Study of the parameters that influence the behaviour of I-girder bridges during fire events

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Abstract. The structural response of bridges against fire is an under researched topic not covered in current design codes in spite of its frequency and consequences. This paper uses Computational Fluid Dynamics simulations to study the parameters influencing the temperatures in the gas surrounding I girder bridges during a fire, since this is a critical parameter governing the response of the bridge. The structural behaviour of a 21 meters span bridge has been carried out with numerical models to show that the position of the fire has also an influence on the times and type of failure.

1. INTRODUCTION

The structural response of bridges against fire is an under researched topic not covered in current design codes in spite of its frequency and consequences as it is shown in Peris-Sayol et al [8]. In this paper, 154 bridge fires that happened between 1997 and 2015 were studied, and the bridge damage level and the main factors involved in bridge fire damage were characterized. This analysis showed that the scenarios likely to cause damage to concrete and steel bridges are a tanker fires close to the structure and a high calorific storage fire under the bridge, being overpasses the most susceptible infrastructure.

The temperature of the gas surrounding a specific bridge deck is a critical parameter governing the response of the bridge to a fire due to its influence on the mechanical properties of the bridge construction materials. High temperatures can cause the collapse of the bridge due to loss of resistance of the materials as it happened in the MacArthur Maze in Oakland in 2007 or in a bridge near Hazel Park in Detroit in 2009. In both cases a tanker truck carrying gasoline crashed under the bridge and caught fire, provoking temperatures higher than 900°C and decreasing the mechanical resistance of the bridge in a relatively short time. Both bridges collapsed around 20 minutes after the tanker caught fire.

This paper uses Computational Fluid Dynamics simulation to study the parameters influencing the temperatures of the gas surrounding I girder bridges during a fire. More specifically, the study considers four geometric parameters

Vertical Clearance (m)	Bridge Substructure Configuration	Span (m)	Heat Release Rate (kW/m^2)	Position	Width (m)
6	Piers	16	1800	Center-Span	13
9	Abutments	24	2400	Abutment	23.4

Table 1. Parameters Studied

Figure 1. Parameters studied in the analysis. 3D view of two CFD models.

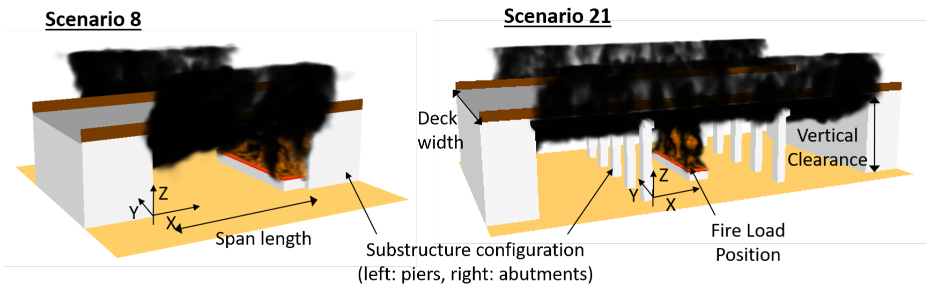
(vertical clearance, bridge substructure configuration, span length and bridge width) and two fire scenario parameters (position of the fire load and type of fuel). This study complements previous work [8] since the parameters analyzed by CFD were impossible to characterize in real cases. Also, in this paper, the structural behavior of a 21 meters span simply supported steel-girder bridge against tanker with finite element models has been studied to see if the position of the fire influence on the times and type of failure.

2. CFD ANALYSIS

This section explains the parameters analyzed, the methodology used and the CFD model building.

2.1. Parameters Studied

This study considers six parameters: four of them describe the geometry of the bridge (vertical clearance, bridge substructure configuration, span length and bridge width) and two of them (position of the fire load and type of fuel) are related to the fire scenario. Other parameters such as the soot yield or the position of bridge transverse diaphragms have not been included in this study. Table 1 and Figure 1 describe the parameters considered and the value for each parameter. It must be noted that, for all the bridges studied in this paper, the distance between two adjacent girders was taken as 2.6 m and the girder depth as 0.8 m. All the bridges also had a concrete slab 0.2 m thick on top of the I-girders.



2.2. Computational Fluid Dynamics Models (CFDs)

FDS Software 6.1.1 [4] has been used to obtain the temperatures in the gas surrounding the bridge deck. FDS was developed at the National Institute of Standards and Technology (NIST) and applies computational fluid dynamics (CFD) techniques to fire engineering. FDS has been successfully used to study real bridge fires [1, 2, 12]. Building the FDS model requires defining: (1) a control volume with its boundary conditions representing the volume in which the entire analysis is carried out, (2) a geometry included in the control volume which represents the geometry of the case study, (3) a mesh or discretization of the control volume, (4) material properties, (5) fire sources, (6) a combustion model, and (7) sensors or elements of the model where the outputs are recorded.

2.2.1. Control Volume and Mesh The control volume used in this study includes the bridge as well as part of its approaches. The model varies according to the scenario from 28 to 58 meters in the x-direction, 27 to 30 meters in the y-direction and 12 to 15 meters in the z-direction. The variations depend on the span length, vertical clearance, span width and abutment configuration considered. The total amount of cells in the model ranges from 1,134,000 to 3,262,500, having all cells dimensions of 0.20 m according to FDS Technical Reference [5] for coarse mesh. This mesh is fine enough for the purpose of the present study.

2.2.2. Fire Load and Combustion Model The FDS model includes the tanker of the tanker truck modeled as a horizontal surface of 12 x 2.5 meters at one meter above the road level. The CO and soot yields have been chosen according to the values showed in the table A.39 of the SFPE Handbook Manual [3] for hydrocarbon liquids and have values of 0.019 and 0.059 respectively. It has been assumed that diesel and gasoline have the same yields.

2.2.3. Adiabatic Temperatures The adiabatic surface temperature developed by Wickström et Al. [11] has been used to transfer the information obtained by the fire model to the thermal model. This adiabatic surface temperature is a fictitious temperature obtained by FDS assuming that the structural element is a perfect insulator and is commonly used for calculating both convective and radiative heat transfer. The use in this paper of adiabatic temperatures is justified because it is a value that does not depend on the material of the bridge and can be used as an input in the thermo-mechanical models.

Adiabatic temperatures are measured in FDS by sensors. Sensors have been placed in cross sections along the bridge spaced 20 cm with three sensors each located in: bottom flange (sensor 0), the south face (sensor 1), and the north face (sensor 2). The total number of sensor varies according to the span length. Only the temperatures of the most heated girder are analyzed here.

2.3. Design of Experiments

A combination of all six parameters with two levels each would have required 64 simulations. Running so many simulations was undesirable due to the high computational cost. A Taguchi's method [10] has been carried out to reduce the simulations to 32, where fire scenarios are modeled to extract the maximum information and to know which interactions are important. The resulting scenarios that had to be run are shown in table 2.

2.4. Results and Discussion

Table 3 shows the maximum web and flange adiabatic temperatures reached on the structure. Web temperatures are the average of the temperatures in the two web faces.

To assess the significance of the parameters on the maximum adiabatic temperatures reached over the structure, an analysis of variance (ANOVA) using the STATGRAPHICS software [9] was carried out. An ANOVA statistical test compares the means of three groups in response to one or several variables and is used to determine the impact of independent variables (e.g the parameters studied) on the dependent variables (temperatures reached by the structure) in a regression analysis. This impact is given by a coefficient known as the p-value. Low p-values indicate a significant influence (Values below of 0.05) Table 4 and 5 show the ANOVA results.

The main conclusions of this analysis are:

1. Bridge span and bridge width do not have a significant influence on the maximum adiabatic temperatures reached on the bridge (p-values of 0.10 and 0.52 for the bottom flange temperatures and 0.35 and 0.77 for web temperatures respectively), although they do have a significant influence on the distribution of temperatures along the longitudinal axis of the bridge.
2. The bottom flange adiabatic temperatures are influenced mainly by the vertical clearance, the fuel type and the position of the fire load (p-values below 0.05 and close to 0). Web temperatures are influenced by the parameters mentioned before, but also by the bridge substructure configuration (p-value of 0.0074) due to the effect that the presence/absence of abutments has on the accumulation of smoke between two consecutive girders.
3. A tanker fire with the tanker close to the abutments is the fire load position that provokes the maximum adiabatic temperatures (values between 1100 and 1300 °C). This is due to the Coandă effect that makes the fire flames adhere to the walls of the abutments. This effect can make the fire cause problems even in bridges with high vertical clearance.
4. The location of the maximum adiabatic temperatures depends on the bridge substructure configuration and the position of the fire. If the fire happens under an intermediate span, then the maximum temperatures are usually in the bottom flange, because there is less accumulation of smoke within the girders. If the fire is close to the abutments, then the smoke accumulates within the girders and the maximum temperatures are located in the web.

Nº Case	**Clearance (m)**	**Substructure**	**Span (m)**	**HRR (kW/m^2)**	**Position**	**Width (m)**
1	9	Piers	24	2400	Abutment	23.4
2	6	Piers	24	2400	Abutment	13
3	9	Abutments	24	2400	Abutment	13
4	6	Abutments	24	2400	Abutment	23.4
5	9	Piers	16	2400	Abutment	13
6	6	Piers	16	2400	Abutment	23.4
7	9	Abutments	16	2400	Abutment	23.4
8	6	Abutments	16	2400	Abutment	13
9	9	Piers	24	1600	Abutment	13
10	6	Piers	24	1600	Abutment	23.4
11	9	Abutments	24	1600	Abutment	23.4
12	6	Abutments	24	1600	Abutment	13
13	9	Piers	16	1600	Abutment	23.4
14	6	Piers	16	1600	Abutment	13
15	9	Abutments	16	1600	Abutment	13
16	6	Abutments	16	1600	Abutment	23.4
17	9	Piers	24	2400	Center	13
18	6	Piers	24	2400	Center	23.4
19	9	Abutments	24	2400	Center	23.4
20	6	Abutments	24	2400	Center	13
21	9	Piers	16	2400	Center	23.4
22	6	Piers	16	2400	Center	13
23	9	Abutments	16	2400	Center	13
24	6	Abutments	16	2400	Center	23.4
25	9	Piers	24	1600	Center	23.4
26	6	Piers	24	1600	Center	13
27	9	Abutments	24	1600	Center	13
28	6	Abutments	24	1600	Center	23.4
29	9	Piers	16	1600	Center	13
30	6	Piers	16	1600	Center	23.4
31	9	Abutments	16	1600	Center	23.4
32	6	Abutments	16	1600	Center	13

Table 2. Experimental Design of the Simulations

Maximum Temperatures			**Maximum Temperatures**			**Maximum Temperatures**		
Case	**Flange**	**Web**	**Case**	**Flange**	**Web**	**Case**	**Flange**	**Web**
1	1126	1014	12	1114	1160	23	909	886
2	1323	1294	13	990	820	24	1073	1166
3	1301	1340	14	1253	1157	25	694	629
4	1248	1312	15	1178	1215	26	1043	1038
5	1170	1064	16	1225	1290	27	711	650
6	1288	1278	17	905	877	28	1022	1028
7	1170	1226	18	1162	1208	29	702	646
8	1081	1133	19	902	871	30	1037	1044
9	990	821	20	1158	1208	31	696	641
10	1246	1173	21	704	646	32	973	1000
11	1188	1216	22	1157	1204			

Table 3. Maximum adiabatic temperatures reached over the structure.

Flange Temperatures	**Sum of Squares**	**d.f.**	**Mean Square**	**F-ratio**	**p-value**
Principal Effects					
A: Vertical Clearance	294352	1	294352	107.8	**0.000**
B:Bridge Substructure	782	1	782	0.3	0.604
C: Span Length	8739	1	8739	3.2	0.104
D: Heat Release Rate	81467	1	81467	29.8	**0.000**
E:Position of the Fire Load	511435	1	511435	187.3	**0.000**
F:Bridge Width	1214	1	1214	0.4	0.520
Interactions					
AB:Clearance-Bridge Sub.	60498	1	60498	22.2	**0.001**
AC:	145	1	145	0.1	0.822
AD:	6628	1	6628	2.4	0.150
AE:Clearance-Position	93894	1	93894	34.4	**0.000**
AF:	11044	1	11044	4.0	0.072
BC:	724	1	724	0.3	0.618
BD:	655	1	655	0.2	0.635
BE:	194	1	194	0.1	0.795
BF:	4866	1	4866	1.8	0.212
CD:	11940	1	11940	4.4	0.063
CE:	857	1	857	0.3	0.588
CF:	2484	1	2484	0.9	0.363
DE:	10029	1	10029	3.7	0.084
DF:	6705	1	6705	2.5	0.148
EF:	3588	1	3588	1.3	0.278
Residuals	27313	10	2731		
Total	1.14E+06	31			

Table 4. Results of the Anova analysis for flange temperatures

Web Temperatures	**Sum of Squares**	**d.f.**	**Mean Square**	**F-ratio**	**p-value**
Principal Effects					
A: Vertical Clearance	533413	1	533413	93.8	**0.000**
B:Bridge Substructure	63858	1	63858	11.2	**0.007**
C: Span Length	5517	1	5517	1.0	0.348
D: Heat Release Rate	151161	1	151161	26.6	**0.000**
E:Position of the Fire Load	444768	1	444768	78.2	**0.000**
F:Bridge Width	532	1	532	0.1	0.766
Interactions					
AB:Clearance-Bridge Sub.	83045	1	83045	14.6	**0.003**
AC:	510	1	510	0.1	0.771
AD:	4305	1	4305	0.8	0.404
AE:Clearance-Position	121255	1	121255	21.3	**0.001**
AF:	17145	1	17145	3.0	0.113
BC:	33	1	33	0.0	0.940
BD:	3086	1	3086	0.5	0.478
BE:Bridge Sub.-Position	38680	1	38680	6.8	**0.026**
BF:	6239	1	6239	1.1	0.320
CD:	12050	1	12050	2.1	0.176
CE:	523	1	523	0.1	0.768
CF:	2076	1	2076	0.4	0.559
DE:	10553	1	10553	1.9	0.203
DF:	6037	1	6037	1.1	0.327
EF:	5513	1	5513	1.0	0.348
Residuals	56867	10	5687		
Total	1.57E+06	31			

Table 5. Results of the Anova analysis for web temperatures

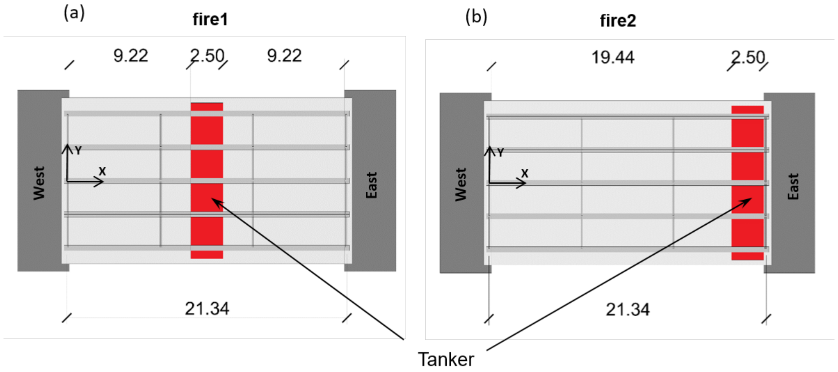


Figure 2. Fire scenarios considered

3. FEM ANALYSIS

In this section a FEM Analysis of a 21.34 m span and 5 m vertical clearance steel-girder bridge has been carried out. The bridge deck has five W36x300 hot rolled steel girders that support a reinforced concrete slab 0.2 meters deep not connected to the girders and, therefore, there is no composite action. The thermo-mechanical response of the bridge is obtained with the finite element software Abaqus. The Abaqus analysis consists of 2 steps. In the first step the thermal analysis is carried out by using the adiabatic surface temperature given in the previous analysis as input and the heat transfer method provides the transient nodal temperatures against time using the thermal properties of the material. In the second step (the structural analysis), the nodal temperatures are read from the thermal analysis and corresponding temperature-dependent material properties are used to find the equilibrium of the structure at each time step. More information about the model building can be found in [6, 7].

Two different fire scenarios with the tanker truck centered under the central girder of the bridge have been considered (See Fig. 2). The first scenario with the tanker located under the bridge mid-span (scenario “fire1”) and the second with the tanker close to the east abutment (scenario “fire2”).

The purpose of carrying out two different fire scenarios is to see if the bridge have different structural behaviour when the position of the fire changes, even if the maximum adiabatic temperatures reached over the structure are in the same range (1200°C - 1300°C) as it is shown in Fig. 3, where the adiabatic temperatures along the most exposed bridge girder (Girder 3) at the steady state of the fire event are shown. Web temperatures are always higher than bottom flange temperatures due to the accumulation of smoke in the space between girders. The existence of sudden temperature steps circa 150°C for *fire1* and 80°C for *fire2* are explained due to the existence of a confinement caused by the diaphragms.

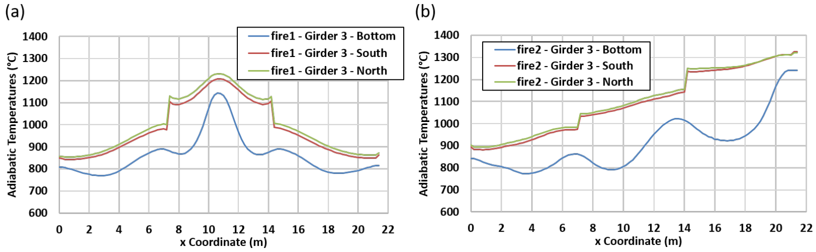


Figure 3. Adiabatic temperatures in Girder 3 for both fire scenarios

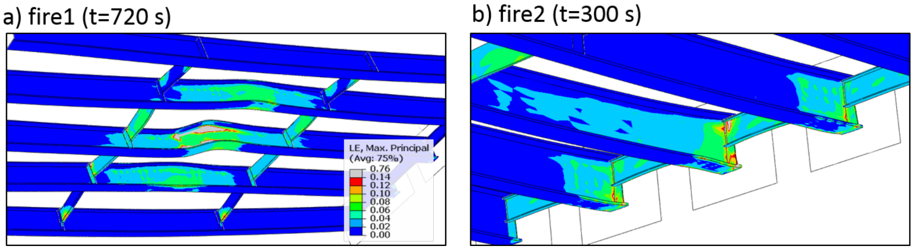


Figure 4. Comparation of yielding areas and deformations. a) fire under the bridge mid-span. b) fire close to the abutments.

Figure 4 compares yielding extension and deformed shapes for both fire scenarios at collapse time.

As it is shown above, the failure of the structure is different depending on the position of the fire. When the fire is located under the mid-span, the failure occurs after 12 minutes because a high web yielding appears at mid-span in the central girders. If the fire source is located close to the abutments the structural integrity of the bridge would be affected, collapsing around 4 minutes, 8 minutes earlier than the *fire1* scenario. This is caused by a high web-yielding that appears on the contact with the abutment, creating high stresses into the girder in the area affected by the fire. This effect did not appear at *fire1* scenario.

4. CONCLUSIONS

This paper studies the factors that influence the maximum temperatures of the gas surrounding I-girder bridges and also applies a methodology to obtain the structural response of a 21.34 meters span steel-girder bridge subjected to two different fire scenarios.

Results show that vertical clearance, type of fuel and position of the fire load are the most influential parameters for the flange temperatures. Web temperatures are also influenced by the bridge substructure configuration. This type of analysis is very relevant as it constitutes the basis for the development of parametric temperature curves specific for bridges.

Also, it has been shown that the position of the fire load has an influence on the type and time of failure even if the maximum adiabatic temperatures are on the same range. This conclusion should be taken into account when performing a conventional analysis of the structural behaviour of bridges against fire.

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