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Analysis of a bridge failure due to fire using computational fluid dynamics and finite element models

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ABSTRACT

Bridge fires are a major concern because of the consequences that these kind of events have and because they are a real threat. However, bridge fire response is under researched and not covered in the codes. This paper studies the capabilities of numerical models to predict the fire response of a bridge and provides modeling guidelines useful for improving bridge design. To reach this goal, a numerical analysis of the fire of the I-65 overpass in Birmingham, Alabama, USA in 2002 is carried out. The analyses are based on computational fluid dynamics (CFD) for creating the fire model, and finite element (FE) software for obtaining the thermo-mechanical response of the bridge. The models are validated with parametric studies that consider heat release rate of the spilled fuel, discretization of the fire temperature in the transition from CFD to FE modeling, and boundary conditions. The validated model is used in a study to evaluate the influence of fire scenario (CFD versus standard fires), and live load. Results show that numerical models are able to simulate the response of the bridge and can be used as a basis for a performance-based approach for the design of bridges under fire. Additionally, it is found that applying the Eurocode standard and hydrocarbon fires along the full length of the bridge does not adequately represent a real bridge fire response for medium-long span bridges such as this case study. The study also shows that live loads essentially do not influence the response of the bridge.

1. Introduction

Bridges are a critical component of the transportation system whose loss can result in important social and economical consequences (e.g. Chang and Nojima [1], Zhu et al. [2]). Therefore, a lot of effort has been paid to understand and predict the effects on bridges of accidental extreme load events such as earthquakes, winds, scour, and ship collisions (e.g. Ghosn et al. [3], Cheng [4]). Fire is an additional major hazard in bridges for two reasons. First, traffic on bridges damaged by fire is usually hard to detour and affects the traffic quality in the region. For example, the collapse of two spans of the MacArthur Maze in Oakland, USA on April 29th 2007 due to a fire resulted in repairs and rebuilding operations costing more than US $9 million [5,6]. Another example is provided by a bridge fire caused by a dump truck in Robbinsville (NJ, USA) on October 3rd 2012. This fire forced to close the Interstate 95 Highway as well as 79 km of the New Jersey Turnpike, one of the major highways in the US East Coast, and affected the traffic in areas located hundreds of kilometers away of the accident in the states of Delaware and Connecticut. The accident also caused serious traffic disruptions for 6 weeks following the event [7]. Secondly, bridge fires are a real threat as shown by data of a voluntary bridge failure survey, which was responded by the departments of transportation of 18 US states [8]. This survey was conducted in 2011 and collected data related to 1746 bridge failures and showed that fire had caused more bridge collapses than earthquakes (seismic states like California participated in the survey).

Despite its importance, bridge fires have got very little attention in the past as proved by Garlock et al. [9]. In fact, fire safety engineering and structural fire engineering have mainly been concerned with building and tunnel fires (e.g. Buchanan [10], Couto et al. [11], Quiel et al. [12], Gunalan and Mahendran [13], López-Colina et al. [14], Moliner et al. [15] and Seif and McAllister [16]), but bridge fires are different to those and deserve a particular approach. This is due to several reasons such as the cause of fire,

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the fire loads, the fire ventilation conditions, the use of fire protection, and the type of connections among structural members used (see Payá-Zaforteza and Garlock [17] for more details).

Within this general context, and using a case study, this paper (a) delves into the fire response of steel girder composite bridges as this type of bridge is widely used [18] and is especially vulnerable to fire events [9], and (b) illustrates modeling techniques that can be used to predict the fire response of steel bridges. To reach this goal, the authors have performed a numerical investigation of the behavior of the I-65 overpass in Birmingham (AL, USA) during the fire event on January 5th 2002. The event resulted in the demolition of the overpass and the rebuilding of a new structure and affected highways carrying 240,000 vehicles per day. The numerical investigation is based on data provided by the Alabama Department of Transportation (ALDOT) and comprises a fire model of the event using computational fluid dynamics (CFD) techniques with the software FDS [19], and a thermo-mechanical model of the response of the bridge using Abaqus [20]. Numerical results were validated by comparison with the information provided by ALDOT which (a) enables a better understanding of the advantages and the limitations of numerical models to explain the fire response of bridges and (b) paves the way for the use of these models to study the improvement of the fire response of bridges in high fire risk situation. This kind of knowledge is of major importance for two reasons. First, previous research (see e.g. Payá-Zaforteza and Garlock [17], Aziz and Kodur [21]) is scarce and based more on standard fires or predefined fire events, than on the analysis of real cases and therefore has limitations. And second, it is difficult to conduct full scale experimental studies on bridges because of the dimensions of their structural members and the fire loads required.

2. Case study

The I-65 overpass is a three spans bridge located in Birmingham (Alabama, USA) which enables the Interstate I-65 North highway to cross over the I-65 Interstate South highway. The original design of the bridge had a total length of 88.53 m. distributed in a central span of 37.32 m. and two lateral spans of 25.91 and 25.30 m (see Fig. 1). Each span was a simply supported deck with a composite cross section defined by a reinforced concrete slab structurally connected with shear studs to built-up I-sections made of A36 steel.

Fig. 1c shows the cross section of the central span which was the span that experienced the most damage during the fire. It had seven built up I-girders with a variable depth between 1.442 m (mid-span section) and 1.432 m (supports section). The girders supported a reinforced concrete slab 15.40 m. wide having an average depth of 0.16 m. Fig. 2 provides the geometric definition of Girder 1 which experienced the largest deflections during the fire event. Girder 1 had a total of 34 stiffeners. Four of them were located on the girder supports and had a thickness of 25.4 mm (1 in.) and the rest were located on the side of Girder 1 facing Girder 2 and had a thickness of 11 mm. Cross braces were placed every 6.2 m. and at the supports to provide lateral stability to the bridge deck. There were two expansion joints between the central span and the lateral spans each one having a width of 38 mm.

At about 10:15 am on January 5th, 2002 a tanker truck traveling North on the I-65 carrying 37.5 m^3 of gasoline, swerved and crashed into the piers supporting the North East end of the central span. The columns survived the impact because they were protected by a 0.50 m height wall but when the truck and the spilled fuel caught fire under the overpass, the composite bridge suffered serious damage after some minutes (see Fig. 3). When the fire department quelled the fire, the girder of the central span named Girder 7 in Fig. 1c had small deflections (see Fig. 3b) but Girder 1 was very damaged and had deflections of almost 2.5 m in a section located around 15 m. from its North end (Fig. 3a) [22]. The bridge deck could not be rehabilitated and was demolished and replaced by a new precast prestressed concrete deck. The new structure was opened to traffic 54 days after the accident. The cost resulting from closure of the overpass was estimated at 100,000 US $ per day (5,400,000 US $ in total) and the cost of the new bridge was 3,396,421 US $ [22,23]. Therefore, the final cost of the accident can be estimated to be around 8.8 US $ millions.

In the next few sections a numerical analysis of the Alabama case study is carried out in three steps. First, a model of the fire event is built with the computational fluid dynamics software FDS [19]. Then, temperatures in the most fire-exposed girder of the overpass are obtained through a thermal analysis with the software Abaqus [20]. Finally, the structural response of the most exposed girder is obtained using Abaqus [20] and considering non-linearities (geometrical and mechanical) as well as temperature dependent material properties.

3. Computational fluid dynamics (CFD) model

A fire model of the event was developed with the software Fire Dynamics Simulator (FDS) [19]. FDS is a software designed to predict the values of fire engineering related variables such as temperatures, heat fluxes or gas pressures in fire events. It is based on CFDs techniques and contains large eddy simulation (LES) turbulence models. The software has been developed at the National Institute of Standards and Technology (NIST) of the USA and has been extensively validated experimentally [24].

Building a FDS model requires defining: (1) a control volume with its boundary conditions which represents the volume where all the analysis will be carried out, (2) a geometry included in the control volume which is submitted to fire load, (3) a mesh or a discretization of the control volume, (4) material properties (conductivity, density, specific heat and emissivity), (5) fire sources, (6) a combustion model, and (7) sensors or elements of the model where outputs of the analysis (e.g. temperatures) are recorded. All the FDS models were run as a MPI parallel job on a cluster made of HP Proliant DL 580 servers (4 six-core AMD Opteron Model 8439 SE), under a Torque resource manager and scheduler. The resources assigned were 16 cores and 8 GB RAM per core. A typical simulation took 3 days and 4 h.

3.1. Control volume

The control volume must be wide enough to adequately represent the volume affected by the fire but small enough to enable the model to be run in a reasonable computing time. Fig. 4 shows the control volume used in this research as well as its boundary conditions. It contains the I-65 overpass as well as its approaches and surroundings, and has plan dimensions of 115.2 m per 39.6 m and a height of 16.2 m. The volume has a total of 6,998,400 parallelepiped cells, having all the cells dimensions of 0.24 m per 0.22 m per 0.20 m. The overpass geometry was obtained from the original construction drawings of the bridge provided by ALDOT and was simplified as detailed in [25].

The size of the control volume and the size of the FDS mesh were obtained through a three step sensitivity study. First, the FDS mesh was fixed and the size of the control volume was obtained (step 1). Second, the size of the control volume was fixed and the FDS mesh was refined (step 2). Third, it was necessary to check that the control volume did not have to be modified due to changes in the FDS mesh between step 1 and step 2 (step 3). These steps are described next.