BRIDGE FIRE HAZARD: AN OVERVIEW

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ABSTRAKT

Článek prezentuje současný stav poznání v oblastech týkajících se požárů mostních kosntrukcí. Jsou popsány nedávné požární incidenty, které vyústily ve vážné narušení nebo úplný kolaps mostní konstrukce. Jsou uvedeny nejnovější vědecké publikace týkající se požárního rizika na mostních konstrukcích v oblasti rizikového inženýrství, návrhu konstrukcí za požáru, požární ochrany a analýzy konstrukcí po požáru. Přístupy k modelování požáru pro účely návrhu konstrukcí za požáru a ochranné prvky určené pro zmírnění případného požáru na mostech jsou uvedeny následovně. Možný budoucí výzkum vyplývající z obsáhlé rešerše literatury je uveden na závěr.

KLÍČOVÁ SLOVA

Požární riziko • dopravní infrastruktura • mosty • návrh konstrukcí za požáru • ochranná opatření

ABSTRACT

The following paper presents the current state of specific topics related to fire incidents on bridges. It also describes recent fire-induced damages of bridges. The paper analyses the latest research related to fire hazard on bridges - presented in the field of risk engineering, structural fire engineering, fire protection engineering, and forensic engineering. Approaches to fire modelling, as a part of structural fire engineering, are described in the following section. Protective measures, which can be applied in order to mitigate the fire impacts on bridges are discussed as follows. At last, it suggests possibilities for future research, based on the literature review.

KEYWORDS

Fire hazard • transportation infrastructure • bridges • structural fire design • mitigation strategies

1. INTRODUCTION

There is almost three times as much fire-induced collapses of bridges as of those induced by earthquake (Garlock et al. 2012, Naser & Kodur 2015). Bridge disruption in general brings huge economical and social impacts to the state. The economical burden not only is formed by the direct loses stemming from the replacement of a part or the whole structure of the bridge. Huge part is also formed by indirect loses caused by the inability to use the bridge, as an element spanning across usually not simply crossed area. The social burden comes along with the overall organisational activities addressing the system dysfunction, such as detouring the traffic, which can affect the transport quality in the region. In case the impacted bridge is considered to be a part of critical infrastructure of the state, disruption of one element can potentially have diverse impacts - other than economical - to different elements forming part of the critical infrastructure (Eid et al. 2017).

2. IT IS REALLY HAPPENING

According to the data gathered in a survey in 2008 from Department of Transport offices in 18 US states regarding bridge failures, there is almost 3 times fire-induced bridge failures than failures induces by earthquake. The data assembled during the years 1990 - 2005 revealed that out of 1746 bridge failures 52 was due to fire, 19 due to earthquake (Garlock et al. 2012, Naser & Kodur 2015). According to (Kim et al. 2016) annually there is in average 8 cases of bridge collapse due to fire in South Korea. Another interesting set of data is provided in (Proske 2018), where a cause-proportional collapse rate is given. For bridges over water fire-induced collapse occurs in 1.97 %, for earthquake in 0.49 % of cases, whereas for bridges over roadways and railways it reaches to 6.90 %, for earthquake 2.30 %.

This information is especially concerning taken into the account the fact, that there are essentially no provisions related to the structural fire design, whereas for the structural design concerning earthquake there are. Also, the statistical data do not provide information about damages caused by fire, which can eventually lead to direct replacing of the whole or part of the structure.

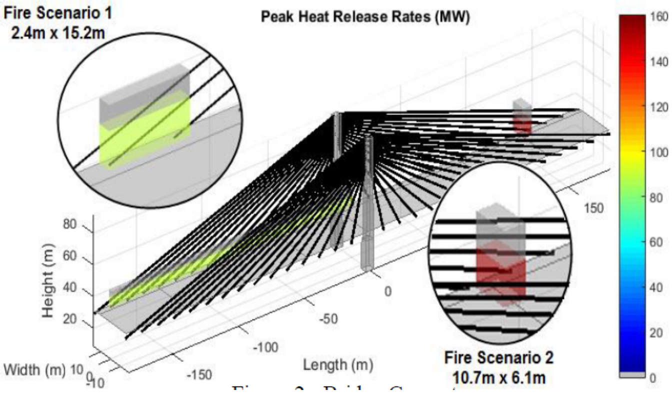

Figure 1: *Proposed model of fire scenario for evaluation of the structural response of the bridge to fire (Quiel, Yokoyama, Mueller, Bregman & Marjanishvili 2015).*

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In recent years there has been number of notable fire-related accidents on bridges with often severe consequences leading to extensive damage or total collapse. The most recent notable bridge fire occurred in Atlanta on bridge consisting part of interstate route 85 in March 2017 (see Fig 2), serving over 200.000 cars a day. The bridge was composed of 10 pre-stressed concrete girders which were placed on three RC piers. The fire was induced by arson which set alight large PVC pipes stored under the bridge. The temperatures quickly reached 900 - 1100 °C as reported by Department of Transportation, Georgia. After 30 minutes of fire a 30.3-m-long span collapsed damaging adjacent piers and spans. (Kodur & Naser 2021*b*)

The post-fire investigation revealed spalling on the piers and on the girders both which collapsed and the adjacent ones. The loses were estimated to be $ 10 million and it took few weeks to replace the structure. The post-fire damage is shown in Fig. 3 (Kodur & Naser 2021*b*).

Another example of fire which resulted in a complete collapse of the structure of the bridge was incident happening on I-80/880 interchange in Oakland, CA, USA in 2008, also being referred to as MacArthur Maze. The deck of the bridge was a composite, comprised from reinforced concrete slabs and six welded plate girders placed onto reinforced concrete columns. A gasoline tanker crashed and overturned, resulting in a spill of 32 m^3 of gasoline under the I-580 bridge. Collapse of two spans occurred 22 minutes into the ignition of the fire (see Fig 4). The loses were estimated to $9 million with assumed indirect economic loses $6 million a day. It took 26 days to reopen the bridge to the traffic (Garlock et al. 2012).

3. EXTENT OF DAMAGE

The events of fire occurring on the bridge or in its vicinity does not necessarily lead to the complete collapse of the structure. It can, however cause minor or major damage and influence the traffic and overall functioning of the bridge. The extent of damage caused to the bridge is influenced by both aspects related to the structure of the bridge and aspects related to the fire itself.

An analysis of the influence of these aspects to the extent of fire-induced damage on bridges was conducted by (Peris-Sayol et al. 2017). A data was collected from 154 cases of past bridge fires. Information about aspects considering the bridge characteristics and origin of fire were assembled and sensitivity analysis conducted to assess the influence of the aspects to the total damage of the bridge. Five bridge damage levels were considered varying between superficial damage and complete collapse of the structure. Bridge-related aspects included bridge site, deck material, structural system and bridge span and width. Fire-related aspects included the origin of fire, in case of burning truck or storage a fuel type and its characteristics were considered together with its position towards the bridge. It concludes that most severe damages are caused by tanker trucks, where gasoline has caused more damages that diesel - the question however is what is the proportion of gasoline to diesel transportation.

When it comes to location of the fire source, it compares the damage severity with regards to the position of the tanker truck. It concludes that the accidents with burning tanker truck directly under the bridge or on the top of the bridge with a significant fuel spillage under the deck cause significantly higher damage levels than to those cases when the trucks are ignited on the top of the deck.

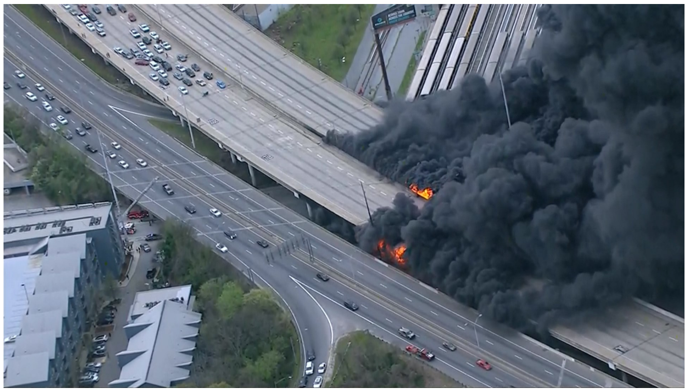

Figure 2: *Fire underneath I-85 bridge in GA, USA in 2017. The fire was induced by arson of PVC pipes storage under the bridge. This led to collapse of one span (Johnson 2017).*

Figure 3: *Post-fire damage at I-85 bridge in GA, USA in 2017. Collapsed girders and spalling of the concrete layer of the piers are visible (Kodur & Naser 2021*b*).*

Figure 4: *Collapse of I-580 bridge in CA, USA in 2008 as a result of gasoline tanker crash and consequent spillover of the highly flammable liquid (Quiel, Yokoyama, Bregman, Mueller & Marjanishvili 2015). Photo taken from (Jennings & Winton 2011).*

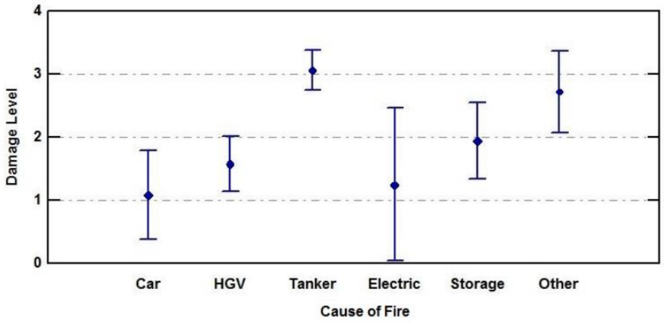

Figure 5: *Relation of fire source and the damage level induced by the fire. It shows that the most severe damage is caused by tankers carrying different types of flammable liquids which usually have high calorific content, such as gasoline or diesel (Peris-Sayol et al. 2017).*

In paper (Kodur & Naser 2021*a*) dependencies of significant features related to the bridge, fire and traffic to the fire risk of the bridge were analysed using machine learning tools. It works on basis of analysing data from previous incidents and determining the key features of the general population of bridges which failed under the fire incident. The key features are compared to those of studied bridge - which helps to identify endangered bridges and determine possible events which may lead to damage or failure of the structure. It also shows the possibility to train the machine learning tool to account for the dependencies among the key features influencing the bridge vulnerability towards the fire hazard.

4. RELATED CODES, STANDARDS AND PROVISIONS

Generally, the process of determining the structural fire response can be understood as a sequence of 3 separate steps, as given in EN 1990 (BSI 2010).

1. Fire scenario shall be based either by taking into account nominal fire exposure or modelled fire exposure by performance-based approach.
2. Analysis of heat transfer within the structural element with regard to boundary conditions - simply how the heat transfer is considered and implemented.
3. Analysis of mechanical behaviour of structural members at elevated temperature.

The structural fire design of bridges is not covered by Eurocodes. In Designer's Guide to Eurocode 1: Actions on Bridges (Calgaro et al. 2010) is specifically stated:

"The structural fire design of bridges is not dealt with in this Designers' Guide. This type of design situation is normally not covered by the Eurocodes, even though the consequences of accidental exposure of bridges to fire actions (e.g. lorries burning over or below a bridge deck) are increasingly taken into account for the design of important and monumental bridges. However, the fire Parts of Eurocodes may be used as guidance for the type of problem under consideration."

In other words, standardised curves - hydrocarbon curve and modified hydrocarbon curve - can be implemented, however no specific guidance on how the fire hazard should be taken into account is provided. Also, fire load that bridges should withstand, way of protecting existing structures against extreme fires and post-fire damage evaluation are not incorporated.

Furthermore there is no decay phase of the standardized curves, which does not correspond to the realistic scenario. Both above mentioned curves are plotted in Fig.6 using in-house software FMC <3 (Benýšek & Štefan 2015–2018).

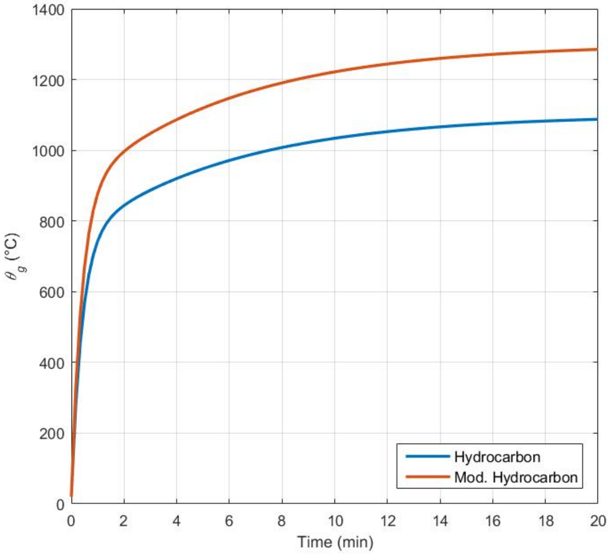

Figure 6: *Hydrocarbon curve and modified hydrocarbon curve as representatives of code-given fire models, which can be applied for structural design of bridges. Plotted from in-house software FMC (Benýšek & Štefan 2015–2018).*

Taken into account American provisions related to fire hazard on bridges, NFPA 502 (NFPA 2017) provides general fire protection requirements for bridges and elevated highways with length larger than 300 m. The measures include protection of structural elements - protecting critical structural members in a way that high-temperature exposure does not lead to a dangerous weakening or complete collapse of the bridge and in the case of suspension and truss bridges a risk analysis with possible fire scenarios should be incorporated. Incident detection should be incorporated for larger structures including manual fire alarm boxes and CCTV systems for situation monitoring as well as traffic control. Provisions on active fire facilities, such hydrants and extinguishers, together with recommendations on drainage system design are included. Lastly, provisions related to hazardous locations together with control of hazardous materials are given. However, specific guidance for structural designers on the fire consideration is missing.

5. RESEARCH

After a series of accidents having led to extensive damage or total collapse of the structure and a very little guidance in related codes on how to take into account the fire incident in the structural design, number of research papers has arisen in the past decade. The papers are addressing the broad topic of fire-related incidents on bridges and can be grouped into 4 groups addressing main engineering approaches dealing with the bridge fire hazard.

***A.** Risk engineering*

It identifies the critical structures related to a high risk of fire. (Kodur & Naser 2013) developed an approach for assessing bridges prone to a high risk of fire hazard to develop relevant design or protection strategies. This approach determines risk grade of the bridge using weighted factors based on the different features of a bridge grouped into categories related to geometrical properties and design features, likelihood of fire occurrence, traffic demand, economic impact the disruption shall have and expected fire loses.

Simplified risk assessment procedure is included in (Kim et al. 2016) to determine the extent of risk stemming from fire hazard. In (Wang et al. 2018) a mechanism model for risk assessment of bridge fire incident is presented. It evaluates the bridge vulnerability to determine the need of implementing countermeasures.

B. *Structural fire engineering*

A number of papers is concerned with modelling fires and their influence to the structure of hypothetical bridge or conducting a case study of a past event. As the fire modelling approach is the concern of this paper, author collects structural-fire bridge studies according to the fire model.

Standardized methods put forward in Eurocodes for bridge design, a hydrocarbon fire curve, is used as an fire modelling approach in number of papers given in (Quiel, Yokoyama, Bregman, Mueller & Marjanishvili 2015, Table 1). *Computational Fluid Dynamics modelling* was also incorporated by a number of papers to assess the fire outcomes. *Performance-based modelling* addresses the determination of the development of a specific fire scenario. Most notable is work is that of (Quiel, Yokoyama, Bregman, Mueller & Marjanishvili 2015) where a new design framework is proposed, considering a fuel spillover as a source of the fire ignition. The framework which addresses the fire model and its transport to the analysed structural member is shown in Fig 7 and is taken from the mentioned paper. The streamlined design framework for evaluation bridge's response to fire is proposed. It consists of 4 basic steps. 1. Calculating the fire characteristics and geometry, 2. calculating heat transfer from the fire to structural member, 3. calculating the temperature conduction within the structural member, 4. calculating the mechanical response of the structural element. It was then applied for evaluation of the collapse of MacArthur Maze discussed above.

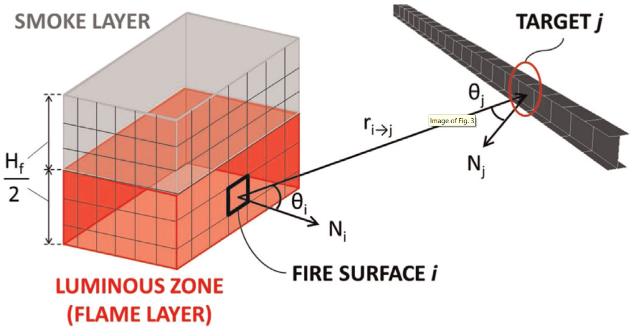

Figure 7: *Proposed model of fire for the use of evaluation of bridge structure exposed to fire (Quiel, Yokoyama, Bregman, Mueller & Marjanishvili 2015).*

Another application of this framework on cable-stayed bridge is shown at the beginning of this paper, in Fig. 1.

Validation of both simplified and advanced numerical models of bridge fire scenarios is included in (Alos Moya 2018) by conducting a series of measurements on experimental reduced-scale bridge.

C. *Fire protection engineering*

To reduce the vulnerability of bridges towards the fire hazard, following measures can be implemented (Wang et al. 2018, Kim et al. 2020, Park et al. 2018):

- Implementing active fire protection, such as fire protection paint or insulation, to the key structural elements.
- Implementing detecting and firefighting facilities.
- Incorporating physical barriers protecting vulnerable structural elements.
- Restricting transport of potentially dangerous cargo - such as fuels, flammable chemicals and other highly flammable and calorific-dense materials.

Furthermore, (Park et al. 2018) introduces strategies to address the materials stored under bridges.

D. *Forensic engineering*

It comes up with a post-fire analysis of the structure to provide a considerable information for making decision about the scope of repairs or complete shut down of the structure. Possible post-fire assessment and repair strategies used in case studies for concrete, pre-stressed concrete and steel are summarized in (Quiel, Yokoyama, Mueller, Bregman & Marjanishvili 2015).

6. FUTURE RESEARCH

Future research topics are based on gaps detected in the literature review and are suggested following.

Development of probability-based framework related to structural analysis. Due to high level of uncertainties connected to determination of fire performance of a structure, probabilistic frameworks are coming to the forefront to estimate probability of failure of a structure. The quantification of the structure's resistance to fire hazard is in principle coupling the probability of occurrence of a structural damage with probability of occurrence of fire. These critical states can be defined with the underlying physics principles of the given fire scenario.

Development of multi-physics analysis framework. That is coupling fire modelling, heat transfer to the structure and the thermo-mechanical analysis. The analysis can be based on work of (Choi et al. 2010) where each of the steps is conducted separately.

Taking into account the current state of the structure in thermo-mechanical analysis. The influence of chemical and physical degradation of the structure and material could be taken into account while conducting analysis of the bridge's response to fire.

Development of overall fire management system. That could consist of:

1. Designating key bridges / in other words structures of bridges which are forming part of critical infrastructure of the state (Setola et al. 2016). Importance factor (Kodur & Naser 2013) can be incorporated to assess the criticality of such a structure, or other approaches, such as in (FEMA 2003) can be used for the evaluation.
2. Developing realistic worst possible fire scenarios specific for the bridge site.
3. Developing or optimization of the emergency response plan with close cooperation with local firefighters' department.
4. Conducting regular drills of the emergency response plan.

Incorporation of active fire safety features. Those can include automatic recognition of elevated temperature which could be coupled with an announcement system connected to the firefighter department.

7. CONCLUSION

In order to maintain the level of safety of the state, it is essential to evaluate the criticality of key bridge structures and the potential impacts should the disruption due to fire occur. Raising interest among the scientific field aiming at understanding the fire development including its cause, the way the fire influences the structure of the bridge and ways to overcome often severe consequences of the incident is included. The consequences of fire can be addressed both by preventive and reactive measures. This paper is providing an overall overview of the fire hazard related to bridge structures and is raising an awareness of the possible impact the occurrence should have to the state and its protected interests. It emphasized the need of development of a consistent approach by coupling current research with the state authorities for providing a comprehensive level of safety of its protected interests.

ACKNOWLEDGEMENTS

This work was supported by the Grant Agency of the Czech Technical University in Prague, grant No. SGS21/040/OHK1/1T/11.

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