VALUTAZIONE DEL COMPORTAMENTO AL FUOCO DI PONTI IN ACCIAIO E COMPOSTI: DALLO STATO DELL'ARTE ALLE ANALISI AVANZATE

ASSESSMENT OF STEEL AND COMPOSITE BRIDGES FIRE BEHAVIOUR: FROM THE STATE OF THE ART TO ADVANCED ANALYSES

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ABSTRACT

Fire risk is becoming crucial to be taken into account even in the infrastructure as bridges. Indeed, vehicles which daily use the road network are increasing as a consequence of the rapid urbanization and, more importantly, the transport of flammable furniture, as fuels, is evenly interesting more and more the highways and national roads. However, there is no economic benefits to consider always the fire load combination into the design or verification regardless of the case study analyzed. For these reasons it would be useful to define a general approach which allows to identify the cases in which the fire assessment is needed. This work principally provides a deeply review of the state of the art about this topic by starting from the analysis of technical codes, then investigating the scientific literature. The approaches proposed both in codes and papers will be explained and commented in order to draw conclusions about the benefits of carrying out a fire verification using each one. Moreover, several real fire scenarios were selected and modelled through advanced fluid-dynamic analyses, to define the corresponding natural fire curves. Finally, a typological steel-concrete composite bridge has been selected and parametric advanced thermo-mechanical analyses were performed, in order to underline the differences between the approaches in terms of fire modelling, verification criteria and structure classification. The results will be shown in the displacement and resistance domains.

SOMMARIO

Il rischio d’incendio sta diventando un aspetto cruciale, per il progetto o verifica, anche delle infrastrutture come i ponti. Infatti, il volume di traffico che quotidianamente impegna la rete stradale è in aumento a causa della rapida urbanizzazione e, conseguentemente, aumenta anche il trasposto di materiale combustibile come i carburanti. Nonostante ciò, considerare la combinazione di incendio non comporta automaticamente un vantaggio economico indipendentemente dal caso studio. Per queste motivazioni sarebbe utile definire un approccio generale che consenta di identificare i casi in cui la verifica in condizioni di incendio è necessaria. Questo lavoro fornisce un'approfondita revisione dello stato dell'arte sul tema, a partire dall'analisi delle normative tecniche e poi investigando la letteratura scientifica. Gli approcci proposti sia nei codici che nella letteratura saranno esposti e commentati per trarre conclusioni sui possibili benefici conseguenti all'utilizzo dei due approcci. Inoltre, diversi scenari di incendio sono stati scelti per l'analisi del caso studio e la corrispondente curva di incendio naturale è stata valutata tramite analisi fluido-dinamica avanzate. Infine, un tipico ponte composto acciaio-calcestruzzo è stato scelto per effettuare un'analisi termo-meccanica avanzata parametrica al fine di evidenziare le differenze fra gli approcci in termini di modellazione dell'incendio, criteri di verifica e classificazione della struttura. I risultati saranno mostrati sia nel dominio degli spostamenti che delle resistenze,

1 INTRODUCTION

Take into account fire risk, in design and verification of bridges and infrastructures, is becoming crucial as, according to the scientific literature, the number of fires involving transportation structures is increasing in the last years. A lot of studies have collected data and statistics in terms of number of fires, which part of them also involved bridges, the causes of the fires and also the consequences in terms of economical and human losses and logistical consequences as the eventual interruption of the road network service. For these reasons, it would be definitely useful a general approach which allows to identify the case in which the fire load combination must be taken into account in the design and verification also with economical advantage. Starting from the risk definition as the combination of the probability of occurrence of an event, its magnitude in relation with the vulnerability of the structures and the value exposed to the event, it is possible to define a methodology to select the structural typologies more vulnerable and define the performance that each of them must reach to ensure a minimum fire safety. The technical literature provides statistical analyses of national polls about the occurrence of fire events: a comparison between the fire probability of occurrence in buildings and bridges shows that in the first case the probability is 29.5% against the 2.3% of bridges [1]. Thus, considering these probabilities, it seems that the fire risk on bridges is not particularly relevant. Even if the probability of bridge fires is not particularly high, their consequences can be significant, so to design and verify bridge structures in case of fire is necessary. Finally, the volume of vehicles which interests a bridges could be very different as a function of its location in the road network, that can lead to a huge difference in terms of value exposed and then in the risk even if the other parameters appear as comparable. Thus, this work aims to provide a technical review of the state of the art and a parametric thermo-mechanical analysis, which allow to underline the differences between the approaches proposed in national codes and scientific literature.

2 STATE OF THE ART

For the assessment of the structural fire resistance, two approaches are proposed in technical references, such as Eurocode: the prescriptive-based and performance-based one. The first one allows to classify the structure in a discrete number of classes as a function of the time collapse of the structure facing a standard fire curve. For the buildings case the fire curve used is the ISO834 curve, the structural members are typically exposed to a generalized fire and their time collapse is related to the class (R30, R60 and so on). A similar method in the case of bridges is not available in technical references even if in many case the bridges could result much vulnerable to fire. This is principally due to the high static utilization of structural element in order to reduce the cross-section and then the cost of investment, also small cross-section and important span length make the bridges structural elements to be typical slender. However, Kodur and Naser [2] developed a methodology defined in the prescriptive-based approach. The method provides for the classification of the bridges based on the fire risk by defining an importance factor IF. This importance factor takes into account the same factors of the risk definition as it depends on the vulnerability of the bridge to fire as well as the criticality in terms of traffic flow and economical or human losses. The vulnerability of a bridge to fire depends on the geometric dimensions, material properties, design characteristics of its structural elements and the probability of fire danger in the vicinity of it. The key characteristics that define the importance of a bridge, such as fire vulnerability and critical nature, are grouped into five classes. Each class covers several parameters (geometrical features, hazard fire likelihood, traffic demand, economic impact, expected fire losses) of influence that contribute to the calculation of the importance factor, which is evaluated through a weighted factors approach. Generally, the weightage factors are assigned in ascending numerical order, with the largest value indicates the highest risk of fire. The combination of all these factors leads to the importance factor evaluation that measures the fire risk grade of each bridge. The importance factor can be classified according to fire risk, that can vary from low to critical. The method proposed by Kodur also provides the verification criteria, for low fire risk, no verification of the bridges has to be performed. While, the method proposes a fire verification in the time domain by monitoring the maximum displacement, which has to be lower than L/30 (where L is the length of the bridge span) for one hour in case of high risk or two hours in case of critical one. This verification must be led by using the hydrocarbon fire curve, in order to take into account, the most probable fire nature in bridges [6].

3 FIRE DESIGN AND VERIFICATION OF BRIDGES

In the case of structures, the performances required to the structural elements can be classified into five performance levels, which are valid whether a prescriptive or a performance approach is chosen. The performance level that must be ensured depending on the intended use of the buildings, thus the new national code [3] allows to select one of the following possible approaches:

- compliant solutions: i.e. prescriptive approach. No further technical evaluation is required and it is an indirect verification because each level of performance must be linked to a REI/R requirement. This means that the load-bearing capacity (R), integrity (E) and insulation (I) requirements must be guaranteed for a fixed period of time;
- alternative solutions: i.e. performance approach. In this case the performance level is assigned to the examined structure by evaluating resistance and displacement during the fire event.

About the verification criteria, the PA approach provides a verification in terms of minimum fire resistance in the time domain, classifying the structures in a discrete number of classes (R30, R60, etc.) facing the standard ISO834 fire curve. All these aspects about the fire resistance of buildings cannot be directly applied to infrastructures like bridges, as many differences have to be underlined. As also described before, in the case of buildings, the fire occurs in a compartment and the natural fire curve is influenced by the oxygen available as a function of the openings. In case of bridges, it is not possible to define a confined compartment, so the standard fire curves do not represent the real fires adequately. A better way to define the fire curve in the case of bridges is the computational fluid dynamic (CFD) analysis that allows to model the fire propagation near the bridge structure. Starting from the performance levels for the buildings, the ones related to infrastructures can be defined, taking into account the importance factor proposed by Kodur as a measure of the fire risk of any bridges. In this work, four fire performance levels are defined (Table 1). The first two can be related to low and medium fire risk grades and correspond to the satisfaction of resistance criteria. The other two can be related to high and critical risk grades and, therefore, require an improved performance that can be achieved by limiting displacements. In this way the importance factor also sets the performance level that must be achieved in bridges.

Table 1 Proposed performance levels for bridges

Performance Level (PL)	Description	IF	Fire risk grade
I	The bridge must hold for the time required for evacuation	0.8	Low
II	The bridge must withstand the duration of the fire	1.0	Medium
III	Displacements limited to L/100 for the duration of the fire	1.2	High
IV	Displacements limited to L/250 for the duration of the fire	1.5	Critical

4 ADVANCED THERMO-MECHANICAL ANALYSES

Analyses with hydrocarbon curve

To investigate the response of a typical steel-concrete fully-composite bridge exposed to fire, parametric thermo-mechanical analyses were performed using the FEM software SAFIR [4]. Their results allowed investigating several aspects of fire vulnerability of road bridges. In thermal analyses different emissivity values were considered to take into account the shadow effect offered by the lower flange to the rest of the profile. According to Kodur and Aziz suggestions [5], an emissivity value of 0.7 was chosen for the lateral and lower parts of the bottom flange, a value of 0.5 was used for the remaining part of the bottom flange and for the web, while 0.3 was chosen for the upper flange. Considering this typical steel-concrete bridge located in an urban area, according to the Kodur classification [7], it has an importance factor of 1.2 so its structural members have to guarantee a fire resistance of 60 minutes under the hydrocarbon fire curve. For this reason, it is necessary to carry out thermo-mechanical analyses for evaluating the behaviour of the bridge in fire conditions and to determine whether the bridge can guarantee one hour of fire resistance. The first step was to perform thermal analyses of the composite steel-concrete section. After the thermal analyses, the mechanical ones were carried out considering different structural systems, to evaluate the failure time of the bridge as the constraint and exposure conditions vary. In particular, four systems were considered: (1) simply supported beam constrained with a hinge and a spin, (2) simply supported beam constrained with two hinges, (3a) continuous beam with two spans exposed only on the left span and system (3b) where both the spans are exposed to fire (Fig. 2b).

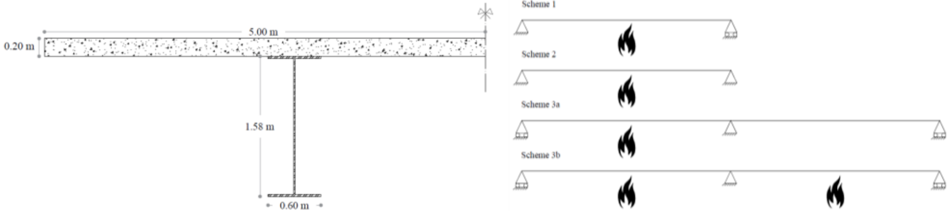

Figure 2a. Bridge structural cross-section – **2b** Static schemes for structural analysis

Each span is 27,5 m long and the applied load is equal to 62 kN/m, corresponding to the structural loads (concrete slab and steel profile) and the not structural loads (road surface) of half section, for symmetry. These conditions in scheme 1 lead to utilization factors of 0,35 (flexural) and 0,19 (shear) at the beginning of the thermal transient. The collapse time obtained in the mechanical analysis in SAFIR with scheme 1 is 414 seconds. After less than 7 minutes the bridge collapses for reaching the resistant moment in the middle of the span. In scheme 2, due to the hyperstaticity resulting from having replaced a spin with a hinge, the chain effect occurs: due to high temperatures there is a decrease in the stiffness of the structural elements and an increase in deformations. The beam progressively loses its flexural stiffness and becomes such a deformable element that it goes into an extensional regime and becomes clinging to the constraints. The chain effect in this case has a beneficial role as it avoids the flexural crisis of the beam, which after almost 16 minutes collapses for reaching the maximum traction effort inside the steel profile (Fig. 3a).

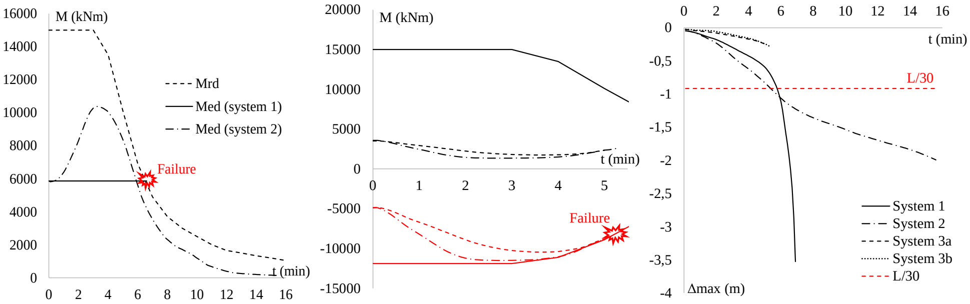

Figure 3a) Bending moments in scheme 1 and 2 under hydrocarbon fire, 3b) Bending moment in scheme 3a and 3b, 3c) Displacements in all schemes

The collapse times and the times at which the maximum displacement L/30 is reached in the four schemes are shown in the following table 2.

Table 2 Collapse times and times at which L/30 is reached

	Scheme 1	*Scheme 2*	*Scheme 3a*	*Scheme 3b*
$t_{R,SAFIR}$ (min)	6,9	15,6	5,0	5,1
$t_{L/30}$ (min)	5,8	5,4	-	-

Depending on the risk level related to the case study bridge a fire protection could be needed. For the Low or medium risk (IF=0.8 or 1.0) that is not required, otherwise for high or critical level (IF = 1.2 or 1.5) the defined criteria result to be not verified, thus a fire protection may be designed in order to allow the bridge enlarge its time collapse under standard fire condition.

Analyses with Performance Based Approach (PBA-FSE)

One of the novelties of this paper is the application of the Fire Safety Engineering (FSE) criteria to the bridges, demonstrating the satisfaction of the proposed fire performance levels, according to the fire risk classification proposed by Kodur [2]. In particular, to simulate fire scenarios more realistic for road bridges, natural fire curves have been obtained through fluid-dynamic analyses in CFAST [6] and the fire performance was assessed according to FSE. The volume below the bridge was modelled in CFAST as explained above: it is a volume 55 m long, 10 m wide and 6.5 m high, corresponding to two bridge spans of equal size. Five fluid-dynamic analyses were carried out corresponding to the fire of five different vehicles: an HGV (247.983 MJ), a truck (100.680 MJ), a school bus (41.432 MJ), a car with an internal combustion engine (ICE) (11.188 MJ) and an electric car (9.326 MJ). In all these scenarios [8] the vehicle was located in the most critical position, i.e. in the middle of the left span of the bridge. The temperatures were recorded by 10 thermocouples arranged along the longitudinal development of the beam at a height of 4.92 m, corresponding to the lower flanges of the steel profiles. The thermocouples layout and the 10 zones in which the volume below the bridge was divided are shown in Fig. 4b.

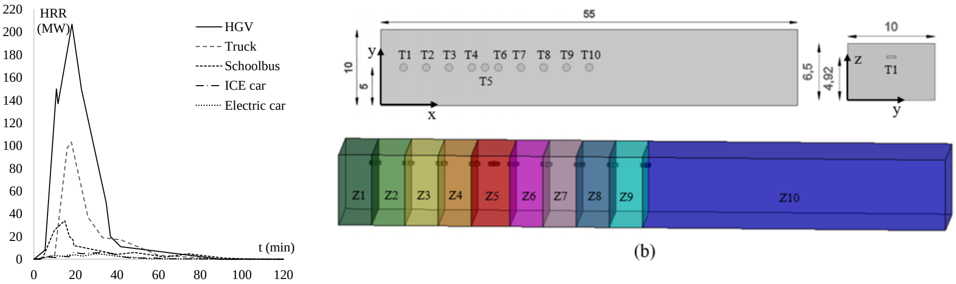

Figure 4a. HRR curves for the five vehicles – **4b** Thermocouples layout and discretization

After obtaining the natural fire curves in the fire scenarios, advanced thermo-mechanical analyses were carried out following the performance-based approach, using, as input in the thermo-mechanical analyses, the different temperatures recorded during the fluid-dynamic analyses (Fig. 4b). The first step was to perform thermal analyses of the bridge sections, varying the fire scenarios; Fig. 5a represents the maximum steel temperatures $\theta_{a,max}$ reached in the profile; these temperature evolutions vary according to the ambient temperature, indeed moving away from the fire, they rapidly decrease due to the elevated ventilation.

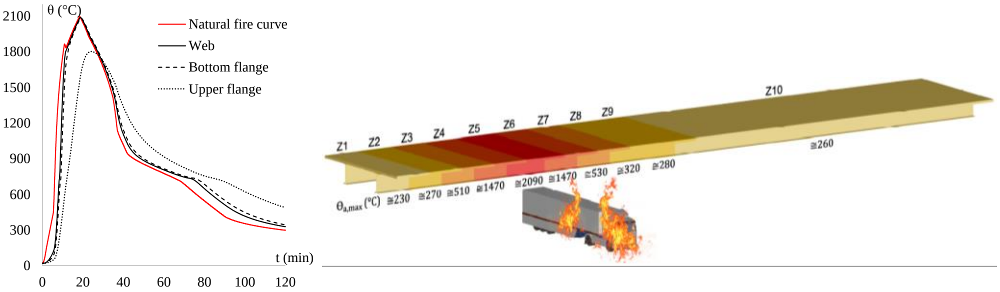

Figure 5a. Temperatures in the steel profile (Scenario 1 – zone 5) – **5b** Maximum temperature in steel profile

Table 3 summarizes the results of the five fire scenarios analysed with the performance-based approach considering the scheme 3a.

Table 3 Collapse times and times at which L/30 is reached

	HGV	*Truck*	*Schoolbus*	*ICE car*	*ELE car*
Failure	YES	YES	NO	NO	NO
Time Collapse(min)	9.2	15.2	-	-	-

Comparison between the analyses

From the comparison between the results obtained with the two approaches, it is evident that carrying out an advanced analysis following a performance-based approach allows to consider less sever and more realistic fire conditions, thanks to the use of natural fire curves, which lead to an optimization in protections design. In order to compare all the performed analyses, a benchmark between all the results is discussed in the following. The Table 4 summarised all the results of the thermo-mechanical parametric analyses with the prescriptive approach and Table 5 for the performance based one.

Table 4. Results obtained in prescriptive approach analyses

#System	Fire curve	Protection thickness (mm)	Failure time (min)	Δt_{II} (m)	$\Delta t_{II}/L$ (-)	PL
System 1	Hydrocarbon	-	$5.8<t_I$	∞	∞	-
		16	$106.7>t_{II}$	0.36	$1/86 \geq (\Delta / L)_{III}$	II
System 2	Hydrocarbon	-	$5.4<t_I$	∞	∞	-
		16	$84.6>t_{II}$	0.67	$1/41 \geq (\Delta / L)_{III}$	II
System 3a	Hydrocarbon	-	$5.0<t_I$	∞	∞	-
		16	$91.0>t_{II}$	0.16	$(\Delta / L)_{IV} \leq 1/172 \leq (\Delta / L)_{III}$	III
System 3b	Hydrocarbon	-	$5.1<t_I$	∞	∞	-
		16	$89.0>t_{II}$	0.14	$(\Delta / L)_{IV} \leq 1/196 \leq (\Delta / L)_{III}$	III

Table 5. Results obtained in performance-based approach analyses (continuous beam bridge - scheme 3a)

#Scenario	Total HRR (MJ)	Protection thickness (mm)	Δmax (m)	Δmax/L (-)	Failure	PL
Scenario 1 (HGV)	247.983	-	∞	∞	YES (9.2 min)	-
		16	0.113	$(\Delta / L)_{IV} \leq 1/243 \leq (\Delta / L)_{III}$	NO	III
Scenario 2 (Truck)	100.680	-	∞	∞	YES (15.2 min)	I
		16	0.095	$1/290 \leq (\Delta / L)_{IV}$	NO	IV
Scenario 3 (School bus)	41.432	-	0.211	$(\Delta / L)_{IV} \leq 1/130 \leq (\Delta / L)_{III}$	NO	III
Scenario 4 (ICE car)	11.188	-	0.088	$1/313 \leq (\Delta / L)_{IV}$	NO	IV
Scenario 5 (Electric car)	9.326	-	0.064	$1/430 \leq (\Delta / L)_{IV}$	NO	IV

CONCLUSIONS

This paper proposes the base of a strategy for the design and verification of bridges under fire conditions. To understand all the parameters that can influence the fire behaviour of bridges, parametric analyses of a typological steel-concrete fully-composite bridge were carried out, using the prescriptive and performance based approaches. Starting from a deep literature review, some preliminary conclusions can be drawn:

- fire can represent a severe hazard for bridges and it can lead to significant damages or failure of structural members. The effects of fire on bridges can be mitigated by designing appropriate fire resistance to structural members;
- the probability of bridge fire is lower than the building one. However, the impact of a fire on bridge structure can be more critical due to lack of adequate fire protection and fire-fighting measures;
- to date, there is no specific regulatory framework for the design and assessment of bridges in fire conditions;
- the methodology proposed by Kodur et Al. could be a valid guideline in case of prescriptive approach application, taking into account the level of vulnerability and the critical nature of the bridge to evaluate its importance factor;

- four performance level can be defined for the assessment of fire resistance of bridges, starting from the ones proposed for structures by the Eurocodes and these performance levels can be linked to the fire risk classification proposed by Kodur et Al..

To understand all the parameters that can influence the fire behaviour of bridges, and to apply the methodology proposed in the first part of the paper, parametric analyses of a typological steel-concrete fully-composite bridge were carried out, using both the prescriptive based approaches. The main conclusions are the following:

- according to the prescriptive approach and considering the hydrocarbon fire curve, the bridge failure was always achieved in about five minutes. To avoid the structural collapse, a fire protection has to be designed for the structural element, satisfying a performance level II and also a limited damage according to the performance level III;
- for satisfying the performance level IV, for which no damage has to be provided, a proper thickness fire protection has to be designed;
- thanks to the fire protection the risk of bridges can be mitigated, changing its classification according to the Kodur methodology.

From the application of the performance based approach, it emerges that:

- considering the fires of the most common light vehicles, the unprotected bridge does not fail for the entire duration of the fire with limited or no damage. In case of fires involving heavy vehicles, the application of fire protection is required, ensuring limited damage;
- the application of performance based approach allows to consider more realistic fire conditions, thanks to the use of natural fire curves, leading to an optimization of the protection system design;
- the proposed performance level for bridges allows to quantify the structural fire response of the bridges, according to its intrinsic fire risk, providing also technical criteria for its verification.

REFERENCES

[1] National Fire Protection Association (2007), NFPA 551 – Guide for the Evaluation of Fire Risk Assessments.

[2] Kodur V.K.R., Naser M.Z. 2013. *Importance Factor for Design of Bridges Against Fire*, Engineering Structures 54, 207-220 pp.

[3] Ministero dell'Interno, Dipartimento dei Vigili del fuoco, del Soccorso pubblico e della Difesa civile, Direzione centrale per la Prevenzione e la Sicurezza tecnica, 2022. *Norme tecniche di prevenzione incendi.*

[4] Franssen J.M. (2005), SAFIR – A Thermal/Structural Program Modelling Structures under Fire, Engineering Journal, A.I.S.C., Vol. 42, No. 3.

[5] Kodur V.K.R., Aziz E., Dwaikat M. (2013), Evaluating Fire Resistance of Steel Girders in Bridges, Journal of Bridge Engineering, ASCE, 18(7): 633-643.

[6] Gallo M., de Silva D., De Falco L., Nigro E., (2022), Structural fire design and assessment of bridges: State oft he Art, 14th PhD Symposium 5-7 September 2022 8pp

[7] Dwaikat M., Kodur V.K.R. 2011. *A performance based methodology for fire design of restrained steel beams*. J Construct Steel Res, 67:510–24.

[8] De Silva D. Gallo M., De Falco L., Nigro N., (2022), Fire risk assessment of bridges: from state of the art to structural vulnerability mitigation, Journal of Civil Structural Health Monitoring (under review)

KEYWORDS

Fire safety, Steel and composite bridges, Performance-based approach, Fire scenarios, Thermo-mechanical analysis