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A streamlined framework for calculating the response of steel-supported bridges to open-air tanker truck fires

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ABSTRACT

Several recent fire-induced bridge failures have highlighted the need for improved simplified tools to evaluate the response of bridges to fire. A streamlined design framework is proposed for efficient calculation of a steel-supported bridge's response to an open-air hydrocarbon pool fire resulting from a tanker truck crash and subsequent fuel spill. The framework consists of four steps: (1) calculate the fire's characteristics and geometry; (2) calculate the heat transfer from the fire to the structural elements; (3) calculate the temperature increase of the structural elements; and (4) calculate the resulting material and mechanical response of the structural elements. The approach, which uses a modified discretized solid flame model to represent the pool fire, synthesizes calculation techniques based on both first principles and empirical data to quantify the extent of damage caused by the fire hazard. Due to its efficiency, this approach can be used to calculate an envelope of effects for a wide range of fire parameters. The framework is applied to a case study of the 2007 fire event and collapse of an overpass bridge at the MacArthur Maze freeway interchange near Oakland, CA, USA. The framework is then demonstrated as a design tool to determine the extent of the overpass' vulnerability to a similar fire along the freeway below.

1. Introduction

Fire represents one of the most severe threats to the integrity of our built infrastructure. Our transportation infrastructure is particularly susceptible to fire due to the constant presence of vehicle traffic and the potential for crashed or overturned vehicles to become fuel sources due to their flammable contents. Single or several passenger vehicles involved in a collision can themselves present a threat to bridges and tunnels due to the combustion of their contents, including the on-board hydrocarbon fuel and, increasingly common, hybrid batteries. However, the more severe threat is presented by large semi-trucks transporting large quantities of combustible cargo, hydrocarbon fuel, or other hazardous materials. Due to their confined environment, tunnels have received significantly more consideration than bridges with regard to designing for fire, as demonstrated by the recent release of a NCHRP report which provides design guidance for tunnel fires [1]. Little guidance, however, is provided in either the relevant US [2] or European [3] standards regarding the approach to calculating applicable fire hazards for bridges.

Tanker trucks ferrying gasoline and diesel, which are common and necessary to meet our society's current transportation demands, have provided the fuel for most of the recent severe fire events involving bridge structures, including but certainly not limited to the collapse of the MacArthur Maze I-80//I-580/I-880 interchange overpass in Oakland, CA, USA in 2007; the near-collapse of the I-65 overpass near Birmingham, AL, USA in 2002; and the severe damage leading to demolition of the Route 22 overpass at I-81 near Harrisburg, PA, USA in 2013. More comprehensive lists of recent severe bridge fire events in the US, which clearly highlight the threat posed by tanker truck fires, have been compiled by Garlock et al. [4] and as part of a recently concluded National Cooperative Highway Research Program (NCHRP) study of bridge fire hazards [5]. Damaged bridges can cost millions of dollars for repair and due to economic loss per day of road closure – losses for the MacArthur Maze fire in 2007 were estimated at more than $9 million for repair and $6 million per day in economic losses [4].

This study focuses on the effects of open-air hydrocarbon pool fires resulting from a tanker truck crash or sabotage since the

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Table 1
Summary of the modeling approaches used in previous structural-fire bridge studies.

Section	Authors	Location	Bridge type	Fire model	Heat transfer model	Structural model
2.1. Standard fire and other simplified methods	Dotreppe et al. [8]	Vivegnis Bridge, Liege, Belgium	Tied steel arch plus concrete deck	Standard hydrocarbon fire curve	Applied temperature time history to "exposed" surfaces of 2-D solid element thermal FE cross-sections	Beam and shell elements for structural FE model of the bridge
	Liu et al. [9]	MacArthur Maze, Oakland, CA, USA	Steel girders with concrete deck	Standard hydrocarbon fire curve	Applied temperature time history to "exposed" surfaces of 3-D solid element thermal FE model	Solid and shell elemens for structural FE model of a single girder and slab
	Kodur et al. [10]	Hypothetical	Steel girders with concrete deck	Standard hydrocarbon fire curve	Applied temperature time history to "exposed" surfaces of 3-D solid element thermal FE model	Solid and shell elements for structural FE model of a single girder and slab
	Paya-Zaforteza and Garlock [11]	Hypothetical	Steel girders with concrete deck	Standard hydrocarbon fire curve and a design fire	Applied temperature time history to "exposed" surfaces of 3-D solid element thermal FE model	Solid elements for structural FE model of a single girder and slab
	Aziz and Kodur [12]	Hypothetical	Steel girders with concrete deck	Standard hydrocarbon fire curve and two design fires	Applied temperature time history to "exposed" surfaces of 3-D solid element thermal FE model	Solid elements for structural FE model of a single girder and slab
2.2. Computational fluid dynamics (CFD) modeling	Choi [14]	MacArthur Maze, Oakland, CA, USA	Steel girders with concrete deck	Constant heat release rate per unit area of 2500 kW/m^2	Applied temperature time histories based on CFD modeling to 3-D solid FE model	Solid elements for structural FE model of the overpass bridge
	Bajwa et al. [15]	MacArthur Maze, Oakland, CA, USA	Steel girders with concrete deck	Constant fire temperature of 1100°C	Applied temperature time histories based on CFD modeling to 2-D solid FE model	Solid elements for structural FE model of the overpass bridge
	Wright et al. [5]	I-65 Overpass, Birmingham, AL, USA	Steel girders with concrete deck	Heat release rate time histories for a fuel tanker and other burning vehicles from published sources	Applied temperature time histories based on CFD modeling to 3-D solid FE model	Solid elements for structural FE model of the overpass bridge
	Alos-Moya et al. [16]	I-65 Overpass, Birmingham, AL, USA	Steel girders with concrete deck	Several constant heat release rates per unit area that are representative of a burning tanker truck	Applied temperature time histories based on CFD modeling to 3-D solid FE model	Solid elements for structural FE model of the overpass bridge
	Tonicello et al. [17]	Hans-Wilsdorf Bridge, Geneva, Switzerland	Helical steel arch bridge	Heat release rate time histories for burning vehicles from published sources	Assigned isotherm temperature time histories to finite elements based on CFD modeling	Beam and shell elements for structural FE model of the bridge
2.3. Intermediate models	Bennetts and Moinuddin [18]	Hypothetical	Cable-stayed bridge	Calculated max. radiation heat flux to targets based on size of tanker truck for an assumed duration	Applied heat flux as an equivalent max. temp. to multi-layered lumped thermal mass elements	Lumped mass material weakening relative to applied load
	Astaneh et al. [19], Noble et al. [20]	MacArthur Maze, Oakland, CA, USA	Steel girders with concrete deck	Constant fire temperature of 1200°C	Analytically calculated heat flux from a "fire bath" solid flame model, applied to 3-D solid element thermal FE model	Solid element structural FE model of the overpass bridge