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Analysis of the influence of geometric, modeling and environmental parameters on the fire response of steel bridges subjected to realistic fire scenarios

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This paper studies bridge fires by using numerical models to analyze the response of a typical girder bridge to tanker truck fires. It explains the influence of fire position, bridge configuration (vertical clearance, number of spans) and wind speed on the bridge response. Results show that the most damage is caused by tanker fires close to the abutments in single span bridges with minimum vertical clearance and under windless conditions. The paper provides new insights into modeling techniques and proves that bridge response can be predicted by FE models of the most exposed girder, which saves significant modeling and analysis times.

1. Introduction

The loss of a critical component, such as a bridge, from a transportation system can have serious social and economic consequences (e.g. Chang and Nojima [1], Zhu et al. [2]). Bridge engineering should therefore pay a lot of attention to designing for accidental load events, such as earthquakes, winds or ship collisions (see e.g. Ghosn et al. [3] and Cheng [4]). Recent studies also show that bridge fires are another major hazard. Mostafaei and McCartney [5], Wright et al. [6] pointed out that more than 500 fatal crashes happened on bridges in the last fourteen years across the US and Canada. These events had large direct costs (related to repairs and reconstruction work) and indirect costs (traffic delays from bridge closures and rebuilding). For example, the collapse of two spans of the MacArthur Maze in Oakland, USA on April 29th 2007 due to a fire gave rise to repairs and rebuilding operations costing more than US $9 million [7]. In addition, the closure of the Maze was estimated to have a total economic impact of US $6 million a day on the San Francisco Bay Area [8]. Another example is provided by the bridge fire caused by a tanker truck that crashed on the Interstate 81 Highway near Harrisburg (PA, USA) on May 9th 2013. This fire forced the closure of one highway exit and resulted in region-wide traffic disruptions. Repair work took seven months at a direct cost of more than $13 m [9].

Recent reviews of the literature (Garlock et al. [10], Mostafaei et al. [11]) show that, despite their importance, bridge fires have received very little attention from research groups. In fact, fire safety engineering and structural fire engineering have mainly been concerned with building and tunnel fires (see e.g. Jiang and Usmani [12], Couto et al. [13], Quiel et al. [14], Moura Correia et al. [15], Moliner et al. [16], Xi et al. [17], Elhami et al. [18], Wang et al. [19], Maraveas and Brakas [20]). However, bridge fires have special characteristics and deserve a particular approach. This can be due to several reasons, such as the cause of the fire, fire loads, fire ventilation conditions, the use of fire protection measures, and the type of connections between structural members (see Payá-Zaforteza and Garlock [21] for further information).

Within this general context, this paper carries out a comprehensive parametric study of the fire response of a typical steel girder bridge subjected to real fire scenarios. The analyses use numerical models to study the influence of the position of the fire, the geometry of the bridge (type of bridge substructure and vertical clearance), and the magnitude of the wind loads in the bridge's response to the fire. The study also addresses important numerical issues, such as the modeling of the bridge deck bearings and the bridge deck elements that should be included in the models. A method based on Computational Fluid Dynamics (CFD) was used for the fire models and finite elements were used to obtain the bridge's thermo-mechanical response. This method was validated

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by Alós-Moya et al. [22] with data collected from an actual case of bridge failure. We consider the analyses presented here to be of great importance since: (a) steel girder bridges are widely used [23] and are especially vulnerable to fire events [10], (b) research on bridge fires is scarce and is based more on the use of standard fires or predefined fire events than on the analysis of realistic fire scenarios, and (c) the paper proposes new modeling techniques and enables a qualitative and quantitative understanding of the factors that influence the fire response of a bridge. This study complements previous works (see e.g. Wright et al. [6], Payá-Zaforteza and Garlock [21], Aziz et al. [24], Quiel et al. [25], Gong and Agrawal [26]) and paves the way for easier identification of critical bridges with respect to fire risks, as well as for the wider application of numerical models to improve bridge fire response and bridge resilience.

2. Case study and parameters analyzed

The prototype bridge used in the present study is a simply supported bridge designed by the Federal Highway Administration (FHWA) of the United States of America. The bridge spans 12.2 m and its vertical clearance is 5 m. Its cross section and plan view are shown in Fig. 1. The bridge consists of five hot rolled type W33x141 steel girders. The beams support a 0.2 m thick reinforced concrete slab but the slab is not connected to the girders and, therefore, there is no composite action. This was a common design decision for bridges with span lengths smaller than 15 m at the time when the bridge was designed (Xanthakos [27]). Transverse diaphragms are placed at mid span and at the supports to laterally stiffen the bridge deck. The bridge has two expansion joints at its extremities with a width of 3.6 cm. At ambient temperature, material properties are those of the nominal values for A36 steel, which means its minimum yield stress is 250 MPa. The response of one of the bridge girders to the hydrocarbon fire was previously analyzed by Payá-Zaforteza and Garlock in [21]. This paper delves further into this case and studies the influence of several parameters on the response of the bridge to realistic fire scenarios after a tanker truck accident, including the following parameters:

- Position of the fire load (see Section 3).
- Structural boundary conditions (see Section 5.1).
- Elements included in the thermo-mechanical finite element model, i.e., analyzing only one girder versus the entire bridge (see Section 5.2).
- Bridge vertical clearance (see Section 5.3).
- General configuration of the bridge: single span versus three-span bridge (see Section 5.4).
- Wind action during the fire event (see Section 5.5).

All the analyses are carried out following a three-step numerical approach. In the first step a model of a fire scenario is built with FDS computational fluid dynamics software [28]. The temperatures in the most fire-exposed girder in the bridge or in the full bridge are obtained through a thermal analysis by Abaqus software [29]. Finally, the structural response of the bridge is obtained on Abaqus [29] considering both non-linearities (geometrical and mechanical) as well as temperature-dependent material properties.

3. Computational fluid dynamics model

Two fire models of hypothetical fire events were developed with FDS software [28]. FDS uses computational fluid dynamics (CFD) techniques and contains large eddy simulation (LES) turbulence models. It is used to predict in a control volume engineering variables such as temperatures, heat fluxes or gas pressures involved in the event. FDS was developed at the National Institute of Standards and Technology (NIST) in the USA and has gone through an extensive validation program [30]. The use of FDS to study bridge fires was validated by Alos-Moya et al. [22] using FDS and Abaqus to analyze an overpass failure caused by a tanker fire.

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 (conductivity, density, specific heat and emissivity), (5) fire sources, (6) a combustion model, and (7) sensors or elements of the model where the outputs (e.g. temperatures) are recorded. The components of the FDS model are described below.

3.1. Control volume and mesh

The control volume used in this study includes the bridge as well as part of its approaches. It measures 43.92 m × 30.82 m × 10.20 m along the x, y and z-directions respectively. The volume has a total of 1,658,880 parallelepiped cells and all the cells have dimensions of 0.20 m × 0.19 m × 0.21 m. This control volume and mesh size were the result of a sensitivity analysis and are a trade-off between precision and calculation times. It is important to note that the FDS mesh size does not coincide with the mesh used in the thermo-mechanical models built with Abaqus. Therefore, the authors developed a procedure to transfer the FDS results to Abaqus. This procedure is described in Section 4.4.

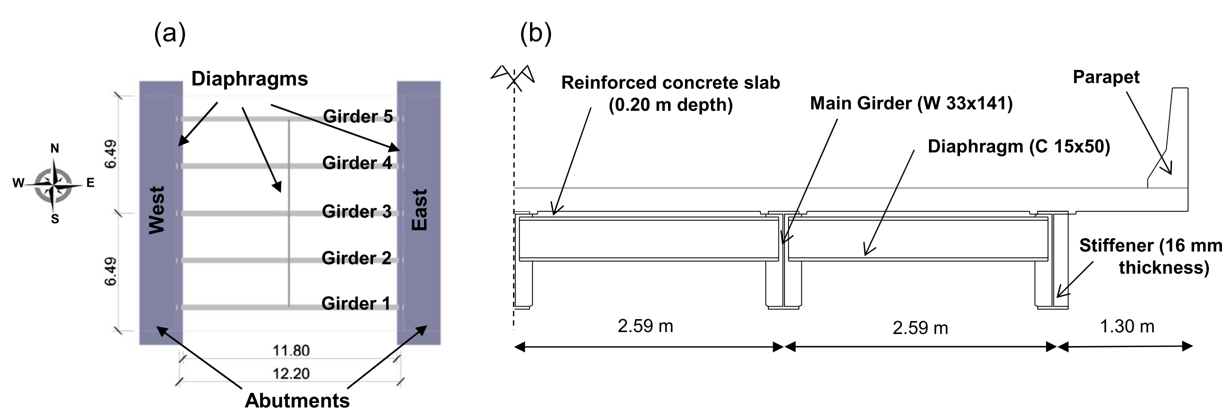

Fig. 1. Bridge definition. (a) Plan view (without the concrete slab). (b) Half section.