects on the performance of fiber reinforced polymer (FRP) members due to the effects of glass transition which compromises the structural properties of the polymer matrix and reduces composite action between glass, aramid, or carbon fibers with the resin. Due to the lack of fire resistance requirements for bridge structural members, FRP members or reinforcements can be often applied in bridge infrastructure with little attention for the fire performance of the system. This section details the limited research studies conducted in examining the fire performance of FRP bridge members in Table 7 followed by a discussion of significant literature.

Little research has examined the effect of fire on FRP bridge elements. Early numerical models of FRP bridge decks have shown the most influential material properties in determining fire performance are the thermal conductivity, coefficient of thermal expansion, polymer resin type, and glass fiber type (Alnahhal et al. 2006). Experimental tests of FRP and GFRP (glass fiber reinforced polymer) bridge decks (Alnahhal et al. 2006; Nicoletta et al. 2019) have shown good fire resistance properties for small-scale fire exposures, however evidence of complex interactions

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between GFRP reinforcement and concrete as a result of heating have been identified by Nicoletta et al. (2019) that require additional research.

Large scale experimental fire tests on carbon fiber reinforced polymer (CFRP) reinforced prestressed concrete bridge girders by Beneberu and Yazdani (2018) provide information on the vulnerability of both adhered CFRP wrapping and prestressed concrete to realistic fire exposures. The test bridge consisted of three prestressed concrete girders reinforced: one control girder, one CFRP-wrapped girder, and one fire-protected CFRP girder; the girders supported precast deck panels and a cast-in-place deck (Beneberu and Yazdani 2018). Fire was inflicted via a hydrocarbon pool fire in a 6.10 m by 3.05 m pan with a volume of 4.23 m^3 at a height of 1.2 meters below the bottom of the concrete girders for a duration of one hour. Thermocouples recorded a peak fire temperature of over 1100°C with some wind-induced temperature variations exceeding 600°C between 2.3 and 3.3 minutes into the test (Beneberu and Yazdani 2018). The girders were significantly damaged by the fire exposure. Beneberu and Yazdani (2018) observed that the glass-transition temperature of CFRP epoxy was exceeded within 41 seconds of ignition and CFRP debonding occurred after 6 minutes. Approximately 25% of the concrete volume was lost due to spalling resulting from thermal shocking via large temperature fluctuations early in the test (Beneberu and Yazdani 2018). Multiple prestressing strands were found to be fractured and exposed; the fire protection was effective in keeping CFRP-concrete interface temperatures below the glass transition point and protecting concrete and steel elements (Beneberu and Yazdani 2018). In subsequent work, flexural testing of the prestressed concrete girders by Beneberu and Yazdani (2019) assessed the residual strength following the fire exposure. It was found that the unprotected CFRP-reinforced girder lost 59% of its theoretical flexural strength while the fire-protected CFRP-reinforced girder experienced no reduction in flexural capacity (Beneberu and Yazdani 2019). The

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fire-protected CFRP-reinforced girder did however experience CFRP debonding which is contrary to the American Concrete Institute (ACI) guidelines which predict a failure mode involving prestressing steel yielding and CFRP wrapping failing in tension (Beneberu and Yazdani 2019). Beneberu and Yazdani (2019) highlight the potential risk of failure facing prestressed concrete I-girders that are exposed to hydrocarbon pool fires.

While timber is considered a polymer alike to FRPs, there is limited to no fire research available regarding this type of infrastructure. For example, there is limited to no guidance available within the recently published Wood Bridge Reference Guide in Canada pertaining to the fire-design of timber bridges (Woodworks 2019). The fire performance of timber bridges is a research need particularly within the context of vulnerable transportation networks for wildfire community evacuations where smaller timber bridges may be relied on. The authors highlight potential flammability aspects where ember generation in a wildfire is a credible scenario for a loss of a timber bridge.

Implications for Bridge Fire Experimentation

Bridge fire experiments are rare due to high costs and safety and environmental concerns. Many institutions lack the size of fire testing and load-inducing equipment required to test bridge structural systems at a meaningful and credible scale. Large-diameter hydrocarbon pool fires can be one of the most severe and realistic exposures a bridge may experience in its lifetime (Peris-Sayol et al. 2017). Fire experiments that make use of non-standard open-hydrocarbon pool fires are even rarer despite yielding results that would be otherwise unobtainable (Alos-Moya et al. 2017; Beneberu and Yazdani 2018). For example, experimental tests have shown that the natural variations in open-air hydrocarbon pool fire temperatures exacerbate the spalling of prestressed concrete as a result of thermal shocking (Beneberu and Yazdani 2018). There is contention among

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researchers working on the fire safety of bridges as to the applicability of furnace testing with standard fire curves (such as ASTM E119, ISO 834, and the Eurocode standard fires) and open-air fire testing with realistic (but less easily characterized) non-standard fires. Readily characterized furnace tests facilitate numerical modelling validation while non-standard fire tests replicate realistic structural responses that would not be realized in standard fire tests. Many researchers have emphasized the inapplicability of standard fire curves due to a failure of these curves to capture the cooling phase (Kodur et. al 2010; Paya-Zaforteza and Garlock 2012; Beneberu and Yazdani 2018), temperature variation (Alos-Moya et al. 2014; Alos-Moya et al. 2017; Beneberu and Yazdani 2018), maximum member temperatures (Wright et al. 2013), localized nature (Alos-Moya et al. 2014; Alos-Moya et al. 2017; Beneberu and Yazdani 2018; Hu et al. 2018), intensity (Paya-Zaforteza and Garlock 2012; Beneberu and Yazdani 2018), and rapid temperature increase (Beneberu and Yazdani 2018), created by large, open-air, hydrocarbon pool fires. Furnace tests also fail to consider the influence of fuel load position, vertical clearance, and longitudinal temperature gradients. The applicability of the Eurocode hydrocarbon fire has been questioned as well on the basis that it fails to represent the peak temperatures achieved in more realistic hydrocarbon fire curves such as that proposed by Stoddard (2004) (Paya-Zaforteza and Garlock 2012) but may be too severe when uniform heating is considered (Paya-Zaforteza and Garlock 2012; Hu et al. 2018). Alos-Moya et al. (2014) suggest Eurocode standard and hydrocarbon fires are only applicable in short-span bridges where fire localization is less critical. The use of localized fire exposures is critical in determining the structural response of medium and long-span bridges since bridge failure modes vary depending on if heating is uniform or localized. Under localized exposure, local failures from extreme heating have been shown to occur before global failures due to excessive deflection (Wang and Liu 2016) which may not be the general

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case under uniform heating. Axial elongation of bridge structural members has been identified as a critical effect since typical expansion joint widths are not sufficient to prevent contact with abutments/adjacent bridge spans in a fire (Giuliani et al. 2012; Paya-Zaforteza and Garlock 2012; Woodworth 2013; Wright et al. 2013; Gong and Agrawal 2016). This has also been reported in actual bridge fire events (Godart et al. 2015; Zobel et al. 2016). Furnaces can practically support limited spans of samples in the order of a few meters. Axial elongation is proportional to the length of heating along a bridge, therefore uniform heating will produce unrealistic thermal expansion value compared to localized fires.

Despite the limitations introduced by standard fire testing in bridge fire applications, high temperature data of bridge structural systems is still valuable in validating models and investigating controlled failure modes. Bisby et al. (2013) and Gales et al. (2012) make a similar argument with respect to building fire testing in which the applicability of standardized fires diminishes with increasing scale and complexity of experimentation. Based on Bisby et al. (2013), the opposite can be said where standardized fires gain applicability for smaller systems where specific behaviours such as flexural behaviour and material properties can be studied without complicating factors. The above limitations arise when standard fires are applied to large scale bridge structural systems. This is known as "consistent crudeness" coined by Platt et al. (1994) and Buchanan (2001) where it is suggested researchers must strive for a consistent level of fidelity or reality in how structures and their respective fires are considered. As experimentation is rare, this methodology can be applied to modelling endeavors as well.

Knowledge Gaps and Future Research Targets

Further research to develop bridge fire resilience framework is needed. The authors have addressed this need by proposing a framework in previous studies that has a basis for determining

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and ensuring operational resilience. This framework for improving the fire resilience of bridge infrastructure is as follows (Nicoletta et al. 2018):

1. Increase bridge inspection scope to determine the significance of individual bridges to the overall transportation network in the event of a fire induced structural failure;
2. Determine bridge vulnerability to potential fires following a detailed fire hazard identification process and engagement with all the stakeholders;
3. Identify critically vulnerable bridges and the associated fire risk based on the performance requirements set by the relevant stakeholders; and
4. Make design and retrofit guidance on improving bridge fire resistance available to practitioners. Post-fire review requirements must also be established.

While the authors have focused specific attention into commonly used materials, there exists other material types that need further investigation as they are also considered in normal practice such as timber bridges. Specifically based upon the literature review provided herein future research areas suggested by the authors are presented in Table 8.

CONCLUSIONS AND RECOMMENDATIONS

This study provided a comprehensive first-stage state of the art review of the research conducted to date on the topic of bridge fires in effort to summarize key findings and make available the most relevant information for practitioner and researcher use. The key research themes considered are the determination of bridge fire risk and hazard and the structural response of various bridge structural and material types. While this approach has generated a specific guide for priority areas of research focus the fire practitioner could consider, some limitations to the authors' approach must be acknowledged. Material innovations are emerging that are being considered for this infrastructure type such as timber. These in turn must be considered for fire research as well

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though, to the knowledge of the authors, have not been been considered by the research community thus far as they are just emerging. In addition, most fire-design frameworks appear to be generated to deal with the concept of fire resistance. In the authors' opinion, this approach (originally coined for buildings and not infrastructure) has a degree of incompatibility to the expected function of bridge structures (for example the expected thermal boundary which should be utilised). It is advisable that the fire practitioner community develop an agreed-upon consensus document on establishing a proper testing protocol for this infrastructure type as second-stage research. This should work towards establishing an experimental center for research that can specifically procure the needed equipment to assess the fire hazard from an experimental view. Some labs are in existence that deal with scale at ambient temperatures, but they are not designed to handle the fire case. This may not be with difficulty giving the expense such an endeavour would have. While the authors comprehensively evaluated articles available in the English language, non-English literature may also have valuable test and data that can be considered, and the reader is encouraged to explore these to build upon this first-stage research framework provided herein.

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904 # LIST OF TABLES

905 **Table 1.** Relevant literature on bridge fire hazard and risk assessment framework.

Study Title	Author(s) (Year)	Research Topic	Summary
Bridge Fire Hazard and Risk Assessment Framework			
Review and Assessment of Fire Hazard in Bridges	Kodur et al. (2010)	Overview of the potential hazards created by fires and considerations for design	The document details bridge fire hazards and significant case studies. Issues and knowledge gaps in literature and a design methodology are presented.
Vulnerability of Bridges to Fire	Giuliani et al. (2012)	Discussion of the necessity of bridge specific code requirements and a review of case studies	The authors differentiate between bridge and building fires. Case study analysis concludes that the majority of bridge fires are caused by gasoline tankers and most bridges do not collapse. Authors speculate more bridge fires occur than are reported especially outside of the U.S.
Fire Hazard in Bridges: Review, Assessment and Repair Strategies	Garlock et al. (2012)	A detailed overview of significant bridge fire events, bridge fire literature, best practices post-fire repair and assessment strategies, and research gaps in the field	This document is the first and key reference publication that provides significant context to the issue of bridge fire safety. Details of real bridge fire incidents and relevant research studies are discussed. Best practice post-fire assessment and repair techniques with respect to concrete and steel bridges are presented to inform practitioners and researchers. A series of lessons learned through case studies is also presented.
Fire Hazard Assessment for Highway Bridges with Thermal Mechanical Modelling	Woodworth (2013)	A dissertation concerning bridge fire hazard assessment through statistical analysis and thermo-structural modelling of a bridge fire with FDS and ABAQUS	A review of statistical data found wild and trash fires occur frequently when compared to vehicles fires on bridges but are typically small in severity and not reported. Interstate highway bridges have the largest fire risk and more vehicle fires occur in rural areas where accident rates are larger.
Highway Bridge Fire Assessment Report	Wright et al. (2013)	A significant report on bridge fire hazards based on case study review and scenario modelling	The main risk to consider is loss of bridge service. It is reasonable to expect one bridge to permanently lose service from a fire per year in the U.S. Improving highway safety on/near bridges reduces crash and fire risk. The fire response of steel bridges is governed by the presence of redundant unexposed girders.
A Probabilistic Assessment for Classification of Bridges Against Fire Hazard	Naser and Kodur (2015)	Presents a rational method for assessing bridge fire risk and vulnerability to potential fire hazards	The proposed assessment provides a framework to identify critically vulnerable bridges based on bridge and traffic characteristics. Importance factors are assigned to inform design.

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Re-testing of a Fire Damaged Bridge	Alexander Au (2016)	Post-fire assessment, repair, and long-term testing of a fire damaged concrete overpass.	Load tests conducted 6 years after initial post-fire repairs found little deterioration in strength. The post-fire retrofitting techniques were deemed successful.
Resilient Bridge Design Framework to Extreme Fire Loading	Mueller et al. (2016)	Methodology for designing fire resistant bridges applied to a case study.	The proposed framework successfully established the maximum fire exposure threat and informed design decisions in the case study considered. A resilient design approach is adopted which considers potential acceptable damage states as opposed to strictly designing against collapse.
Qualitative Assessment of the Fire Hazards Beneath Bridges	Kotsovinos et al. (2016a)	The paper presents a hazard assessment process for the characterization of the threat to a bridge from potential fires beneath it.	The hazard assessment facilitates an understanding of any necessary mitigation measures/restrictions that need to be imposed by the operators of the region below the bridge and/or the amount of fire protection to be provided to the bridge structure.
Detailed Analysis of the Causes of Bridge Fires and Their Associated Damage Levels	Peris-Sayol et al. (2017)	Data review and analysis of more than 150 bridge fire scenarios	The analysis shows tanker truck fires are the most damaging fire type a bridge can experience. Gasoline fires were responsible for most bridge damage with typical fuel volumes ranging from 30-35 m^3.
Quantified Fire Risk Assessment for the Design of Bridges Against Fire	Flint et al. (2017)	Methodology for the characterization of fire hazards in bridges	Risk based methodology that utilises Quantified Risk Assessment as part of the decision making process for the design of bridges. A case study of a cable stayed bridge is presented.

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Table 2. Weighted classes to assess bridge fire hazard (adapted from Naser and Kodur 2015).

Class	Parameter	Weight
1. Geometric Features, Materials, Design Characteristics	Structural system, material and components; lanes; current condition	0.47
2. Fire Hazard Likelihood	Firefighter response time; historical/architectural significance; potential fire scenario	0.22
3. Traffic Demands	Average daily traffic; location	0.11
4. Economic Impact	Vicinity to alternate routes; predicted repair time; predicted repair cost	0.12
5. Expected Losses Due to Fire	Potential life and property loss; environmental damage	0.08

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Table 3. Relevant literature on bridge fire modelling and fire scenarios.

Study Title	Author(s) (Year)	Research Topic	Summary
Bridge Fire Modelling and Scenarios			
Thermal Structural Analysis of the MacArthur Maze Freeway Collapse	Noble et al. (2008)	Early modelling endeavor of the MacArthur Maze collapse using Lawrence Livermore National Laboratory (LLNL) finite element software	The developed numerical model is approximate in nature but provided a simple method to estimate failure times.
Integrated Fire Dynamics and Thermomechanical Modelling of a Bridge Under Fire	Choi et al. (2012)	Framework for bridge fire analysis using FDS and ABAQUS was developed and applied to the MacArthur Maze case study	A numerical model was validated using existing data from RC beams exposed to fire. The overall behaviour of the MacArthur Maze collapse was recreated.
Analysis of a Bridge Failure due to Fire Using Computational Fluid Dynamics and Finite Element Models	Alos-Moya et al. (2014)	FDS and ABAQUS modelling of a tanker fire below a steel girder bridge the thermo-structural response with emphasis on various fire parameters	The numerical models were in agreement with observations of the case study considered. The Eurocode standard and hydrocarbon fires were found to not accurately represent bridge fire scenarios. Uniform bridge heating is only reasonable for short span bridges.
Protection of Cable-Stay Bridges from Accidental and Man-Made Fire Hazards: A Rational Physics-Based Approach to Analyzing Vulnerabilities and Mitigation	Woodworth et al. (2015)	Presents an approach to consider potential fire threats through fuel containment, drainage, and burning rates	The rational method proves useful for the performance-based design of bridge deck drainage systems. The relationship between deck drainage spacing and fire size is approximately linear. Overall risk assessment is improved.
Analysis of the Influence of Geometric, Modelling, and Environmental Parameters on the Fire Response of Steel Bridges Subjected to Realistic Fire Scenarios	Peris-Sayol et al. (2015)	This parametric study considering the effect fire position, structural boundary conditions, model scale, vertical clearance, span type, and wind on a steel bridge using FDS and ABAQUS	The modelled behaviour of the most exposed girder is representative of the full structure when appropriate boundary conditions are used. Fires close to abutments produced higher temperatures and had shorter times to failure. Faster wind speeds reduced the effect of the fire.
A Streamlined Framework for Calculating the Response of Steel-Supported Bridges to Open-Air Tanker Truck Fires	Quiel et al. (2015)	Structural bridge fire modelling framework for analyzing members exposed to fires	The proposed modelling framework was efficient in recreating bridge fire responses over a variety of fire parameters. Authors note the inadequacy of standard fires in the context of bridge fire-design and develop a simplified fire model to be used in design.

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Performance-Based Prioritization of Fire Mitigation for Highway Bridges	Quiel et al. (2016)	Development of a tool to identify and prioritize application of fire protection	Proposed tool creates an envelope for a variety of fire exposures that can be used to identify structural elements where fire protection is required.
Analysis of the Factors that Influence the Maximum Adiabatic Temperatures in I-girder Bridges	Peris-Sayol et al. (2016)	Parametric study using fires modelled in FDS and statistical analysis to determine influential factors	Six parameters - four geometric and two fire - are varied to determine the influence on gas temperatures near structural elements. Fire load position, fuel type, and vertical clearance factors have the largest impact on steel girder flange temperatures. Steel web temperatures are also heavily affected by bridge substructure.
New Design Fires for Performance Based Engineering of Highway Bridges	Hu et al. (2016)	Development of potential bridge fires for use in design and applied to a case study	Classification of potential bridge fires was shown to enable more realistic estimates of bridge response.
Thermal Fluid-Structure Interaction and Coupled Thermal-Stress Analysis in a Cable-Stayed Bridge Exposed to Exposed to Fire	Nariman (2018)	Applying a model to determine vortex, drag, lift, and vibration responses to a bridge exposed to the standard fire	The developed model is adequate in determining vibration, vortex lock-in regions, and deck fatigue resulting from fire scenarios.
Valencia Bridge Fire Tests: Validation of Simplified and Advanced Numerical Approaches to Model Bridge Fire Scenarios	Alos-Moya et al. (2019)	Application and evaluation of a simplified fire correlation and FDS to model a large experimental bridge fire scenario	Heskestad and Hamada's analytical correlation for predicting gas temperatures was found to be representative in recreating experimental values for three of the four test scenarios with HRRs ranging from 361 to 1130 kW and flame length to ceiling height ratios of less than 2.0. Despite some deficiencies, the authors recommend using Heskestad and Hamada's correlation for the preliminary design of future bridge fire tests and indicate its potential as a starting point in real bridge fire analyses. FDS was found to be representative of all fire scenarios examined.

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Table 4. Relevant literature on the effect of fire on steel and composite steel-concrete bridges.

Study Title	Author(s) (Year)	Research Topic	Summary
The Effect of Fire on Steel and Composite Steel-Concrete Bridges			
Failure of a Tied-Arch Bridge Submitted to a Severe Localized Fire	Dotreppe et al. (2005)	Modelling of the response and collapse of a steel tied-arch bridge exposed to a hydrocarbon fire using SAFIR	The qualitative response and failure mode of the bridge was replicated with good agreement to observations of the event.
A Numerical Investigation of the Fire Response of a Steel Girder Bridge	Paya-Zaforteza and Garlock (2012)	Parametric study examining effects of deck restraint, structural steel type, constitutive relationships, live loading, and fire scenario	Results showed the presence of live loading had little effect on bridge behaviour, thermal expansion will routinely be larger than expansion joint widths and should be accounted for in models, and stainless performed better than carbon steel, among others. Specific local behaviours for each parameter studied are described.
Evaluating Fire Resistance of Steel Girders in Bridges	Kodur et al. (2012)	Thermo-structural analysis of a steel bridge girder exposed to a hydrocarbon fire in ANSYS	Authors review the major differences between bridge and building fire exposures. The developed model was validated and successfully applied to a case study. It was found the inclusion of steel-concrete composite action significantly increased fire resistance.
Post-Fire Strength Assessment of Steel Bridges Based on Residual Out-of-Plane Web Deformations	Glassman and Garlock (2014)	Parametric study of to determine the post-buckling shear strength of fire damaged steel bridge girders	Factors influencing the web shear response of steel girders were varied to assess the shear strength reserve in fire damaged steel girders based on post-fire observations. Steel webs that were loaded to shear buckling capacity at varying elevated temperatures and reloaded at ambient showed little reduction in post-buckling shear strength.
Diagnosis, Assessment and Repair of the Mathilde Bridge Close to Collapse during a Fire	Godart et al. (2015)	Review of the response and management techniques taken by municipalities surrounding the Mathilde Bridge in France after a large fire	A steel girder bridge was exposed to a large fire. The authors consider the assessment, analysis, and repair process undertaken by engineers to restore bridge operation. Post-fire assessment test and modelling methods are discussed. Good initial design was attributed in preventing significant economic loss.
Behavior of Steel Bridge Girders under Fire Conditions	Aziz et al. (2014)	Experimental tests and subsequent ANSYS modelling of three composite concrete-steel	The experimental time to failure under standard fire exposure was between 30-40 minutes in bottom flange yielding in girders with web slenderness of 50 and web shear buckling for web slenderness

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		bridge girders exposed to the ASTM standard fire	exceeding 100. Closer stiffener spacing was found to increase girder fire resistance.
Response of Fire Exposed Steel Bridge Girders	Aziz (2015)	Dissertation detailing the material and structural behaviour of composite steel-concrete bridge girders exposed to a standard fire	This study covers multiple research topics involving experimental and material tests of AASHTO designed composite bridge girders as well as modelling efforts to estimate girder post-fire residual capacity and determine the most influential structural parameters on fire resistance.
Computational Study of Highway Bridges Structural Response Exposed to a Large Fire Exposure	Nahid (2015)	Dissertation involving the numerical modelling of composite steel-concrete bridges with varying geometries and fire exposures	The modelling procedure and methods of reducing computational time are described in detail. A range of structural element heights were determined for which permanent damage would not be sustained for a variety of fire exposures. Localized fires were shown to cause failure via excessive material degradation while uniform heat exposures cause failure via excessive deflection.
Preliminary Investigation of Composite Steel Box Girder Bridges in Fire	Braxtan et al. (2015)	Uncoupled thermal and structural modelling of a weathering-steel box girder under hydrocarbon fire exposure	The max displacement was achieved after 11 minutes and failure occurred after 13 minutes of Eurocode hydrocarbon fire exposure at midspan. The girder appeared to fail in web shear buckling when heated next to the support. Authors highlight a need for understanding local effects of steel box girders in fire.
Numerical Simulation of Fire to a Long Span Truss Bridge	Gong and Agrawal (2015)	Forensic FDS and ABAQUS modelling of steel bridge stringers exposed to an HGV fire applied to a case study	The developed fire and thermo-structural models showed good agreement with the damage modes and measured deformations of the actual event.
Lazienkowski Bridge Fire in Warsaw – Structural Damage and Restoration Method	Zobel et al. (2016)	Review of the assessment and analysis of bridge fire that occurred on a steel girder bridge in Poland	A variety of qualitative damage descriptions of the concrete deck, steel girders, bearing supports, and other structural members are provided. Post-fire material property tests are also discussed. The authors note that the majority of residual bridge deformations are a result of post-fire thermal contraction.
Buckling Instability Behaviour of Steel Bridge Under Fire Hazard	Wang and Liu (2016)	Numerical modelling in FDS and ANSYS of a steel box girder bridge exposed to a variety of vehicle fires at midspan	The developed model shows that the critical shear buckling stress in the box girder web is exceeded after 17 minutes of exposure to a tanker truck fire. Shear buckling failure occurs before midspan deflection limits are reached. After 15

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			minutes of fire exposure, web temperatures are shown to accelerate rapidly.
Safety Evaluation of a Large-Span Double-Deck Cable-Stayed Steel Bridge Under Fire	Liu and Lou (2016)	Full fire, heat transfer, and structural analysis of fire scenarios on the bottom deck of a double-deck steel bridge	Under a variety of fire scenarios modelled in FDS, transverse steel truss members were found to be adequate except in the case of a tanker truck fire. The authors suggest several traffic management recommendations to limit the risk of fires as a result of vehicle collisions.
Thermo-Structural Response of Highway Bridge Structures with Tub Girders and Plate Girders	Nahid et al. (2017)	FDS and ABAQUS modelling of steel plate girder and steel tub girder bridges exposed to an HGV fire at midspan are compared	The fire exposure used in this study was intended to fail the steel plate girder so the response of the tub girder could be compared. As expected, the plate girder bridge failed under the given fire exposure while bridges with single and multiple tub girders did not. Adding a flame shield between flanges of the plate girders did not prevent failure. The tub girders were found to have superior moment capacity compared to the plate girders.
Strategies for Enhancing Fire Performance of Steel Bridges	Kodur et al. (2017)	Methodology to determine fire risk and mitigate fire hazard in bridge infrastructure	A procedure is presented to evaluate the fire risk of a given bridge by determining an importance factor. This importance factors gives information on the critical nature of the bridge which can be used in deciding fire hazard mitigation methods. A fire resistance of 60-120 minutes for bridges is suggested.
Valencia Bridge Fire Tests: Experimental Study of a Composite Bridge in Fire	Alos-Moya et al. (2017)	Experimental tests of a composite steel-concrete bridge exposed to a real gasoline pool fire	Experiment provided information on the accuracy of using small-scale pool fires to represent bridge fire scenarios as well as data to be used in model validation. The structural and material responses are documented in addition to the effects of varying fire locations and environmental conditions.
Recommendations for Improving Fire Performance of Steel Bridge Girders	Whitney et al. (2018)	ABAQUS modelling of a composite steel-concrete bridge girder exposed to standard and hydrocarbon fires to examine varying girder parameters	Bridge section factor, girder flange and web thickness, steel material properties, concrete slab width and thickness, and applied fire protection properties were varied to examine the effect on cross-section temperatures. Increasing girder web thickness and introducing intumescent or sprayed fire protection were the most effective parameters in reducing member temperatures.
Fire Resistance of Composite Steel and	Hu et al. (2018)	Modelling the effect of bridge skewness and abutment restraint on a composite bridge exposed	Skew bridges were found to retain greater stiffness during fire exposure than non-skew bridges. The Eurocode hydrocarbon fire is thought to be too

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Concrete Highway Bridges		uniformly to the Eurocode hydrocarbon fire	demanding especially during initial heating.
Effectiveness of Stiffeners on Steel Plate Shear Buckling at Ambient and Elevated Temperatures	Glassman et al. (2019)	Finite element modelling study of steel stiffener role in slender plate shear behaviour at ambient and elevated temperatures	The authors use non-linear FEM modelling to study the role of stiffeners in the shear buckling and ultimate shear capacity of slender steel plates. Stiffeners were found to be more effective when oriented to reinforce the compression field, but this effect diminishes at elevated temperatures. Vertical stiffeners contribute the most to shear buckling and ultimate shear strength by providing lateral restraint to the plate. At elevated temperatures, stiffeners were found to be less effective in providing lateral support and carry more axial force.

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Table 5. Relevant literature on the effect of fire on cable-supported bridges.

Study Title	Author(s) (Year)	Research Topic	Summary
Structural Fire Response of Cable-Supported Bridges			
Evaluation of the Impact of Potential Fire Scenarios on Structural Elements of a Cable-Stayed Bridge	Bennetts and Moinuddin (2009)	Heat transfer modelling of various fire exposures to insulated and uninsulated steel stay-cables	Developed heat transfer models found the presence of a thin mineral wool insulation would likely protect the stay-cables from extreme temperatures for the duration of the fire scenarios considered. Uninsulated cables reach high temperatures quickly.
Study on Thermal and Structural Behaviour of a Cable-Stayed Bridge	Liu et al. (2012)	Heat transfer and structural analysis of a cable-stayed bridge in ANSYS	The cable-stayed bridge was found to be vulnerable to a variety of fire scenarios. The authors note a difficulty in characterizing the fires produced from gasoline trucks.
Safety of Cable-Supported Bridges During Fire Hazards	Gong and Agrawal (2016)	Structural response to a fire scenario was studied for cable-stay, anchored suspension, and self-anchored suspension bridges using non-linear FEA.	Vulnerability was dependent on fire location and level of existing axial force. Self-anchored suspension bridges were most vulnerable due to large thermally-induced axial forces in the deck. Cable-stayed bridges had longitudinally-varying induced axial forces.
Assessing the Fires on the Deck of Cable Stayed Bridges	Kotsovinos et al. (2016b)	A design-based approach to characterize fires for cable-stayed bridges	Authors present an approach to assess the fire hazard and risk on a cable-stayed bridge. Multiple vehicle design fires are discussed as well as goals of fire protection and constraining factors considered in the assessment.

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Table 6. Relevant literature on the effect of fire on concrete bridges.

Study Title	Author(s) (Year)	Research Topic	Summary
The Effect of Fire on Concrete Bridges			
Deflection for Pre-Stressing Concrete Thin-Wall Box Girders Under Action of Multi-Span Loads Exposed to Fire	Zhang et al. (2012)	Numerical modelling of a four-span prestressed concrete box girder bridge exposed to the ISO standard fire in varying regions	The general deflection response of the bridge is presented for each region of heating considered.
Damage Assessment of One Pre-Stressed Concrete Bridge after Fire	Xiang et al. (2013)	Damage assessment of a prestressed concrete bridge exposed to a vehicle fire	Application of qualitative observation-based post-fire damage assessment methods to determine concrete damage. An estimation of bridge residual capacity is presented.
Assessment and Repair of a Fire-Damaged Pre-stressed Concrete Bridge	de Melo et al. (2014)	Review of the damage assessment and repair of the Dean's Brook Viaduct prestressed concrete bridge	Four concurrent stages were undertaken to expedite the repair of the bridge. A recount of the detail damaged assessment tests conducted to assess post-fire material properties is presented. There was no significant loss in tendon prestress in areas where concrete cover remained. Exposed tendons had only localized prestress loss.
Post Fire Guidance for the Critical Temperature of Prestressing Steel	Robertson and Gales (2016)	High temperature experimental tests of prestressing steel for post-tensioned concrete are presented.	Residual steel strength tests over multiple high temperature ranges found conventional guidance for prestressing steel may not be conservative. Revisions to guidance are suggested.
Structural Fire Performance of Contemporary Post-Tensioned Concrete Construction	Gales et al. (2016)	Detailed experimental study considering the fire performance of post-tensioned concrete members and prestressing strands	This project outlines procedures for testing post-tensioned concrete in fire, findings of structural fire experiments, and recommendations for designers. The article is the most up to date literature review of available testing in the public domain and addresses the performance of prestressed concrete bridge girders throughout.
Behaviour of Prestressed Concrete Box Bridge Girders under Hydrocarbon Fire Condition	Zhang et al. (2017)	ANSYS modelling of a prestressed concrete box girder exposed to the ASTM hydrocarbon pool fire	Box girder bottom flange and web elements were shown to have very similar temperatures for all fire exposures. Girder deflection is characterized in four stages. Vertical deflections are found to decrease after a degree of heating due to prestressing tendons resisting thermal expansion of the concrete. The degree of prestressing

is shown to have a significant role in deflection behaviour.

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1031 **Table 7.** Relevant literature on the effect of fire on FRP-reinforced bridges.

Study Title	Author(s) (Year)	Research Topic	Summary
The Effect of Fire on FRP-Reinforced Bridges			
Temporal Thermal Behavior and Damage Simulations of FRP Deck	Alnahhal et al. (2006)	ABAQUS modelling of a bridge consisting of FRP bridge deck exposed to an oil fire in varying regions	The worst-case scenario was determined to be a truck fire above the bridge deck which caused failure in under 7.5 minutes. The most critical factors for the fire performance of FRPs are thermal conductivity, coefficient of thermal expansion, resin type, and glass fiber type.
Numerical Study of FRP Reinforced Concrete Slabs at Elevated Temperature	Adelzadeh et al. (2014)	Modelling of concrete slabs reinforced with GFRP rebar exposed to the ASTM standard fire	The study found the concrete cover thickness has a significant effect on the fire resistance of the member. The temperature-domain method based on steel reinforced members in fire is not fully applicable to GFRP reinforced members.
Fire Test of FRP Members Applied to Railway Bridge	Cabova et al. (2016)	Experimental tests of FRP panels for use in railway bridge decks	Fire tests intended to simulate burning electrical cables were found to have negligible impact on the FRP. The majority of FRP panel configurations were able to support live loads post-fire.
Performance of CFRP-Strengthened Concrete Bridge Girders under Combined Live Load and Hydrocarbon Fire	Beneberu and Yazdani (2018)	Large-scale experimental study of a bridge span support by three prestressed concrete girders reinforced with varying CFRP wrapping and fire insulation	Authors distinguish the differences between standard and realistic fire testing in the context of bridge fire research experiments. The majority of concrete spalling was hypothesized to be a result of thermal shock via wind-induced fire temperature variations.
Residual Strength of CFRP Strengthened Prestressed Concrete Bridge Girders after Hydrocarbon Fire Exposure	Beneburu and Yazdani (2019)	Experimental structural testing of full scale CFRP-reinforced prestressed concrete girders after exposure to a large hydrocarbon pool fire	The authors test three fire-damaged prestressed concrete girders to assess post-fire residual flexural strength. Two of three girders were reinforced with a CFRP wrap prior to fire exposure. One of these girders also included applied fire-protection material. The third girder was unreinforced and unprotected. The unprotected CFRP girder lost 59% of its theoretical flexural strength. The fire-protected CFRP girder did not experience any reduction in flexural capacity but failed in CFRP debonding, contrary to the predicted failure mode in relevant guidelines.
Post-Fire Performance of GFRP Stay-in-Place Formwork for Concrete Bridge Decks	Nicoletta et al. (2019)	Experimental study investigating the post-fire mechanical behaviour of GFRP stay-in-place formwork reinforced	The GFRP-concrete beam experienced no loss in strength after a 14-minute heptane pool fire and moderate damage to the GFRP reinforcement. Evidence of

	concrete beams following hydrocarbon pool fire exposure and simulated fire damage.	thermally-induced non-linearities in structural performance are presented.

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1083 **Table 8.** Required research for the development of bridge fire resilience framework.

Topic	Suggested Research
Fire Hazard and Risk Assessment Framework	There is a lack of statistical data on all aspects of bridge fires especially outside of the U.S. A robust bridge fire reporting system should be developed to facilitate post-fire data collection with respect to structural damage. A study from the economic perspective of bridge fire resilience considering indirect losses would be enlightening. Appropriate tools need to be developed to assist designers in establishing the credibility of a fire scenario. Residual strength assessment and repair strategies are not well developed as many tests rely on qualitative observations. This topic may be difficult to approach based on the reliance on physical experiment specimens to conduct post-fire testing on. Post-fire strength assessments can be conducted using numerical models, but post-fire material behaviour must be ascertained experimentally.
Bridge Fire Scenario Modelling	There is a need to firmly establish what a realistic fire exposure entails with respect to bridge infrastructure. It is the authors' opinion that a realistic bridge fire should consider rapid initial temperature rise, realistic variations in temperature that have the potential to create thermal shock phenomena (especially in structural systems where thermal shocking has been shown to cause variable responses like prestressed concrete), a cooling phase, and a localized area of fire exposure (except in the case of short-span bridges where care must be taken to ensure uniform fire exposure is realistic). Specific research could examine what proportion of bridge fire exposure constitutes a "localized fire" based on the sizes of potential vehicle fires, the predicted containment of spilled hydrocarbon fuels, or in general the characteristics of a given fire scenario.
Steel Bridges	Steel bridges are currently the most researched structural system, but knowledge gaps persist. More experimentation is needed to study aspects of steel girder behavior under hydrocarbon fire exposures such as the effect of extreme localized heating, the global bridge response under non-uniform heating in the transverse direction, the post-fire strength and deformation recovery, and the effect of rapid localized steel quenching from firefighters. Localized behavior in steel box girders is also an understudied topic. Experimental research into the influence of varying structural steel types is also needed.
Cable-Supported Bridges	There is extremely limited experimental data on the response of structural steel cables in fire despite their use in a variety of bridge applications. Currently, cable behavior can be predicted based on unrepresentative fire testing or limited modelling endeavors which prevent the understanding of a realistic structural response and the use of performance-based design. Information is needed concerning the thermal expansion of steel cables of varying configurations like locked coil, parallel, and spiral structural strands, the risk of cable uncoiling as a result of thermal expansion and loss of tension, the influence of lubricants and stopping agents, and the global structural response of cable-supported systems in terms of load shedding to adjacent unheated cables.
Concrete Bridges	In general, there is a lack of experimentation focusing on the fire performance of concrete bridge elements. Even in developed nations, many concrete bridges in service are disrepaired with significant portions of exposed steel reinforcing and reduced cross-sections due to spalling. Specific research could examine the vulnerability of aged and disrepaired bridges to fire exposure and suggest retrofits to reduce fire risk. Guidance is needed on how to assess concrete bridges post-fire with respect to the deterioration of prestressing with fire exposure.
FRP-Reinforced Bridges	High temperature interactions between FRP-reinforcements and concrete in bridge applications are not well understood especially in novel applications such as stay-in-place formwork. The influence of exposed and flammable GFRP reinforcements contributing to fire severity is also a concern in some applications. Methods into

	protecting CFRP wrapping can also be investigating. More experimental efforts are needed to identify unexpected FRP behaviors in fire before modelling is attempted.

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