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Citation for published version:
Hu, J, Carvel, RO & Usmani, A 2021, 'Bridge fires in the 21st Century: A literature review ', *Fire Safety Journal*, vol. 126, 103487. https://doi.org/10.1016/j.firesaf.2021.103487

Digital Object Identifier (DOI):
10.1016/j.firesaf.2021.103487

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Peer reviewed version

Published In:
Fire Safety Journal

Bridge fires in the 21st Century: A literature review

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Abstract

Bridge failures due to fires are more common than failures due to extreme weather or earthquakes. Yet, unlike wind and earthquake loading, fire does not receive the same level of attention. Major 21st Century fire incidents involving bridges are listed and discussed. Various methods by which fire could be considered in design are reviewed and discussed. Sources of fire test data, which include only one full scale fire test to-date, are provided. It is hoped that by considering these factors, codes, standards and engineering practice could be updated to include consideration of fire in routine bridge design.

1 Introduction

This review of bridge fires is motivated by recurring reports of severe fires affecting bridge networks. The following observations raise the concern of the authors that research progress in this area is lacking, due to the general perception of the public. The true cost of this hazard to society remains under appreciated because of the sporadic nature of individual bridge fire incidents (unlike, for example, the ever-present nature of earthquake hazard).

1) **Why are fire loads neglected in bridge design, when other hazards resulting in fewer collapses are routinely considered?**

In bridge design, extreme hazards, such as wind [1], earthquake [2] and snow [3] have been considered as design loads for many years, while fire hazard is typically not considered in the design process. However, severe fire accidents which have consequences for bridges are not as rare as might be generally perceived, when compared to other extreme hazards, such as earthquake or floods.

In 2013, Lee, et al. [4] listed statistics for bridge failures, and the causes of those failures, from 1980 to 2012. It is shown that when considering only external causes, 3.2% of the bridge failures were caused by fires, compared to only 1.8% and 2.1% being due to wind and earthquakes, respectively. They suggest that the lack of failures due to wind and earthquakes may be due to code enforcement and the relatively well understood behaviour of structures in earthquake and windy conditions. This finding is also partially confirmed by another survey conducted by the New York Department of Transportation [5], which reports that nearly three times as many bridges collapsed between 1990 and 2005 due to fires, compared to those due to earthquakes.

2) Severe damage to bridge structures may be unavoidable

Another issue regarding fire hazard to bridges is the difficulty for the fire brigade to prevent severe damage, which is especially relevant if the accident occurs under a bridge in a rural area. In the accident involving the CN Rail trestle bridge, a large section of the bridge was already engulfed in flames when the fire department arrived at the bridge [6]. In some instances, the location of bridges provides '*limited access to hydrants, requiring water to be hauled in by truck*' [9].

Early arrival of the fire brigade does not assure a positive outcome; even if the fire brigade arrive at the scene within 20 min, partial or total bridge collapses due to fire can still occur, as evidenced by the 9 Mile Road Bridge fire in 2009 [7] and the MacArthur Maze freeway fire in 2007 [8]. In those cases, the other factors leading to rapid damage and failure are:

- If fuel spillages are involved, there will be intense heating from the liquid fuel fires which reach peak fire size in a short time. This only allows the fire service a relatively short reaction time, compared to building fires which usually take longer to fully develop into a severe fire.
- Common structural materials used in bridges, such as unprotected steel, have poor fire performance.
- As reported by fire services, wind tends to contribute to the spread of the flames and fire development, and also '*keep the streams of water from reaching deep into the bridge*' [9].
- A number of structural impact protection measures have been adopted in the current bridge designs, including vehicle bollards and crash barriers. Crash barriers may provide an element of protection to the bridge substructure (piers and abutment) but,

usually the substructure is far more resistant to fire than the bridge superstructure and temperatures from vehicle accident fires are usually the greatest under the superstructure.

- The intumescent fireproofing coating is sometimes used as a passive fire protection measure. This has however not been widely adopted due to the expense of fire protection materials including the cost of labour and maintenance.

3) Extreme disruption of the economy and commuters

Fire accidents not only have devastating first and second order effect on bridges, but also economic losses, heritage loss in case of historic bridges, and bridge-specific functions such as commuter patterns, social service and community commerce.

The economic losses include both direct and indirect costs, where the latter can be considerably greater in terms of financial and political challenges for the bridge authorities than the cost of repair or rebuild. This is mainly caused by the interruption of service and disruption of local commerce, also the repair time, which usually ranges from a few weeks [10] to several months [11], in addition to the expense of detours. The direct cost of repair varies largely, not only due to the damage severity, but also due to the commuting demands. This is reflected by the use of financial incentives which are always expected by the contractor for completing the project sooner. In the US, this cost is provided by the Federal Highway funds for such emergency repair work to restore emergency access and begin the most critical repairs [12]. For example, I-70 bridge in Ohio in 2015 where the costs were $1 million [13], and $10 million was allocated for the I-85 in Atlanta in 2017, where an estimated 250,000 vehicles drive through daily [12,14].

4) Limited research (simulations & experiments)

In 2011, the Highways Agency (HA) [15] in England tried to find engineering solutions to enhance the ability of bridges to resist damage due to fire. Risk locations were prioritised based on those '*having potential fire risk from activity beneath or adjacent to strategic road network*'. However, at the time, limited research was available for the HA to consider modifying the existing design practices. Most of the studies conducted in the years since then have included limited experiments and bridge-specific fire models, and limited structural analysis. However, things may now be changing. The only full span bridge fire experiment to-date was conducted in Valencia, Spain [16].

1.1 Objectives

Two reviews regarding bridge fires have been published in recent years. Garlock, et al. [5] presented a review with a particular focus on post-fire assessment and repair strategy. The authors listed 11 cases of major incidents which occurred between 1995 and 2009, and summarized 10 case studies of the structural assessment of fire damaged bridges. With the increasing needs of performance-based fire design in Canada, Nicoletta, et al. [17] also reviewed available research to '*guide design and assessment as well as direct future study*.'

To complement the previous reviews, this paper aims to provide a comprehensive review for research institutions, highway authorities and industry, including a useful database to give an insight into the issues concerning bridges and fire. It complements the previous reviews by summarizing various recent major accidents (**Section 2**), identifying potential scenarios that could result in a bridge failure or severe damage. For practitioners to select the parameters used in simulations, fire models (**Section 3**) and FE structural models (**Section 4**) have been reviewed and compared in detail. The various failure criteria currently used are also discussed in **Section 4** for post-fire assessment. Experiments involving full scale bridges or structural components of bridges in fire are reviewed in **Section 5**. Risk assessment is usually the ultimate goal for such studies, therefore this process is reviewed in **Section 6**. Finally, in **Section 7**, this paper identifies the gaps in knowledge that remain, future research needs and suggests ideas for future full-scale fire testing.

2 Fire accidents

Table 1 lists major accidents in the 21st century, so far, in reverse chronological order. The two incidents which have been studied in detail and published as case studies are indicated. The details of the incidents have been obtained from journal papers, web news and reports, and the key information including bridge types, fire scenarios and structural damage have been presented, where available. For clarity, the structural damage has been listed in three categories:

1) **Total collapse,** which refers to the condition in which one or more spans exhibited large deflections and lost their load-bearing function;
2) **Partial collapse,** which implies some of the structural components of one or more spans exhibited large deflections, and
3) **Critical defect**, which is used when the structure exhibited some deformation or section loss but did not collapse.

In some accidents, even when the damage was merely a critical defect, the bridges or bridge deck were still demolished and replaced [18], often due to the severe damage such as concrete cracking [19]. Alternatively, Peris-Sayol et al. [20] defined five levels of damage which can be used for a more detailed classification.

Observations from real accidents, primarily made by fire departments, may provide a general idea of gas and structural temperatures during such incidents. However, these estimates are unlikely to be sufficiently accurate to acceptably validate Computational Fluid Dynamics (CFD) models or structural heat transfer analyses.

There is very limited information in the literature concerning structural surface temperatures. One example is the maximum surface temperature of the steel plates was estimated to be about 500°C in the Wiehltal bridge fire [5].

In the Mathilde Bridge accident [21] the fire department estimated the temperature of the flames to be 650~800°C, while in the Wiehltal bridge fire [5] a temperature of 1200°C was estimated.

In the accident at MacArthur Maze, 1650°C was estimated and reported by the initial media. However, this is highly questionable as the flame temperature in an open environment should be around 1000°C, irrespective of size or fuel [22]. The flame temperature could not be much higher unless it involves some peculiar chemicals. C. Bajwa et al [8] estimated the temperature of the fire below the bridge section to be '*850~1000°C based on the samples collected and the results of thermal exposure tests. Near the truck, the maximum exposure temperature was estimated to be at least 720°C but less than 930°C'*. Another estimate was made for this accident where 1100°C was suggested based on experimental and analytical evaluations of large pool fires [8]. Any temperature estimates made without proper sensing equipment should be viewed with some scepticism.

Table 1 Major fire incidents in bridge networks in the 21st century

Bridge	Location / Date	Cost (Currency in US Dollar or Pound Sterling)	Structural Damage / Failure Time	Fire Information (Causes / Fire Duration)	References
I-75 Brent Spence Bridge	Kentucky, USA. 11/11/2020	$12 million	Damage: Critical defect (a section of the concrete deck and steel stringer beams were replaced)	Causes: Two-truck collision Duration: Several hours	[23]
Cedar Covered Wooden Bridge	Madison County, U.S.A. 15/04/2017	$720,000 to rebuild (This bridge was destroyed by fire once before, in 2012. $1 million on reconstruction cost)	Damage: Critical defect	Causes: Arson Duration: 2 hours (The bridge was fully engulfed when the fire crews and law enforcement got to the scene about 20 min later.)	[24]
I-85 Overpass	Atlanta, Georgia, U.S.A. 30/03/2017	$16.6 million in total ($10 million in emergency relief funds toward clean-up and short-term repair of the highway)	Damage: Partial collapse (a 30 m section collapsed) Failure time: within 30-45 min	Causes: Arson Duration: about 2 hours	[12,14,25,26]
CN Rail trestle wooden bridge	Mayerthorpe, Alberta, Canada. 26/04/2016	$7.6 million (including the costs of rebuilding the trestle and servicing customers while the bridge was out)	Damage: Total collapse (only some pillars from the truss still standing up) Failure time: It took only hours for the bridge to burn down	Causes: Arson (grass fire) Duration: Within an hour of being observed, the fire had engulfed the entire bridge	[6]
Wooden Train bridge	Porcupine Plain, Saskatchewan, Canada. 25/03/2016	Not specified (This bridge was a well-known historic landmark)	Damage: Total collapse	Causes: Grass fire (a homeowner started a grass fire which spread to the bridge)	[27]

Bridge	Location / Date	Cost (Currency in US Dollar or Pound Sterling)	Structural Damage / Failure Time	Fire Information (Causes / Fire Duration)	References
I-70 Highway Bridge	Ohio, U.S.A. 27/06/2015	$1 million	Damage: Critical defect (The flame cracked the concrete, melted metal reinforcement bars and compromised structural steel)	Causes: Vehicle fire (a tanker truck carrying ethanol overturned)	[13]
Peytonsville Road Bridge on I-65	Franklin, U.S.A. 15/08/2014	$10 million +	Damage: Critical defect	Causes: Vehicle fire and explosion (a tanker truck ran into a bridge support column, causing a fire and a large explosion) Duration: 30 min	[19,28]
Overpass (under construction)	Hesperia, California, U.S.A. 05/05/2014	$6 million	Damage: Total collapse	Causes: Metal-cutting accident accidentally ignited temporary wooden supports of the bridge	[29,30]
Al-Sheikh Mansour Bridge	Cairo, Egypt. 11/02/2014	Not specified	Damage: Total collapse	Causes: A fire broke out in shacks under the bridge caused gas cylinders exploded	[31]
Ed Koch Queensboro Truss Bridge	Connecting Manhattan to Queens, New York City, U.S.A. 16/08/2013	Not specified	Damage: Critical defect Two exterior stringers of the upper deck supporting an exterior lane were severely deformed and damaged.	Causes: Vehicle fire (tractor-trailer) Duration: 30 min	[10]
Harmony Ridge Wooden Trestle Bridge	Lampasas County, Texas, U.S.A. 19/05/2013	$10 million to rebuild	Damage: Total collapse	Duration: Firefighters spent 15 hours attempting to extinguish the blaze, before deciding to let it burn out. The entire trestle was engulfed within 20 min after the fire started	[32–34]

Bridge	Location / Date	Cost (Currency in US Dollar or Pound Sterling)	Structural Damage / Failure Time	Fire Information (Causes / Fire Duration)	References
Mathilde Bridge	Over Seine River, Rouen, France. 29/10/2012	Not specified	Damage: Critical defect	Causes: Vehicle fire (a tanker truck carrying more than 20,000L of oil and gas caught fire) Duration: 2 hours to control and extinguish the fire	[21]
Paramount Boulevard Bridge	Montebello, California, U.S.A. 14/12/2011	$40 million	Damage: Critical defect	Causes: Vehicle fire (a tanker carrying 8800 gallons of gasoline caught fire)	[18]
Yuqing Bridge	Wuyishan, Fujian Province, China. 28/05/2011	Not specified	Damage: Total collapse Failure time: Collapsed within 40 min	Causes: Children playing with fire	[35]
Deans Brook Viaduct	Mill Hill area, North London, UK. 15/04/2011	£4.5 million	Damage: Critical defect	Causes: Arson	[11,36]
Bucheon viaduct	South Korea. 2010	$13 million for the restoration of the bridge Total loss: $200 million	Damage: Critical defect	Causes: A tank-truck under the viaduct	[37]
9 Mile Road bridge over I-75	City of Hazel Park, Mich. U.S.A. 15/07/2009	Many millions of US dollars	Damage: Total collapse Failure time: The collapse of one span in about 20 min	Causes: Vehicle fire (a speeding driver hit a fuel tanker carrying 13,000 gallons of fuel, causing the tanker to impact into a column supporting the bridge)	[38]

Bridge	Location / Date	Cost (Currency in US Dollar or Pound Sterling)	Structural Damage / Failure Time	Fire Information (Causes / Fire Duration)	References
MacArthur Maze I-80/880 interchange	Oakland California, U.S.A. 29/04/2007	$6 million a day economic loss during the 26-day closure	<u>Damage</u>: Total collapse <u>Failure time</u>: The collapse of portions of the overpass in less than 20 min	<u>Causes</u>: Vehicle fire (a double tanker truck carrying 8600 gallons of gasoline overturned and burst into flames)	[5,8,39,40]
Bill Williams River Bridge	U.S.A. 28/07/2006	Not specified	Not specified	<u>Causes</u>: Vehicle fire (fuel truck)	[41]
Brooklyn-Queens Expressway	New York, U.S.A. 16/01/2006	Not specified	<u>Damage</u>: Partial collapse (girders and the heavy wooden timbers they supported collapsed)	<u>Causes</u>: Vehicle fire (tanker) <u>Duration</u>: 2.5 hours (For roughly 20 min, flames heated the large steel girders of a temporary bridge)	[42]
Wiehltal bridge	Near Cologne, Germany 26/08/2004	$42 million just for temporary repairs to restore traffic flows and $400 million for the total crash cost	<u>Damage</u>: Critical defect	<u>Causes</u>: A car collided with a tanker truck, causing the truck to fall 100 ft (30.5 m), followed by a fire under the bridge structure. <u>Fuel area</u>: 33 m^3 of fuel	[5,20,43,44]
Oaklawn Road Motorway bridge	Surrey, UK. 26/02/2003	Not specified	<u>Damage</u>: Critical defect	<u>Causes</u>: Vehicle fire <u>Duration</u>: 2 hours	[45]
Turkey Creek Wooden Bridge	Sharon Springs, Kansas, U.S.A. 12/04/2002	$250,000 to replace the lost coal cars $3.13 million to replace the current timber bridge with concrete structure.	<u>Damage</u>: Total collapse	<u>Causes</u>: A wheel bearing overheated and started to melt causing molten metal to fall onto railroad tracks	[46,47]

Bridge	Location / Date	Cost (Currency in US Dollar or Pound Sterling)	Structural Damage / Failure Time	Fire Information (Causes / Fire Duration)	References
I-65 Overpass	Birmingham, Alabama, U.S.A. 05/01/2002	$8.8 million	Damage: Partial collapse (significant deflection of 2.5 m but did not completely collapse)	Causes: Vehicle fire (a gasoline tanker truck collided with the pier of the overpass. 9,900 gallons of diesel fuel was consumed) Duration: 45 min	[48], [44]

3 Vehicle fire models

In some of the cases presented in Table 1, the bridge fire was literally the bridge itself on fire as the primary fuel load. This only really occurs for timber structures. In general, when ‘bridge fires’ are discussed, the phrase typically means fires on or under bridges, which may have an impact on the performance of the bridges. Garlock [5] defined the term ‘bridge fires’ as ‘*typically petrol fires, also referred to as hydrocarbon fires or liquid pool fires, which are characterized by fast heating rates and can reach very high temperatures within the first few minutes of fire exposure.*’ In this work, the phase ‘bridge fires’ will be used in general terms to denote a vehicle or liquid fuel fire under or on a bridge.

3.1 Fire loads

If fire is considered at all in bridge design, it is typically considered as a source of heating at the surface of the structure. Fire models may be used to define these thermal inputs; these are sometimes constant, sometimes varying with time. Having established the thermal input at the surface, heat transfer analysis can then be conducted to determine structural temperatures, and the structural response to the fire can be determined.

Currently, the most common way to define the temperature boundary condition is to use prescriptive code-based ‘fire curves’ such as the Hydrocarbon fire curve [49], the external fire curve [7] or the ISO fire curve [50]. Temperature boundary conditions can also be derived from estimated incident heat flux. The incident heat flux from a fire source to a target (e.g. structural members) can be calculated from empirical correlations (e.g. Shokri and Beyler method [51]). For the fire sizes that outside the experimental dataset, the empirical methods are not applicable. Alternatively, analytical models (e.g. point-source fire model and cylindrical source fire model) can be used.

In addition to those pre-defined fire curves and simplified fire models, CFD fire simulations are sometimes used to define fire scenarios analytically. In CFD models, incident heat flux coming from each cell toward is calculated at each time step. Fire Dynamics Simulator (FDS) can solve the combustion, heat transfer and the flow filed directly, and the accuracy of the results are highly reliant on the users' inputs. The third-party review or validations against experimental data are therefore recommended.

The early research on bridge structural response under fire loading focused on predicting the local damage due to a standard fire, that is, an assumed time-temperature curve. However, the standard fire models provided only a one-dimensional uniform thermal field. This is a significant simplification of reality, so some studies have simulated two and three-dimensional fire domains using CFD models; where the FDS [52] is the most commonly used simulation tool.

3.2 Fire intensity

The fire intensity can be defined using the heat release rate (HRR) for the scenario of interest, this may be divided into typical ranges for various vehicle categories. NFPA 502 (2017) [53] suggested the experimental and representative HRR of design fires for "*the bridges spanning moving traffic or a bridge spanning a freeway or interstate highway*", without fixed water-based fire-fighting systems, corresponding to various vehicle types, as shown in Table 2.

Table 2 HRR for typical vehicles, NFPA 502 (2017)

	Experimental HRR (MW)	**Representative HRR (MW)**	**Time to Peak Representative HRR (min)**
Passenger car	5 - 10	5	10
Multiple passenger cars	10 - 20	15	20
Bus	25 - 34	30	15
Heavy goods truck	20 - 200	150	15
Flammable / Combustible liquid tanker	200 - 300	300	-

Following NFPA 502 (2017), "*the designer should consider the rate of fire development*". This section summarises the HRRs and fire growth rates which have been used by other researchers for modelling, as shown in Fig. 1. The maximum value of heat release rate per unit area (HRRPUA) is commonly defined to be no more than 2500 kW/m^2. For building fires, UK guidance suggested various ranges of HRRPUA for places with different occupancy types.

Hopkin et al. (2019) [54] reviewed the recommended values of HRRPUA that are used in the UK.

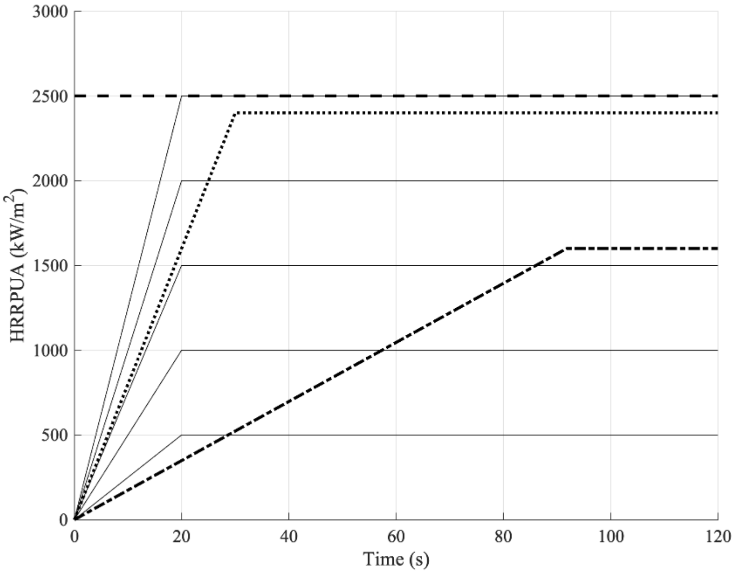

Figure 1 Comparison of HRRPUA curves used in CFD models in recent research (dashed line - [39]; solid lines - [48]; dotted line - [55]; dashdotted line - [10]). The time beyond 120 s is not plotted for better observation of the growth rate. All the curves remain constant until the end of simulations, while the dashdotted line is linearly decaying to 0 from 1200 s to 1800 s.

3.3 Fuel bed area

In most of the recent research, the fuel bed has simply been modelled as a rectangular shape and the top surface of the fuel bed is generally defined as the burning surface. For example, Peris-Sayol et al. [56] represent the size of the fuel bed as 12 × 2.5 m at 1 m above the road level. A burning area and fuel spilled area have been assumed by Alos-Moya et al. (2014) [48] with respective areas of 30 m^2 and 155.15 m^2. Gong and Agrawal (2015) [10] used 1.5 × 1.8 m which is approximately equal to the actual size of the cabin of the truck. Choi et al. (2012) [39] assumed 90% of the total spilled gasoline (8600 gallons) is on the bridge deck and other 10% of gasoline is on the ground. Wright et al. (2013) [44] used an equivalent diameter of 13.1 m for a fuel bed which is estimated based on visual observation - rectangular in shape with an approximate area of 134 m^2.

4 Thermo-mechanical finite element models

Bridges in fire have attracted researchers' attention since 2005 when a numerical simulation was performed by Dotreppe et al. (2005) [57] to study the failure mode of a tied-arch bridge exposed to fire. Finite element models played a significant role in providing a pre/post-fire assessment of bridges under fire loading. By using performance-based methods, bridge performance can be analysed for realistic fire loads and the structural weaknesses and strengths under fire loading may be determined. In such analyses, the time to failure for various scenarios can be predicted, and the critical load paths in the structure can be identified from the deformation and the change of internal forces (e.g. bending moments and axial forces).

Table 3 summarises the published thermo-mechanical models and compares the key inputs for performing finite element models. The software ABAQUS is most commonly used and other software packages are popular, such as ANSYS [8,58], LS-DYNA [8], SAFIR [57] and other self-developed codes [21].

4.1 Parametric study

In the past few years, several researchers have investigated the structural behaviour of bridge components under fire loading through FE models or experiments, mainly on a single composite girder [58–60]. Parameters affecting failure time/mode, such as web slenderness and spacing of stiffeners, have been studied. However, the estimated failure time and failure mode of a single component is questionable to represent the failure behaviour of a whole bridge frame. Therefore, other researchers [39,48,55,61] have simulated full-scale bridges and Alos-Moya et al. (2017) [16] conducted a 6 m span bridge test in Spain which will be discussed in Section 5. In these studies, certain key factors which may affect bridge fire resistance have been discussed, including vertical clearance [44,55], fire intensity [44], fire position [44], the exposure scenario, the number of spans [55], bridge shape [61], material types [44,62] and load combination [10,48,57,62].

The simulation of abutments has been considered in FE models [48,55,62] since Payá-Zaforteza and Garlock (2012) [62] first studied their influenence on structural response. Then, Hu et al. (2018) [61] conducted simulations including the abutment for a skew shape bridge and concluded that modelling the abutment is of little benefit for both rectangular and skew shape bridges.

The main challenge for simulating the structural response of bridges is validation, due to a lack of experimental data. Some studies (e.g. Refs. [10] [44]) have used other fire test results and validated by comparing the deformation, in which experimental results for building components were used [10]. These case studies used estimated or observed accident information such as deflection [48] or the decrease of temperature along the span [57] to compare with simulated results. Flame heights and gas temperatures were validated using other fire tests [44].

Table 3 Parameters used in thermo-mechanical FE models

Authors	Modelled Structures	FE Simulation Tool	Parametric Study	Fire Model	Live Loads	Element Types
Hu et al. (2018) [61]	Composite highway bridge	ABAQUS	• Rectangular vs. skew bridge shape • With and without abutment restraint • Element types	Hydrocarbon fire	None	• HT: DC2D4 • Structure: B31, S4R, R3D4
Peris-Sayol et al. (2015) [55]	Simply supported bridge	ABAQUS	• Single girder vs. full bridge (one/three spans) • With and without abutment restraint • Vertical clearance: 5, 6, 7, 8, 9 and 10 m • Spans numbers in full bridge model	CFD fire model	None	• Structure: C3D8 • Abutment: R3D4
Payá-Zaforteza and Garlock (2012) [62]	Simply supported bridge	ABAQUS	• With and without abutment restraint • Type of steel • Load combination	• Hydrocarbon fire • Stoddard fire	Uniform live load: 10,700 N/m	Structure: C3D8
Gong and Agrawal (2015) [10]	• A single girder • Damaged deck	ABAQUS	Vehicular loads	CFD fire model	• Vehicular live load has been applied on the upper deck • Two load patterns for the lateral distribution, have been assumed to create the most severe loading condition	• Steel stringers and cross beams: S4R • Concrete slab: C3D8 • Vertical and horizontal bracings: two-node linear beams

Authors	**Modelled Structures**	**FE Simulation Tool**	**Parametric Study**	**Fire Model**	**Live Loads**	**Element Types**
Aziz et al. (2015) [58]	A single girder	ANSYS	• Load level • Web slenderness • Spacing of stiffeners	Temperatures measured in fire tests were applied as a thermal-body-load at the nodal points of the girder	None	• Structure: SHELL181 and SOLID185 • Contact: CONRA174 and TARGE179
J. Alos-Moya et al. (2014) [48]	A single girder	ABAQUS	• With and without abutment restraint • Live load	• CFD fire model • Standard fire • Hydrocarbon fire	1.2, 2 and 4 kN/m	Structure: C3D8
Bajwa et al. (2012) [8]	The entire main spans; A bolt	ANSYS COBRA-SFS LS-Dyna	None	CFD fire model	None	Unknown
Wright et al. (2013) [44]	The main span was modelled by removing the skew	ABAQUS	• Fire intensity (vehicle type) • Fire location • Beam material • Vertical clearance • Fire duration (heating + cooling phase)	CFD fire model	None (Web buckling modes were initiated utilizing small concentrated loads on the web surface)	Deck and girders: quadratic solid elements
Dotreppe, Majkut, and Franseen (2005) [57]	A tied-arch bridge	SAFIR	Traffic loads	Hydrocarbon fire	Various traffic loading cases	• Main structure: 3D beam elements • Suspenders: truss elements

4.2 Failure criteria

Failure criteria are necessary for interpreting results of the structural analysis of the effect of fire on bridges. This section discusses the global and local failure criteria specifically for bridges in fire.

Global failure is determined to happen when there is:

- **Runaway behaviour** of deflection in the slab or beams (drastic increase in the rate of vertical deflection).
- **Reversal of horizontal displacement** at the free end-supports. This would suggest that the bridge span has softened to a point where the loads overcome the effect of thermal expansion [63,64] and the ends of the structure are pulled back towards the centre.
- **Inward horizontal displacement** at the free end exceeding the distance between bearing centreline and abutment edge, this would indicate that the superstructure has lost vertical support.
- Or, the British Standards criteria [65] are met: a beam shall be regarded as failed if there is no capacity to support the test load which is determined if either of the following empirical criteria are exceeded:
    - A deflection of L/20
    - The rate of deflection (in mm/min), calculated over 1 min intervals, on each minute from the commencement of the heating period, exceeds the limit set by the following equation:

      Rate of deflection = L^2 / 9000d

      Where L is the clear span (mm) of specimen, d is the distance (mm) from the top of the structural section to the bottom of the design tension zone. *NOTE. This rate of deflection limit shall not apply before a deflection of L/30 is exceeded.*

Note that the code-based failure criteria are based on standard furnace tests which do not account for the complex 3D behaviour in a real bridge. Therefore, the BS476 criterion is merely a reference and should not be considered as true indicator of failure. For example, the above criteria for global failure have been used in Ref. [61] showing no global failure in a bridge model. However, the maximum deflection is more than 0.5 m which shall be replaced in reality.

Local failure is determined to happen when:

- Exceeds bending moment capacity
- Exceeds shear capacity
- Fracture occurs, which is assumed to happen when the ultimate strain of the material is attained. This mode of failure is checked by comparing the maximum principal strain of the structure with ultimate strain based on true values.
- A sudden change in the out-of-plane displacement, which implies the failure due to the initiation of web buckling.

5 Experiments

Due to expensive cost and complicated performance, most existing fire tests data (for example [58]) were performed on structural components of bridges, such as composite girders. The first and only to-date whole bridge test, reviewed in this section, overcame the limitations of these furnace tests.

Valencia Bridge Fire Tests (2017)

The first experiment of a whole bridge structure was conducted in Valencia, Spain, in 2017 [16] and experimental data has been used to validate CFD models performed by FDS [66]. The bridge was a one span (6 m) steel grillage consisting of two girders, compositely supporting a reinforced concrete slab. The fire was represented by a square fuel pan and was placed under the bridge. In total, eight tests in four scenarios were performed with considerations of different fuel bed sizes, fire magnitude and locations (varied at both longitudinal and vertical direction). Two types of square pan dimensions have been used with side lengths of 0.5 m and 0.75 m, corresponding to fire magnitudes of HRR 415 kW and 1131 kW, respectively. In the tests, the deflection of the bridge deck was monitored and the results showed a small deflection. The results provide data for validation of numerical studies and demonstrated that the temperature decay along bridge span is significant and cannot be neglected.

6 Risk assessment

Risk assessment is useful for ranking the priorities of structures that need fire protection or other strategies. Some authorities have been working on risk assessment for bridges in recent years. Following the scrapyard fire which occurred beneath the M1 near Mill Hill, North London in 2011, the Secretary of State for Transport requested that a survey be carried out by both the Highways Agency (HA) and Network Rail to identify the locations of bridge structures at potential risk. HA assessed the potential fire risk locations around the motorways and trunk roads in England. Their report [15] provides recommendations for improving resilience in fire risk situations and suggests 50 priority locations which warrant further investigation. In the assessment, the vulnerability of the structure to fire damage was considered and 50 bridges and viaducts (out of a total of 3205 across the Strategic Road Network) were identified as vulnerable.

A few studies have contributed to the future risk assessment policy for bridges. Naser and Kodur (2015) [67] proposed an approach to assess the vulnerability of bridges to fires. This paper suggests fire resistance requirements for various fire risk categories. Quiel et al. (2015) [68] proposed a framework for analysing bridge structural response. This framework synthesizes calculation techniques to provide an efficient tool for industry, although not using a detailed analysis. Liu et al. (2017) [69] proposed a method to evaluate and classify fire risk of liquid chemical transport vehicles passing highway bridges. An application was demonstrated for the Taizhou Bridge.

7 Review and knowledge gaps

Due to the expense of fire protection materials including the cost of labour and maintenance, the authors suggest that research on improving the inherent fire resistance is more efficient than applying fire protection materials. The HA report [15] recognized that *'It is not practical to totally protect structures from the effects of fire.'* They considered the simplest forms of protection: a spray/trowel applied material, and boarded systems attached to the structure. However, the approach has not been considered further due to the cost of insulation, especially '*the additional ongoing costs for maintaining the protection and extra costs in accessing structural surfaces during inspections*.' These significant costs therefore become an obstacle and are not often considered further. Improving the inherent fire resistance of unprotected bridges could be the main focus of research.

7.1 Fire models

The observations from past accidents and collected information can be used to identify potential fire scenarios that could result in bridge failure and should be modelled in future bridge design analyses. According to the review in Section 2, the fire hazard in bridges is most often associated with gasoline spillage from vehicle fire incidents.

The most severe damage is caused by accidents *under* the bridge. While fire incidents have occurred on top of the bridge deck, this usually has very limited influence on the bridge structure, such as the cab fire on Blackfriars bridge [70] and the car fire on Aberdeen bridge [71]. This was also demonstrated by Peris-Sayol et al. (2016) [20], who showed the damage level is significantly higher when a tanker fire is under the bridge by analysing 154 cases of bridge fires. There has been only one accident on a bridge (Mathilde Bridge as mentioned in Table 1) which resulted in severe damage, this was however due to the fuel spillage which spread downwards [20].

Fully developed fires have the greatest impact on structures and these scenarios can be used as a preliminary and conservative analysis. The uniform fire assumption is widely used, using prescriptive time-temperature curves such as the Hydrocarbon fire. However, the detailed analyses of bridge performance under uniform or prescriptive fires are potentially unrealistic and can be over-conservative. A heterogeneous fire model is therefore needed. This can be achieved using fire inputs from CFD models or other fire models, with spatial decay considered. Third-party review is recommended to assure the accuracy of the results and inputs.

When fire modelling, the fire duration should vary according to the bridge construction. The authors suggest at least a 20-min fire duration for a vehicle fire under a concrete/steel bridge, however up to 15 h fire duration has occurred in wooden bridges [32]. This suggestion takes into account the observations from the actual fire accidents under bridges where it usually takes fire brigade at least 20 min to intervene since the fire started. It also borrows from the design concept of the fire resistance time for buildings where:

1. The fire resistance time required for buildings ranges from 30 min to 120 min [72]. The fire resistance time is designed to ensure that buildings are designed and constructed so that they do not collapse prematurely to provide time for occupants to escape and for the fire service to obtain access. These times are usually much shorter for bridge fires than for building fires.

2. The fire resistance requirements are a function of ‘purpose group’ of the building as defined in Approved Document B or ‘risk profile’ as defined in BS 9999:2017, building height (for evacuation and access for fire-fighters) and sprinklers. For bridges, fire resistance requirements should be a function of construction type, span length, and location. The specific fire resistance of different bridges needs to be studied in detail. The 20 min fire resistance can be a minimum requirement as discussed above.

The fire growth rate for different types of vehicles can be seen in NFPA 502 [53] (as listed in Section 3.1) where HRR of passenger car fires increased at fastest rate – reaching the peak in 10 min. The peak HRR may also be reached within 10 min [53]. It’s the designer’s responsibility to consider the fire growth rate. However, the value of HRRPUA used in FDS models is suggested to be not larger than 2500 kW/m^2. Fire growth rates of up to 5 MW/min have been observed in tunnel fires under low ventilation conditions [73], and this scenario is somewhat analogous to the situation under a bridge, since peak intensity would be reached very rapidly in an open environment.

7.2 Structural models

Finite element simulations are able to offer low-cost assessment to avoid the necessity of conducting complicated and expensive full-scale tests. Also, we can learn how the structural design affects the performance under fire. However, this requires the knowledge of finite element or fluid dynamics and may lead to extensive user effort and simulation times.

There have been barely any studies which have considered live loads on such bridges in fire, which is a reasonable assumption for short-span bridges as the massive black smoke would be a clear stop signal for the drivers. However, for the large bridges with multiple lanes or bridges located above a road with multiple lanes, it is still possible for vehicles to stay in traffic while a car fire accident happened blocking only several lanes (as observed in a car fire on lower deck of Bay Bridge in USA). The live load should therefore be considered in these cases. There appear to have been no numerical studies of wooden bridges in fire, which often have historic and cultural value. Peris-Sayol et al. (2016) [20] found that there are no statistically significant differences in the fire response of composite, concrete or steel bridges, although composite bridges seem to sustain higher damage than the other two types.

Different types of finite elements can be used for different purposes. Solid elements have been used to get a close match to the experimental data [44]. These are also easier for transferring thermal data from FDS to thermo-mechanical analysis in ABAQUS. Shell and solid elements can be used to capture local phenomena such as web buckling that might determine the global response and the failure mode of the bridge. For most bending dominated problems, beam and shell elements are much more efficient and accurate than solid elements [74]. 3D beam elements deal with large displacements, material non-linearity and progressive spread of plasticity within the cross-section as well as along the length of elements. Structural beam-column elements can be used for a low-cost analysis if local buckling behaviour is not important. This may be of interest to practicing engineers.

The key finding that researchers are most interested in is displacement, which is the most straightforward result that can be compared to the failure criteria directly (as discussed in Section 4.2). The displacement is however sensitive to the applied boundary conditions. For those cases where it may be difficult to model the boundary conditions that can provide the accurate prediction of displacement, other outputs such as section force, reaction force and bending moment can be reliable indicators to understand the load distribution (see example [61]).

7.3 Risk assessment

Performance based structural fire engineering is beginning to have an impact on bridge design, because of limitation of codes and standards and increased understanding of structural fire response from building fires and case studies of bridge fires.

The main reasons for bridge failure induced by fire are usually a combination of structural damage including compromised structural steel, or buckled girders or supports. Therefore the vulnerability of those structural components can be ranked. Similar to building fire design, reduction factors can be used to establish a level of safety.

Implementing design codes which require engineers to follow prescribed maximum credible vehicle fires, similar to other actions such as earthquake, wind and floods is desirable. However, there is no need to consider the fire load at all locations. This can be justified by suitably qualified and experienced fire engineers until regulations are in place. The justification method includes a priority list which can be presented to rank the locations which are critical for a vehicle fire to occur. Simulation packages can be used to perform fault-tree analyses to determine the factors and potential failure modes leading to a failure. Since bridges plays an important role on transport links, unlike buildings fires, the location and cost of a bridge should determine the priority for the purpose of property protection.

7.4 Experiments

To the authors' knowledge, there have been very few tests to understand bridge fires, and most of these tests were performed using small fuel pools. In order to truly understand the response of bridges subjected to fires, CFD fire models have been applied by researchers to allow the possibility of a decay of heat fluxes along the span away from the fire, which is not provided by prescriptive curves. However, it is worthwhile to note that the true dynamics of vehicle fires are difficult to fully capture using CFD models. Validation based on experiments are needed, especially full-scale fire experiments under large vehicle fires. Experimental data can provide a solid support for the future guidance. In order to design bridges against fires in a consistent manner, bridge sections can either be tested at their actual dimensions, or calculations can be done if sufficient experimental data is available for extrapolation.

7.5 Suggested policy for government

As presented at the beginning of this paper, severe fire accidents which have consequences for bridges are not as rare as might be generally perceived. Therefore, code implementation should be considered. The design fire loads should be considered in a similar way to design loads of wind or earthquakes. Highways Agency (2011) [15] reported that more than one third of bridges and viaducts have clear spans in excess of 5 m. Therefore, the government could focus on setting up regulations for only the bridges with span larger than 5 m. Defining an allowed fire resistance time can be a start for code implementation and remaining operational after damage may be a key requirement. The standard fire curve was devised for small compartment fires, it is not suitable for bridge design. A designed fire curve with spatial decay should be used for bridge fires.

The drainage system should be designed properly as a passive fire protection measure to lead the spilled fuel travel away from the bridge. For the bridges located above roadways, the drainage system should prevent the fuel spreading downwards to the roadway.

Legal storage beneath bridges and flammable goods in adjacent areas are another reason for fire accidents. In the I-85 Overpass accident in the USA in 2017, the material which burned had been stored in the area for as long as 6 years [75]. Following this accident, CNN [75] contacted departments of transportation about the storage policies in all 50 states and got responses from 44 of them. They observed: *'Some said that materials under bridges are not allowed, but practices vary from state to state, and even the definition of "hazardous" may be part of the reckoning. Until now, Maryland might have allowed contractors or its own workers to store high-density polyethylene on state-owned space under bridges during a construction project.'* The positive news is that *'some departments of transportation have decided to draft or revamp written policies.'*

Various types of storage or parking also exist in Asian countries, such as South Korea [76]. Joo et al. (2017) [76] carried out a field survey to investigate the exact risk due to fire on bridges. It was found that construction materials and other flammable material such as tyres, furniture and straws stored under the bridge cause a potential hazard which may lead to a fire. Other risks include the fuel tankers parked under a bridge. Since 1990, the Korean government and public institutions '*had used spaces underneath bridges as parking lots and facilities for distribution, convenience and sport*' [37]. After the Bucheon viaduct accident in 2010, Korea Expressway Corporation (KEC) modified the practices by performing surveys, classifying representative materials under bridges, combustion tests, fire resistance tests and CFD simulations of the items [37]. Then, KEC assessed '*fire safety for all existing bridges in the metropolitan area*' based on the new modified manual.

The same issue also exists in the UK, for example the M1 Motorway's Deans Brook viaduct accident which happened in 2011 [11,36], where the fire started in a scrapyard. After this fire, the Highways Agency (HA) and Network Rail undertook a high-level scoping study to understand *'the scale of potential risk from activities beneath and adjacent to the elevated sections.'* According to the report [15], *'To reduce the need for compensation payments, avoid severance and prevent sterilization of land, it has been government policy since the 1960's to generally acquire only land required to accommodate the footprint of any bridge piers or* *abutments needed to support structures.'* This policy therefore results in the difficulty of managing material storage on land not under HA ownership. It was found that some high-risk locations have restrictive covenants on land immediately beneath bridges on the network. This report developed a risk assessment criterion and scored the structure vulnerability for prioritization ranking, which shows that structures with a reinforced concrete deck have a lower risk than those structures with vulnerable features (e.g. pre-tensioned, post-tensioned and steel beams etc.).

Industrial estates underneath motorway flyovers are common in the UK. A simple ban of sites or car parking under bridges is not recommended as social influence outweighs the risk from potential fires. However, for critical bridges or motorways, management should be introduced to mitigate the fire risk. Immediate firefighting of a small fire may have the greatest effect in avoiding a major incident. First aid firefighting such as hand-held extinguishers can be the most cost-efficient way to prevent the fire damage to the bridges.

8 Conclusion

The commuting function of bridges characterise the importance of this topic in comparison to other types of fire. Unlike the complexity of building fires, the worst-case fire loading of bridges is easier to determine, but this is rarely applied in design. This review analysed the existing research and highlighted the knowledge gaps and considerations for future simulation and experiments.

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