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RESPONSE OF COMPOSITE STEEL PLATE GIRDER BRIDGES SUBJECTED TO DEBRIS FIRES

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Bridge fires have been a serious concern for asset owners for decades. Considerable research work has been published on the assessment of bridges subjected to hydrocarbon fires and Wildland Urban Interfaces (WUI) fires like bushfires. However, the impact from fires that may have been generated due to onsite-accumulated debris, has been largely overlooked in the past. Prolonged duration of debris fires might well cause significant damage to the bridges, unless properly accounted during the design stage. The current study investigates the influence from debris-generated fires on steel girder bridges, using a reasonably validated advanced numerical modelling framework. Fire development was modelled first as a static, and then a travelling fire, using fire dynamic simulation (FDS) to capture the Adiabatic Surface Temperature (AST) development of the structure. The resulted AST was coupled with thermo-mechanical analysis using sequentially coupled thermo-mechanical analysis procedure in ABAQUS. The numerical model was used to estimate the temperature and displacement development of the bridge. The outcome from the study will facilitate asset managers for conducting necessary risk assessments incorporating the influence of onsite flammable debris for bridges.

Keywords: Wildland urban interface (WUI), Fire dynamic simulation (FDS), Adiabatic surface temperature (AST), Thermo-mechanical analysis.

1 INTRODUCTION

Occurrence of bridge fires is considered rare incidents. However, New York Department of Transportation survey in 2008 (Garlock *et al.* 2012) reported that bridge fire failure was nearly 3 times more than seismic induced failure. Giuliani *et al.* (2012) has also reported that the fire induced bridge failures in USA accounts for about 3% of the total cases surveyed. At the same time, the rapid expansion of urbanization has led to the increased vulnerability of infrastructures to WUI fires. The impact from fires that may have been generated due to onsite-accumulated debris, has largely been overlooked in the past. Prolonged duration of debris fires compared to bushfires or grassland fires might well cause significant damage to the bridges. Given the scant research on wildland urban interface (WUI) fires, this research presents an investigation of a possible bridge response to a debris driven WUI fire.

2 CASE STUDY BRIDGE USED FOR ANALYSIS

A 25m long and 13m wide composite steel plate girder bridge with 5 numbers of girders with 2.5m spacing is modeled to represent a typical bridge structure. Steel plate girder is 1.2m deep and attached to a 175mm thick reinforced concrete slab. Five steel plate girders of 1.2m deep support a 13m wide reinforced concrete slab a depth of 175mm. Refer to Figure 1 for information.

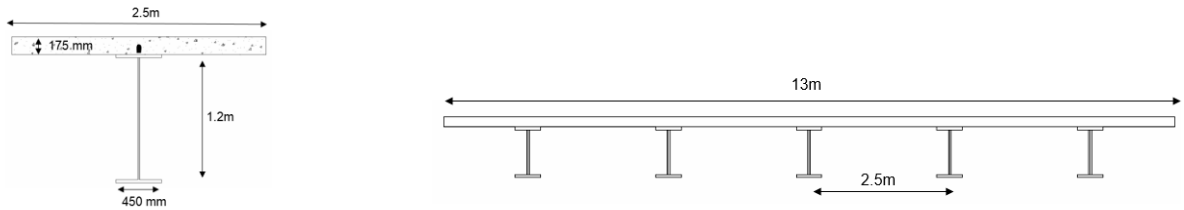


Figure 1. Case study bridge configurations.

3 DEVELOPMENT OF THE COMPUTATIONAL FLUID DYNAMIC (CFD) MODEL

Heating curves used in simple fire models are originally designed for building structures, where fire is naturally constrained in an enclosed space, whereas bridge fires are open environment fires. This difference makes the simple fire models inadequate for capturing the realistic bridge fire behaviours. A more realistic modelling of fire in a bridge can be obtained using computational fluid dynamics modelling. Fire Dynamics Simulator (FDS) (McGrattan *et al.* 2013a) software can be used to develop fire models to predict the fire engineering related variables such as temperatures, heat fluxes or gas pressures in fire events. The simulation results in a three-dimensional, time-dependent, prediction of fire behavior. FDS software has been developed at National Institute of Standards and Technology (NIST) and has been extensively validated experimentally (McGrattan *et al.* 2013b).

Building the FDS model requires defining a control volume with its boundary conditions relevant to the analysis. The geometry representing the case study structure should be included in the control volume with a suitable mesh or discretization of the control volume. The control volume used in this study includes the bridge as well as its two abutments. It measures 31m X 23m X 15m along the x, y and z-directions respectively. The control volume cells have approximate dimensions of 0.2 m.

Results of a vegetative based heavy fuel bed burning experiment reported by Cheney (1990) was used as the representative debris pile in the simulation process (Figure 2). During the experiment, a brigalow (Acacia harpophylla) fuel bed that was composed of 410 kg of fuels less than 25mm and 1145kg of fuels 25-75 mm in diameter with an average fuel load of 100kg/m^2 was burnt on a weighted platform. Figure 2 is the reaction intensity curve obtained for the burning fuel bed. It was reported that the flames spread rate is around 1m/min across the fuel bed.

Fire footprint was modelled as a 5x5m^2 placed directly below the centre of the bridge with the 3.5m effective clearance to the steel girders. The effect of wind was not considered in the FDS model.

Adiabatic surface temperature is a practical tool to express the thermal exposure of a surface to fire. Utilizing the AST helps to reduce the data flow in to the structural models by eliminating the dependency of the surface temperature on the net heat flux. AST temperature development depends on the incident flux and geometry of the structural members and the boundary conditions imposed on the control volume.

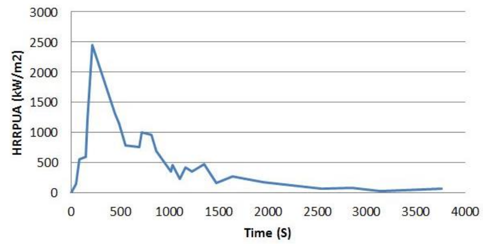


Figure 2. Experimental HRRPUA curve of a debris pile burning (Cheney 1990).

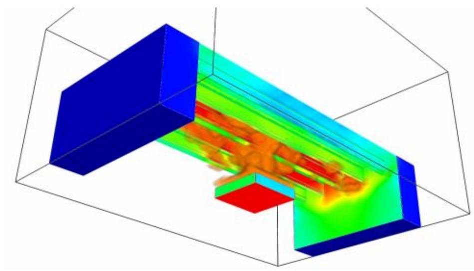


Figure 3. Adiabatic Surface temperature development of the structure.

The FDS model monitored the Adiabatic surface temperature development along the middle girder and the concrete surfaces on either side. AST Sensors measured the 52 cross-sections along the girder length with 9 sensors at each section. Figure 3 shows the colour contour of the AST development of the structure.

4 FINITE ELEMENT MODEL FOR THERMO- MECHANICAL ANALYSIS

Bridge girder is analysed using a sequentially coupled thermo-mechanical analysis with ABAQUS finite element software. It should be noted that FDS solves the CFD problem without considering the deformation of the structure. The thermal analysis provides the transient nodal temperature developments of the structure. Temperature distribution of the system determined with a standard heat transfer analysis that was used in the subsequent thermo-mechanical analysis.

Temperature dependent mechanical properties such as the stress-strain relationship, elastic modulus, and thermal properties such as specific heat, conductivity, and expansion were defined according to the Eurocode for concrete and steel elements respectively. The structural steel mechanical property was defined as nominal yield stress of 359 MPa, Young’s modulus of 210 GPa and a Poison’s ratio of 0.3. concrete compressive strength was taken as 40 MPa to build elevated temperature stress-strain curves.

Adiabatic surface temperatures obtained with FDS model were applied as thermal boundary conditions to the heat transfer analysis of the plate girder structure. Unexposed surfaces were defined to be at ambient temperature. In the thermal analysis a convective heat transfer coefficient of 25, 50W/m^2 K and an emissivity coefficient, of 0.7 were used for the exposed surfaces and a convective heat transfer coefficient of 9W/m^{2}K (EN 1991)was used for unexposed surfaces.

The bridge girder studied in this paper is a composite steel plate girder bridge. The steel girders and the concrete slab are connected with shear connectors to worked together to sustain the loads acting on the bridge. Pin and roller support conditions are used to represent the mechanical boundary conditions of the girder. Lateral movement of the girder is restrained at the support points.

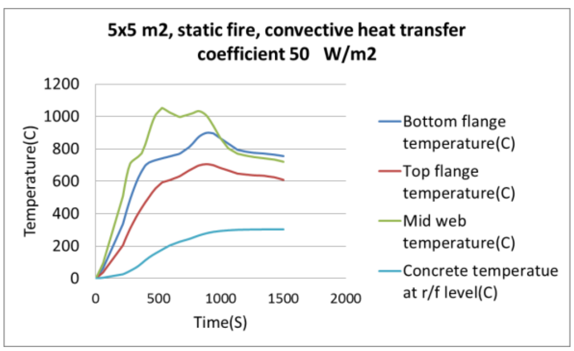
Self-weight of the steel girder and the concrete slab are included automatically by the Abaqus software. In addition to that, a dead load corresponding to the weight of the wearing surface has been also considered. The analysis excludes the effects of live load because of the unlikeliness of having traffic on the deck during a fire situation.

5 PARAMETRIC STUDY AND RESULTS

Fire source footprint was taken to be 5x5m^2, which is placed below the center of the middle girder of the bridge structure. Fire was modeled first as a static fire where the whole surface of fire footprint starts to burn at once to follow the corresponding HRRPUA curve. In a separate analysis fire foot print was divided in to a series of 0.5x5m^2 width rectangular strips perpendicular to the bridge girder. Then, each of those strips were assigned to follow the same HRRPUA curve but with a time lag for the initial ignition time that is calculated based on the experimentally observed progress rate of the flame front across the fuel bed of 1m/minute. In the text this analysis is called as the progressive fire or travelling fire scenario.

5.1 Temperature Development

A large variation of the temperatures along the bridge length was observed in the analysis results. Temperature close to the midspan of the girder was considerably higher than to the support areas as it is expected. Assuming a constant fire load along the bridge span is therefore unrealistic.



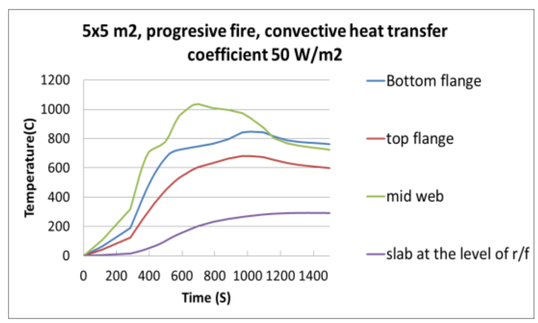


Figure 4. Temperature development of the mid-section of the structure.

Figure 4 shows the time history plots of temperatures for girder midspan cross section. This shows the temperature profiles at the top and bottom flanges, mid web and in the concrete slab at the level of reinforcement. The temperature of steel girder has been observed to increase to a maximum and then decayed gradually with the fire is gradually extinguished. Temperature development of the concrete slab remains below 400°C for the entire time. Top flange temperature development of the structure is well below the temperature development of the web or the bottom flange. This is mainly due to the presence of the concrete slab thermally attached to the top flange of the structure that acts as a heat sink during the fire exposure. Mid web temperature of the cross section goes above 1000ºC. Maximum temperature development of the static fire case is slightly higher than when the fire is modeled as a travelling fire.

5.2 Effect of Heat Transfer Coefficient

Heat transfer from fire zone to boundaries of the girder is mainly through convection and radiation, while conduction is the main mechanism for heat transmission within the girder assembly. Selecting a suitable convective heat transfer coefficient to represent the characteristics of a fire is an important step. According to the Eurocode (EN 1991-1-2 2002), 25, 50, 35 $W/m^2.K$ values are recommended for standard fire, hydrocarbon fire and simplified fire models respectively. Based on this recommendation, CFD based fire response evaluation programs can selects the appropriate values to represent the convective part of the heat transfer mechanism. However, there is lack of guidelines to represent a vegetative based fire. In the current study two convective heat transfer coefficient values 25 and 50 $W/m^2.K$, were utilized to understand the effect along with emissivity coefficient 0.7.

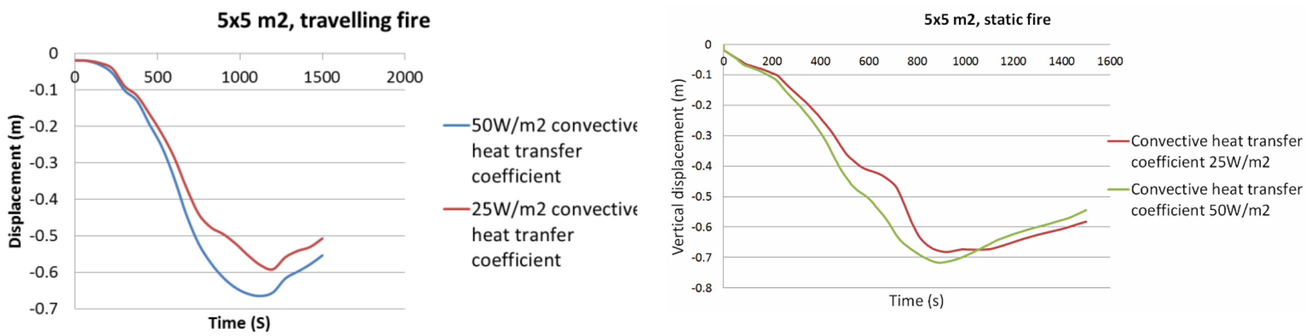


Figure 5. Midspan displacement development of the structure due to different fire conditions.

Both travelling fire and the static fire cases were analyzed using two convective heat transfer coefficients. Figure 5 shows the results related to the midspan displacement development of the girder. Displacement development is slower, and the maximum displacement is lower when a low coefficient of convective heat transfer coefficient is used in the analysis. Effect is more prominent.

5.3 Static vs Travelling Fire Effect

Fire footprint was modelled as a $5x5m^2$ squire placed directly below the centre of the bridge with the 3.5m effective clearance to the steel girders. The effect of wind was not considered in the FDS model.

As it is mentioned earlier, the debris pile burning was modelled first as a static fire and extended to a more realistic progressive fire. Midspan displacement development was monitored in both cases convective heat transfer coefficient was taken as $50W/m^2.K$. Displacement development is slower when the fire is modelled as a progressive fire (Figure 6). This is mainly due to constrained fuel consumption of a progressive fire. However, the maximum displacement development is almost similar in engineering point of view.

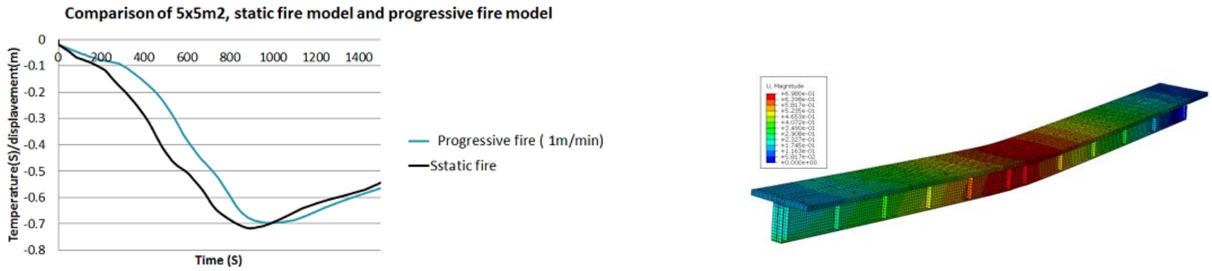


Figure 6. Effect of travelling and static fire on the bridge response.

6 CONCLUSIONS

A systematic approach to investigate the response of a bridge subjected to a debris driven WUI fire event has been presented in this paper. Sequentially coupled thermal-stress analysis has been carried out to evaluate the behaviour of the bridge girders subjected to a vegetative based fire. Fire was modelled in both ways to understand the difference between the modelling the fire as a static vs travelling. Travelling fire modelling resulted a slower displacement development of the girder, however the maximum displacement response is comparable in both cases. Effect of convective heat transfer coefficient on the midspan vertical displacement is prominent when the fire is modelled as a travelling fire than a static fire. Maximum displacement exceeded the allowable serviceability criteria of the structure in all the cases. This case study clearly indicates the risk associated with debris collected around a bridge structure in an accidental fire event.

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