COMPORTAMENTO AL FUOCO DI UN PONTE AD ARCO IN ACCIAIO

FIRE BEHAVIOUR OF A STEEL ARCH BRIDGE

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ABSTRACT

Bridges are strategic infrastructures and must be designed to withstand operating and exceptional load conditions. However, the current structural standards of bridges does not explicitly consider fire actions. In fact, unlike most structures and infrastructures (buildings and tunnels), there is no specific regulatory obligation that requires the designer to verify a bridge according to fire resistance criteria. However, the fire risk is not negligible, as highlighted by the scientific literature. This aspect can lead to a high vulnerability to the fire of bridges and in the event of a fire, a significant impact on the functionality of the infrastructural network can therefore be expected. The present work fits into this context by analyzing the fire vulnerability of an arched steel overpass with an orthotropic slab deck. Different plausible fire scenarios, such as heavy goods truck, were considered below the bridge and were modelled according to nominal curves and natural fire curves such as computational fluid dynamics (CFD). A series of thermomechanical analyses were then developed to identify the failure modes and times of collapse, as well as the deformation behaviour that can cause the loss of functionality.

SOMMARIO

I ponti sono opere strategiche e devono essere progettati per resistere a condizioni di carico di esercizio ed eccezionali. Tuttavia, la progettazione strutturale attuale dei ponti non tiene esplicitamente in conto l'effetto di un incendio. Infatti, al contrario della maggior parte delle strutture ed infrastrutture (edifici e gallerie), non esiste uno specifico obbligo normativo che impone al progettista di verificare un ponte secondo criteri di resistenza al fuoco, benché il rischio di incendio non sia trascurabile, come si evince dalla letteratura scientifica. Di fatto questo aspetto può comportare un'alta vulnerabilità al fuoco dei ponti e in caso di un incendio ci si può attendere quindi un significativo impatto sulla funzionalità della rete infrastrutturale. Il presente lavoro si inserisce in questo contesto analizzando la vulnerabilità al fuoco di un sovrappasso ad arco in acciaio con impalcato a lastra ortotropa. Differenti plausibili scenari di incendio sono stati considerati, quali ad esempio camion che trasportano merci, al di sotto del ponte e sono stati modellati secondo modelli di incendio che si basano su curve d'incendio nominali e naturali, quest'ultime sviluppate secondo modelli di fluidodinamica numerica (CFD). Sono state quindi sviluppate una serie di analisi termomeccaniche in modo da individuare i modi e i tempi di collasso, nonché il comportamento deformativo che può causare la perdita di funzionalità dell'opera.

1 INTRODUCTION

Fire is an action that can severely damage bridge structures, which are not generally designed with fire resistance criteria. In addition, to assess the possibility of structural collapse, which can occur despite the beneficial effect of the ventilation that cools the hot gas that spread during the fire, it is often essential to check the extent of the deformations in the structure. In fact, too high deformations not only may cause the loss of functionality of the bridge, with severe repercussions for vehicular traffic, but can also cause damage to systems and underground services, both urban and extra-urban, often incorporated into the structure, with even more extensive consequences.

In 2002, average annual losses of $ 1.28 billion from fire-damaged bridges were estimated in the United States alone. In particular, the fires that are triggered on the infrastructural network are mainly caused by collision of vehicles with combustible materials and gas explosion from a leaking pipeline attached to the bridge structure [1,2]. Therefore, their intensity can be exceptionally high, also due to the fact that collisions produce the rapid ignitions of highly flammable materials. Bridges and overpasses with girders and with cables / stays made of steel and steel-concrete composite are therefore particularly vulnerable, since: i) being in most cases not designed with fire resistance criteria, the load-bearing capacity decreases rapidly due to the rapid heating of the steel structural elements and ii) are often made with statically determined schemes with low robustness in case of fire. Furthermore, the closure of a bridge can have significant repercussions on the infrastructural network that are also economic.

2 CASE STUDY

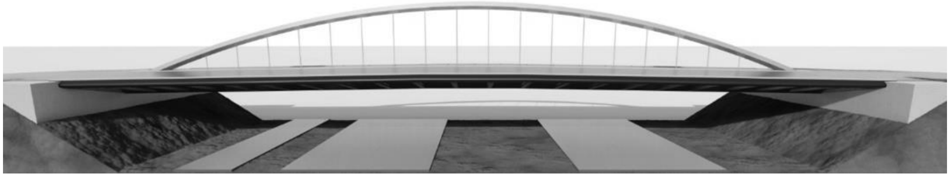


Fig. 1. General view of the bridge (3D render).

The bridge geometry, material models and other assumptions are provided in this section. The bridge analyzed in this paper is an an unprotected single span steel arch overpass, as shown in Fig. 1. The bridge is 65 m long and 14.7 m wide and it consists of an orthotropic slab deck with 2 traffic lanes. The transverse beams are placed every 3 m. Fig. 2 shows its cross section. The bridge has one arch along the span that is centered in the middle of the bridge deck. The steel bridge deck is fully fixed at the junction to the arch and provides lateral stability to the arch. Two different steel grades were used. In detail high strength steel grade (fy≥750 N/mm^2) was adopted for the hangers, while steel grade S355 (EN 10025-2, 2019) was adopted for all other elements, i.e. steel deck and arch.

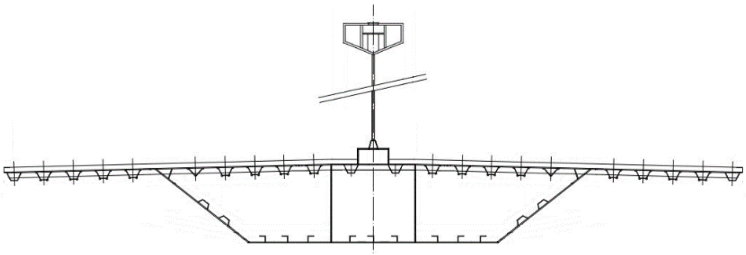


Fig. 2. Section of the bridge.

A 3D thermomechanical model of the bridge was created in the thermomechanical software SAFIR using nonlinear Euler-Bernoulli beam elements. Typically, the restraints at the end of the bridge are considered as free or fixed end conditions. However, the presence of the thermal joints induces restraint conditions that are in between the two limit cases. In this work the modelling of the gap that simulates the thermal expansion joints of the bridge was considered. In detail a gap of 0.2 m was modelled, that can allow for the thermal expansion of the bridge up to end of thermal joint and after that point can consider an inversion of axial force in the deck from tension to compressionA series of thermomechanical analyses were performed to investigate the structural fire behaviour, including the deformation behaviour that can cause the loss of functionality of the bridge.

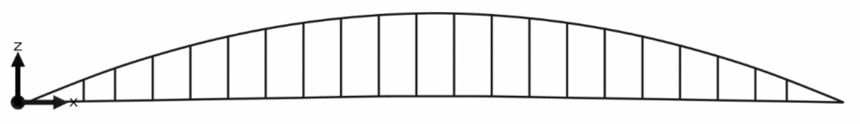


Fig. 3. Numerical model

3 FIRE ANALYSIS

Both a prescriptive and a performance-based approach were applied by employing different fire curves and by selecting different plausible fire scenarios. Indeed, the most common way to define the gas temperature is to use prescriptive code-based fire curves [2]. Therefore, preliminary analyses were performed using nominal curves such as the hydrocarbon and the ISO 834 curve, the former being more appropriate, as illustrated in Fig. 3. Another type of curve used to analyse the fire behaviour of bridges is the fire curve proposed by Stoddard [3] (see Fig. 4). This curve was conceived to estimate the air temperature following a collision between tanker trains, which actually happened on 11 December 2002.

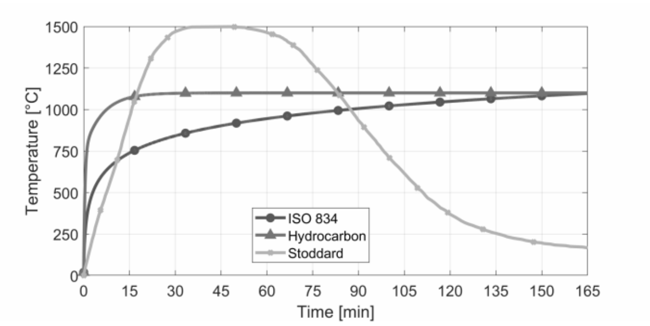


Fig. 4. prescriptive code-based fires curves and Stoddard curve

Because of the length of the bridge, a vehicle fire will naturally induce a non-uniform thermal action on the structure. Indeed, also the nominal fire curves were not only applied to the whole length of the bridge but to different portions, i.e. total length, half-length and one quarter, as illustrated in Fig. 5.

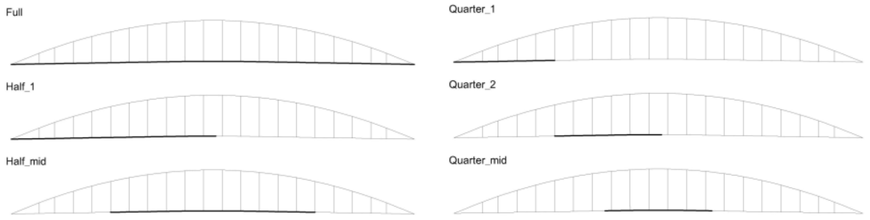


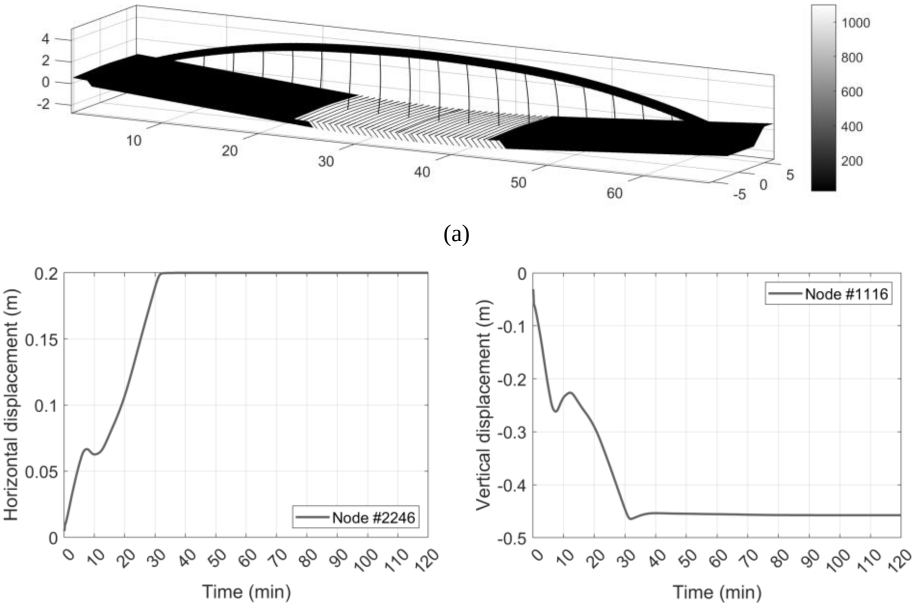
Fig. 5. Portion of the bridge under fire action.

The simulation results using the nominal fire curves were are summarized in Table 1. It is possible to observe that by applying the fire curve to the entire bridge length leads to structural failure. The Stoddard fire curve was the more severe and entailed the collapse under all heating configurations. When the bridge was half heated for both the ISO 834 and the hydrocarbon fire curve, no structural failure was observed. In terms of residual deformation, all maximum vertical displacement values exceed L/150. By assuming a limit value of L/250 as for the serviceability limit state for steel structures, the full functionality of the bridge cannot be assured.

Table 1. Results of the prescriptive code-based fires curves and Stoddard curve.

ID	Nominal curve	Fire location	[min]	Residual deflection [m]	Residual deflection over bridge’s length
#1	ISO834	Full	76	Not applicable	Collapse
#2	ISO834	Half_1	120	-0.49	L/135
#3	ISO834	Half_Mid	120	-0.45	L/145
#4	ISO834	Quarter_1	120	-0.48	L/135
#5	ISO834	Quarter_2	120	-0.46	L/140
#6	ISO834	Quarter_Mid	120	-0.46	L/140
#7	Hydrocarbon	Full	30	Not applicable	Collapse
#8	Hydrocarbon	Half_1	120	-0.47	L/140
#9	Hydrocarbon	Half_Mid	120	-0.51	L/130
#10	Hydrocarbon	Quarter_1	120	-0.48	L/135
#11	Hydrocarbon	Quarter_2	120	-0.46	L/140
#12	Hydrocarbon	Quarter_Mid	120	-0.46	L/140
#13	Stoddard	Full	33	Not applicable	Collapse
#14	Stoddard	Half_1	46	Not applicable	Collapse
#15	Stoddard	Half_Mid	43	Not applicable	Collapse
#16	Stoddard	Quarter_1	44	Not applicable	Collapse
#17	Stoddard	Quarter_2	46	Not applicable	Collapse
#18	Stoddard	Quarter_Mid	46	Not applicable	Collapse

The simulation #12 is selected to review the results in detail, as illustrated in Fig. 6.



(a)

(b) (c)

Fig. 6. Analysis #12: Results at the end of the simulation: (a) Deformed shape and steel temperature; (b) Horizontal displacement; (c) Vertical displacement at mid-span.

Fig. 6b-c illustrates the horizontal and vertical displacement responses measured respectivetly at end node and mid-span node of the bridge. It is worth pointing out that a 0.2 m expansion joint effect was included and after 38 minutes the axial expansion of the bridge reaches the gap, as shown in Fig. 6b. It is possible to notice an inversion of the horizontal and vertical displacements between 7 minutes and 13 minutes from the beginning of the fire. This is caused by the vertical variation of the stiffness center caused by the differential increase in the temperatuters in the section.

Moreover, different plausible natural fire scenarios were also considered, such as heavy goods truck, below the bridge and they were modelled according computational fluid dynamics (CFD) models using FDS (Fire Dynamics Simulator) software. A 3D model of the bridge has been created. The model domain was 65.0 m wide, 20.0 m deep and 15.0 m high to allow the fire sufficient volume for air entrainment and extension of flames. All boundaries were left open to ambient and the initial temperature was 20°C. The model included the ground slope. The geometry of the modeled bridge is shown in Fig 7.

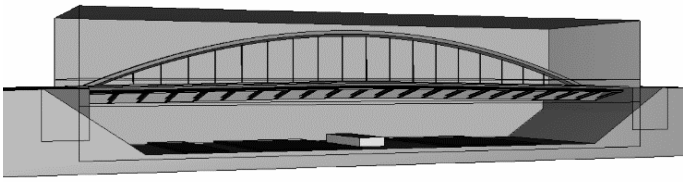


Fig. 7. FDS general view of the bridge model (Truck location A).

To represent in a real way the modelled fire in a CFD model it is possible to apply an HRR (Heat Release Rate) thermal release curve, as also described in the Ministerial Fire Prevention Decree of 3 August 2015 (DM 3AGO (2015)) (Fire Prevention Code). The HRR curve is the variation of the thermal release power in a combustion reaction, which depends on the fuel, the ventilation conditions and the geometric characteristics of the material.
One HRR curve was used for the simulations:

- Truck: the heavy goods vehicle loaded with wood and plastic pallets (Fig. 8) [4].

The fires were placed in four different locations underneath the bridge:

- Location A: the fire was centered at mid-span, both longitudinally and transversely (Fig. 8).
- Location B: The fire location was offset longitudinally from the center of the bridge near the end of the bridge.

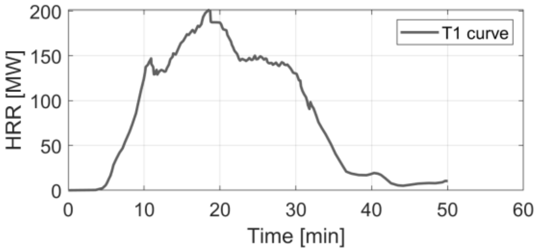


Fig. 8. HRR of the heavy goods vehicle loaded with wood and plastic pallets [4].

Fig. 9 illustrates the development of fire and smoke associate after 23 minutes after the beginning of one fire scenario as an example.

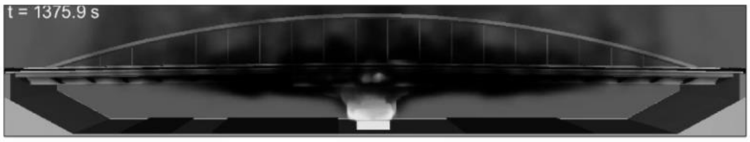


Fig. 9. FDS results general view of the bridge after 23 min (Truck location A)

To measure the temperature evolution of the gas, a total of 2022 adiabatic surface temparature gas-phase devices were placed across the bridge deck, arch and hangers. The output values from these devices were used for performing thermal-structural analysis of the sections in SAFIR.

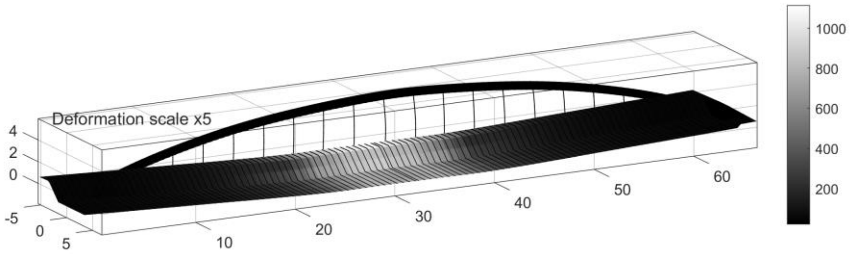
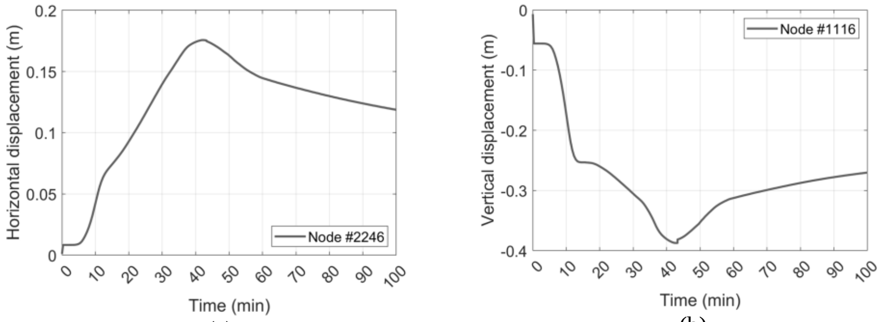


Fig. 10. Deformed shape and steel temperature of the deck after 25 min

As an example, Fig. 10 shows the deformed configuration and steel temperature of the deck 23 minutes after the beginning of the fire scenario modelled in FDS that involved the heavy goods vehicle loaded with wood and plastic pallets. Fig. 11 illustrates the horizontal and the deflection time history of the bridge under the FDS fire load. No structural failure was observed with residual vertical displacement between 20 cm (L/310) and 30 cm (L/240) depending on the fire scenario. In this case, given the fact that a smaller part of the bridge is affected by the fire, it is not trivial to state that a residual displacement less than L/250 can lead to full functionality because the deformation can be highly localised with steep gradients of vertical displacement near the maximum value. This should be investigated more in depth.



(a) (b)

Fig. 11. Displacements time history of the bridge: (a) Horizontal; (b) Deflection.

Table 2. Results of the FDS analysis.

ID	**Nominal curve**	**Fire location**	**[min]**	**Residual deflection [m]**	**Residual deflection over bridge's length**
#1	Truck	Location A	100	-0.27	L/240
#2	Truck	Location B	100	-0.21	L/310

CONCLUSIONS

The paper presented numerical fire analysis and thermal-structural analysis to investigate a steel arch bridge under fire using CFD and SAFIR software.

The results showed that nominal curves are generally conservative and predict much shorter failure times. CFD analyses provided more realistic representations of the bridge fire scenario and in the analysed cases the collapse was not even attained. However, in all cases in which failure was not reached the final deformation state was to such an extent that the bridge was not be fully functional after fire for nominal fire curves by assuming a vertical limit of L/250. For the CFD analyses, smaller residual deformations were observed, but more localised. The modeling of the expansion joint (GAP) in the numerical model allowed to obtain a more realistic constraint condition compared to the boundary conditions frequently used in other studies such as hinge-hinge or hinge-roller constraints.

ACKNOWLEDGMENTS

The support received from the Italian Ministry of Education, University and Research (MIUR) in the framework of the 'Departments of Excellence' (grant L 232/2016) is gratefully acknowledged.

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KEYWORDS

Arch bridge, fire, CFD, orthotropic deck.