MITIGATING THE EFFECTS OF A TANKER TRUCK FIRE ON A CABLE-STAYED BRIDGE

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ABSTRACT

Fire represents one of the most severe threats to the integrity of our built infrastructure. This study focuses on the effects of open-air hydrocarbon pool fires that may result from a tanker truck crash or sabotage since the quantity and flammability of its contents pose one of the worst-case hazards to a nearby bridge. In general, the calculation of a bridge’s response to a vehicle-based fire hazard consists of four steps: (1) calculate the fire’s characteristics and geometry; (2) calculate the heat transfer from the fire to the structural elements via radiation heat flux; (3) calculate the temperature increase of the structural elements; and (4) calculate the resulting material and mechanical response of the structural elements. The authors have developed a streamlined framework for efficient calculation of these steps which synthesizes numerous models based on both first principles and empirical data to quantify the extent of damage caused by a specified fire threat. Due to its efficiency, this approach can be used to calculate the effects of a range of fire types, sizes, and locations to develop an envelope of performance for which the risk of damage and the effectiveness of potential fire protection measures can be evaluated. The methodology is used to demonstrate the design process for determining fire protection on a cable-stayed bridge. This design example shows that explicitly modeling the fire, rather than using the UL 1709 fire curve, better quantifies the extent of fire effects and potentially reduces the required fire protection based on the available capacity.

KEYWORDS

Cable-stayed bridge, hydrocarbon fire, fire protection.

INTRODUCTION

Cable-stayed bridges have emerged as a popular structural form for many recent bridge construction projects, and a vehicle fire on the bridge deck poses a significant threat to the integrity of the stay cables. Several recent cable-stayed bridge projects have required the development of a Threat, Vulnerability, and Risk Assessment (TVRA) to determine design scenarios to mitigate the effects of blast and fire (Woodworth et al. 2015). For fire, these scenarios typically involve the specification of a tanker truck threat with a fuel type and volume—these scenarios apply for both accidental fires (due to vehicular collisions) and intentional fires (due to sabotage). The Post-Tensioning Institute (PTI) has included some considerations for fire resistance in Section 4.5 of their guideline document for the design of stay cables (PTI 2012), but there is a disconnect between these provisions and the typical TVRA fire threats. The PTI provisions are oriented toward the requirement of fire ratings based on standard fire tests in a qualified laboratory. Based on an owner’s pre-established requirements for fire resistance, the stay cable assembly is subjected to a temperature time history that simulates a worst-case exposure to a hydrocarbon fire, similar to UL 1709 (UL 2011). The steel strands must demonstrate “fire endurance” of 30 minutes or greater, as determined by the time needed for the steel to reach 300°C. Also, the assembly is then tensioned to 45% of maximum ultimate tensile strength and heated to 300°C, and it must resist these conditions for at least 30 minutes. The PTI document does not provide guidance for calculating the extent of fire exposure or the resulting cable deterioration for realistic fire scenarios that are typically provided in a TVRA. Additionally, little guidance is provided in either the US (NFPA 2013) or European (CEN 2002) standards for the design of bridges to resist fire hazards.

This paper presents an engineering approach for calculating the extent of fire exposure, the resulting degree of damage, and the required mitigation for stay cables due to a tanker truck fire on the deck of a long-span bridge. This study focuses on open-air hydrocarbon pool fires resulting from a tanker truck crash or sabotage.
since the quantity and flammability of its contents poses one of the worst-case hazards to the bridge components. The calculation of a bridge’s response to a vehicle-based fire hazard generally consists of four steps: (1) determine the fire’s characteristics (e.g. footprint, flame height, duration, and intensity); (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 material and mechanical response of the bridge structure. Using this four-step approach, the authors have recently developed a streamlined framework for efficient calculation of a bridge’s response to a large open-air hydrocarbon fire (typically 4 meters to 25 meters across) which results from a tanker truck crash (Quiel et al. 2015). The approach synthesizes numerous calculation techniques based on both first principles and empirical data to quantify the extent of damage caused by a specified fire threat. The geometry and intensity of the hydrocarbon fire are calculated based on the pool fire footprint and the fuel properties. Heat transfer to the structure is calculated using a modified discretized solid flame (MDSF) approach, and the resulting thermal response of the bridge’s stay cables is then calculated using multiple lumped thermal masses. The model of the stay cable cross section accounts for the potential combustion of the HDPE pipe sheathing, which encases the bundle of steel strands. These temperature time histories are then used to calculate the corresponding structural response. Via this procedure, the proposed framework delivers a novel quantification of the spatial contour and time dependency of stay cable exposure to open-air hydrocarbon fires that result from tanker truck accidents.

Due to its efficiency, this approach can be used to calculate the effects of a wide range of fires sizes (for varying fuel spill footprints) and locations along the deck of a cable-stayed bridge. The results can be used to develop an envelope of performance for which the risk of damage and the effectiveness of potential fire protection measures can be evaluated. The proposed design framework is intended to be used as a tool to calculate the envelope of effects due to potential fire scenarios as they relate to the structural geometry, fire protection requirements, and the structural design of the system. The proposed design framework is not intended to be used as a substitute methodology for situations where a more detailed and computationally intensive approach (via finite element analysis and/or computational fluid dynamics) is warranted, such as in a forensic investigation. The proposed framework may be used as an initial assessment tool to help establish modeling boundaries for the more detailed model or to efficiently develop calculations for a wider range of scenarios. Using an example, the methodology is used to demonstrate the design process for determining the extent and amount of fire protection required for a cable-stayed bridge. This design example shows that explicitly modeling the fire, rather than using the UL 1709 standard fire curve, better quantifies the extent of fire effects and potentially reduces the required fire protection based on the available capacity.

BACKGROUND

Transportation infrastructure is susceptible to fire due to the constant presence of vehicle traffic and the potential for crashed or overturned vehicles and their contents to become fuel sources (especially semi-trucks hauling fuel and other flammable or combustible cargo). Tanker trucks hauling 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. To date, most bridge collapses due to tanker truck fires have involved common highway overpasses (typically supported by steel girders), which represent the majority of our bridge inventory (Garlock et al. 2012; Wright et al. 2013). However, recent events have shown that long-span bridges (particularly signature or landmark bridges) have also been frequently susceptible to vehicle fires. Fire poses a greater hazard to a long-span bridge than an overpass due to elevated consequences of collapse, elevated impact of closure, and the difficulty of firefighting access. Table 1 summarizes several recent fire incidents for long span bridges in North America which involved burning vehicles. All of the incidents in Table 1 did not result in significant damage or collapse since the fires involved either passenger vehicles or semi-trucks carrying non-hazardous cargo. However, the incidents in Table 1 underscore the potential for the occurrence of vehicle fires on the deck of a long-span bridge. Since most long-span bridges must accommodate the transport of fuel and other hazardous cargo, it is reasonable to expect that tanker truck fires similar to those that have caused the collapse of common overpass bridges are at least a statistically possible hazard that should be considered during design.

Few previous research studies have examined the effects of realistic hydrocarbon fires on cable-stayed bridges. Bennett and Moiuddin (2009) examined the effect of a tanker truck gasoline fire on a simplified stay cable cross-section. In that study, the heat release rate for a tanker truck fire on the bridge deck was calculated using semi-empirical models to estimate the magnitude of maximum fire exposure, which was then applied to the stay cables as an equivalent surface temperature based on a peak heat flux from radiation and convection. The cross-section of the cables was thermally modeled using layered lumped masses to account for potential insulation and multiple layers of steel strand. The resulting deterioration of the cable strength was then evaluated. Woodworth
et al. (2015) used a CFD model to calculate the effects of a pool fire on a simplified stay cable assembly example. The results of these calculations provided a spatial distribution and severity of cable temperature increase due to fire exposure. In this study, significant simplifications were made regarding the cross-sectional calculation for the temperature increase in the steel cable, presumably due to the computational expense of the CFD approach.

<table>
<thead>
<tr>
<th>Date</th>
<th>Name</th>
<th>Location</th>
<th>Type</th>
<th>Fire Source</th>
<th>Incident Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>March 2007</td>
<td>Mezcala Bridge</td>
<td>Guerrero, Mexico</td>
<td>Cable-</td>
<td>Tractor-Trailer</td>
<td>1 stay cable ruptured due to fire</td>
</tr>
<tr>
<td>July 2009</td>
<td>Manhattan Bridge</td>
<td>New York, NY, USA</td>
<td>Suspension</td>
<td>Tractor-Trailer</td>
<td>Minor damage</td>
</tr>
<tr>
<td>June 2012</td>
<td>Brooklyn Bridge</td>
<td>New York, NY, USA</td>
<td>Suspension</td>
<td>Passenger car</td>
<td>Minor damage</td>
</tr>
<tr>
<td>August 2013</td>
<td>Queensboro Bridge</td>
<td>New York, NY, USA</td>
<td>Cantilevered Truss</td>
<td>Tractor-Trailer</td>
<td>Some damage to structural steel</td>
</tr>
<tr>
<td>April 2014</td>
<td>Zakim Bridge</td>
<td>Boston, MA, USA</td>
<td>Cable-</td>
<td>Tractor-Trailer</td>
<td>Casing of 1 stay cable partially charred</td>
</tr>
</tbody>
</table>

**METHODOLOGY: A STREAMLINED SIMPLIFIED APPROACH**

The methodology for this study implements the aforementioned four-step approach in a streamlined analytical framework - a complete, detailed description is available in Quiel et al. (2015). This approach is less computationally intensive than CFD solutions and allows for the pool fire to be rationally represented in the solution. By implementing the four-step approach, staff at Hinman Consulting Engineers, Inc. with researchers at Lehigh University have created $FLaME$ (Fire Loading and Mitigation Evaluator), an in-house 3D modeling program that links the actual geometry of the structure with the realistic fire exposure. $FLaME$ has been previously used to successfully model the mode and time to failure of the 2007 MacArthur Maze freeway collapse in Oakland, CA (Quiel et al. 2015) and has been implemented for several recent bridge design projects to calculate the fire protection requirements for stay cables and other steel bridge elements.

First, the hydrocarbon pool fire is modeled using analytical calculations of the fire characteristics (e.g. flame height, heat release rate, duration, and radiative intensity) based on idealized semi-empirical combustion models. The results of these models can then be used to calculate radiation heat transfer from the fire to the structural elements. For open-air (i.e. unconfined) pool fires of this size, radiation is the dominant heat transfer mode and the effects of convection can therefore be neglected (Babrauskas 1983). Once the heat release rate (Babrauskas 2008) and height (Heskstad 2008) of the fire are calculated for the given fuel type, fuel quantity, and pool size, the fire can be represented with a solid flame model (i.e. a radiation-emitting 3D object with the shape of a cylinder, rectangular box, or other irregular trapezoidal or conical shapes) which can be used to calculate heat transfer to structural elements. The solid flame surfaces are discretized into rectangular elements, each of which emits radiation toward potential targets. Calculating the summation of radiation heat flux from the discretized fire surface elements allows the user to choose varying fire footprint sizes and shapes, as well as assign varying distributions of thermal emissivity from each vertical zone of the fire. The temperature of the structural elements can then be calculated using a multiple lumped mass approach, and the resulting structural response due to the temperature increase can be evaluated.

**Step 1: Modelling the Hydrocarbon Pool Fire**

To calculate the fire’s characteristics, the user must first select the fuel type and volume as well as the footprint (shape and dimensions) of the pool resulting from the fuel spilling from the tanker truck. Variables to consider include the assumed rate of spill, the slope of the roadway, the presence of drainage, etc. For many fuel spills, a rectangular or trapezoidal footprint will account for sloping pavement in either one or two directions, respectively. For simplification, the footprint discussed here will focus on a rectangular shape. Most of the semi-empirical equations for calculating pool fire characteristics are based on the circular pool shape – similar expressions for non-circular pool fires are not widely available. The pool fire diameter, $D_p$, is a required variable for most semi-empirical calculations, and therefore an equivalent value $D_{eff}$ can be calculated using a circle...
with the same area as the rectangular footprint. For pool fire footprints with an approximate aspect ratio (long edge to short edge) greater than two, the $D_{f,\text{eff}}$ is calculated using a limited area with dimensions of the short edge length by two times the short edge length from the full footprint. $D_{f,\text{eff}}$ for areas with aspect ratios greater than 2.5 may lead to inaccuracy when using the circle-based semi-empirical equations (McGrattan et al. 2000). Once the maximum heat release rate (HRR) is calculated (Babrauskas 2008), flame heights are calculated using semi-empirical expressions such as those developed by Heskestad (1983) (for no-wind conditions only) or Thomas (1962) (which can accommodate wind tilt). The duration of the pool fire, $t_{\text{f}}$ (sec), can be calculated as the time needed to consume all available fuel over the pool area based on the fuel’s mass loss rate, $m^*$, and density, $\rho$ (kg/m$^3$). A simplified approach to assembling the pool fire’s HRR time history would be to assume a constant HRR over the duration $t_{\text{f}}$. In order to account for a realistic rapid increase of heat release as well as a decay phase, the proposed approach implements a time history model similar to that used for tunnel design fires (Ingason 2006). The time of fire growth, $t_{\text{g}}$, is taken as the minimum of $t_{\text{f}}/5$ or 10 minutes, and the HRR progresses quadratically. The time of fire decay, $t_{\text{d}}$, is taken as the minimum of of $t_{\text{f}}/2.5$ or 20 minutes, and the HRR experiences exponential decay.

**Step 2: Modelling the Heat Transfer from the Pool Fire to the Stay Cables**

The solid flame model with the assumed footprint and calculated height $H_f$ is discretized into $n$ total rectangular elements that each emit radiation heat flux. Gasoline and diesel, which together constitute a large portion of overall truck-transported fuel, produce a large amount of smoke and soot during their combustion and develop a vertical fire structure with two zones: the luminous zone (i.e. unobscured flame region) and the smoke-obscured upper region (McGrattan et al. 2000). The two-zone characteristic of pool fires involving high-soot yielding fuels has been well established in several recent experimental studies (Munoz et al. 2007). Each surface $i$ is assigned an emissive power, $E_i$ (kW/m$^2$) based on its location in either the luminous zone or the smoke zone. For this study, the luminous zone is modeled as the lower half of the solid flame model, which is conservatively consistent with an experimental study of gasoline and diesel pool fires by Munoz et al. (2007). Though several semi-empirical formulas are available to quantify the emissive power of a pool fire’s flames and smoke, values of $E_{\text{flame}} = 100$ kW/m$^2$ and $E_{\text{smoke}} = 40$ kW/m$^2$ are used for this study, again in accordance with the study of Munoz et al. (2007). The radiation heat flux imparted to a target $j$, $q_j^*$(kW/m$^2$), which is located outside the pool fire (i.e. the target is not enveloped by the solid flame model) can be calculated as the summation of each discretized fire surface’s emissivity times the view factor from that surface to the target, $F_{i\rightarrow j}$ (dimensionless):

$$q_j^* = \sum_{i=1}^{n} E_i F_{i\rightarrow j} = \sum_{i=1}^{n} E_i \frac{A_i \cos \theta_i \cos \theta_j}{\pi r_{i,j}^2}$$

where $F_{i\rightarrow j}$ accounts for the area of the fire surface, $A_i$(m$^2$); the standoff between the fire surface and the target, $r_{i\rightarrow j}$(m); the absolute angle between that standoff vector and the fire element’s normal vector, $\theta_i$; and the absolute angle between the standoff vector and the target’s normal vector, $\theta_j$. Fire surfaces that have no “view” of the targets outside the pool fire impart no radiation heat flux.

**Step 3: Modelling the Thermal Response of the Stay Cables**

Having obtained the radiation heat flux for each target, the increase in the target’s temperature can be calculated using a lumped mass approach. This paper will focus on the calculation of the temperature increase of the stay cables since they provide the primary structural support to this bridge type. Stay cables are represented as lumped mass line elements that are discretized along their lengths into multiple targets for which lumped mass heat transfer is calculated. When calculating $\theta_j$ for a line element representing a cable, the normal vector for the line is assumed to be perpendicular to the line element and lies in the same plane as the cable line and the standoff vector between the target $j$ and the radiation-emitting fire surface $i$. Each stay cable is discretized into elements with no more than a 1-meter length. The cross-section of the stay cable consists of a bundle of 7-wire strands that are encased by a high-density polyethylene (HDPE) pipe, and each strand is sheathed in a thin HDPE sleeve. As shown in Fig. 1a, the cross-section of each element is represented with three lumped masses: (1) the fire-exposed portion of the outer HDPE pipe, (2) the non-fire exposed portion of the outer HDPE pipe, and (3) the bundle of steel strands. For this study, it is assumed that lumped masses #1 and #2 each comprise half of the outer HDPE pipe. The outer HDPE pipe can be modeled both as unprotected or as insulated with fire protection using the same lumped mass approach as that used for insulated steel sections (Buchanan 2002).

Fig. 1 illustrates the stay cable cross-section as it begins to deteriorate due to fire exposure. In Fig. 1a, lumped mass #1 is heated by the fire’s radiation, increasing its temperature. Lumped mass #1 subsequently heats lumped mass #2 via conduction along the pipe and via some internal radiation around the strand bundle. It is
assumed for the stay cables in this study that 20% of the radiation emitted by the interior face of lumped mass #1 is transmitted to the interior face of lumped mass #2. This percentage accounts for the radiation that is transmitted around the wire strand bundle through the air gap between it and the outer HDPE pipe. Lumped mass #2 is also cooled via natural convection and radiation to the ambient environment. Lumped mass #3 is heated via 80% of the total radiation emitted from the interior faces of the two lumped masses that comprise the outer HDPE pipe. When encased by the outer HDPE pipe, the wire bundle does not experience any ambient cooling – when the fire ends, it will cool by transmitting radiation back to the outer HDPE pipe as the pipe experiences ambient cooling.

The HDPE is a flammable material and, when heated, will begin to burn when its temperature exceeds 400°C and its surface experiences a critical radiation heat flux greater than 15 kW/m² in accordance with HDPE material data in the SFPE Handbook (Tewarson 2008). When this occurs, the section model transitions to that shown in Fig. 1b, which accounts for the combustion of the outer HDPE pipe. For unprotected cables, the outer face of the fire-exposed lumped mass #1 will experience these conditions first due to the direct radiation from the fire. For protected cables, lumped mass #1 is shielded from direct radiation from the fire – it will therefore begin to melt due to its temperature increase rather than burning due to the lack of critical heat flux. Lumped mass #2, however, experiences both a temperature increase as well as radiation on its interior face from lumped mass #1 and can eventually meet the conditions for combustion. In either case, it is assumed that if either lumped mass #1 or #2 starts to combust that both will burn simultaneously. When burning, an additional 61 kW/m² of direct flame radiation heat flux is applied to lumped masses #1 and #2 (minus a re-radiation of 15 kW/m² to the ambient environment), and their mass is reduced according to HDPE’s published mass loss rate (Tewarson 2008). As the outer HDPE rapidly heats due to direct flame radiation, the strands in lumped mass #3 subsequently experience an increase in radiation. The large resulting temperature increase in lumped mass #3 eventually produces the conditions needed to trigger the combustion of the HDPE sleeves around the wire strands. As shown in Fig. 1c, the thin HDPE strand sheaths will combust rapidly and also apply an additional 61 kW/m² of direct flame radiation heat flux to the steel strands in lumped mass #3. Note that additional combustion of the grease or other lubricant within each strand’s HDPE sheath is not considered. HDPE combustion progresses rapidly (usually taking 10-15 minutes to “burn off”) until only the wire strands remain as shown in Fig. 1d. The fire radiation is then applied directly to the fire-exposed face of the strand bundle’s approximate circumference, and the unexposed face is cooled via natural convection and radiation to the ambient environment.

The total heat transfer for the steel strands in each element along the length of the cable accounts for both the cross-sectional model shown in Figs. 1a through 1d as well as conduction between adjacent elements of along the cable length. Thermal conductivity, k (W/m-K), in the steel strands is temperature dependent and is calculated as an average value based on the temperature of the two adjacent elements. It is assumed that the cross-sectional area and length of each elements are uniform along the length of the beam. The total heat transfer can then be used to calculate the temperature increase of the steel strands by accounting for material volume, density, and specific heat of the steel in that element. When making these calculations, all thermally dependent properties are calculated with a one-time-step lag (at $t-1$) – this approach has been used effectively for time steps of no more than one minute in previous lumped mass heat transfer studies (Quiel and Garlock 2010).
**Step 4: Modelling the Structural Response of the Stay Cable**

The temperature change of the steel wire bundle in each cable element can be used to calculate the corresponding decrease in material strength and stiffness as well as thermal expansion. Time histories of these responses can then be used to evaluate structural behavior either via simple demand-vs-capacity comparisons or by mapping the results to a structural finite element model. In this paper, a design example will be examined using the calculated decrease of yield strength as a simplified indicator of potential collapse. Future research by the authors will examine the consequences of load redistribution in bridge structures due to the calculated effects of fire exposure that are obtained from this framework. The material deterioration model for cold-drawn steel wire according to Hertz (2004) is used for this study.

**DESIGN EXAMPLE**

The methodology outlined above is implemented for a case study of a generic prototype cable-stayed bridge shown in Fig. 2. The bridge spans 183 meters (600 feet) from the centreline of the concrete tower to the end of the longest cable, and two vertical planes of cables are attached to the edge of the deck at equidistant 12-meter (40-foot) spacing. Only one tower of the bridge is shown for simplicity, and the spans and cable layout on either side of the tower are symmetric. The deck is 30.5 meters (100 feet) wide and is assumed to accommodate two lanes of traffic plus a shoulder in both directions. The deck has a 2% lateral grade (cresting at its longitudinal centreline) and 1% longitudinal grade. The number of steel 7-wire strands increases from the shortest to the longest cable from 30 to 45 to 60 strands in groups of five each. The outer HDPE pipe has a slightly larger diameter for larger numbers of strands, ranging from 209 mm (9 inches) to 305 mm (12 inches). The outer HDPE pipe has a thickness of 8 mm (5/16 inches), and the HDPE strand sleeves are 2 mm (1/16 inches) thick. It is assumed that the service load level for each stay cable at the time the fire starts is 50% MUTC, which is conservatively consistent with the recommended load level (45% MUTC) in the PTI testing protocol for stay cables under fire (PTI 2012).

The design basis fire threat considered for this study is that of a tanker truck hauling 34000 liters (9000 gallons) of gasoline. The hazard scenario presumes that the tanker truck is involved in an accident or is sabotaged on the bridge deck, after which its contents start to combust. It is possible that the tanker truck fire could occur at any location along the length or width of the bridge. It is also possible that the fuel will either stay approximately contained within the tanker as it burns or spill onto the roadway as it leaks from the tanker. Due to the slope of the roadway, the spilled fuel will flow both laterally and longitudinally, with some percentage of its leaked...
volume potentially draining into the nearby scuppers before it combusts. The potential for drainage of leaked fuel will be governed by the flow rate of fuel from the truck, the spacing and proximity of the scuppers, and the rate of fuel consumption by the fire.

**Pool Fire Footprint: Controlling Cases**

To simulate a realistic hazard scenario, the user must account for the significant uncertainty in the parameters regarding the location, footprint, and available fuel of the tanker truck fire. In practice, analysis could be performed to obtain estimates for the percentage of available fuel depending on the scupper design and placement relative to a range of fuel leak rates and fire locations. For this study, two hazard scenarios are considered as potentially controlling cases for fire severity and size:

(1) The fuel remains within the tanker, resulting in 100% consumption in an area approximately equal to the footprint of the tanker (50 feet long by 8 feet wide with its base at an 8-foot height). For this scenario, it is conservatively assumed the tanker is located in the shoulder (i.e. at the location nearest the cables).

(2) A moderate leak from the tanker, which is located in the left lane, allows the fuel to spill onto the roadway. The fuel will flow both laterally and longitudinally but will favor the larger lateral grade toward the curb. It is assumed that the leakage flow rate is larger than the fire’s fuel consumption rate such that 25% of the total fuel volume will reach the curb and is drained from the area via the scuppers before it can be consumed. Though the actual shape of the fuel spill will be somewhat trapezoidal, the spill footprint for this scenario is simply represented as rectangular, spanning 35 feet laterally over both lanes and the shoulder as well as 20 feet longitudinally.

The spill footprint parameters of each fire scenario provide bounding cases for fire exposure and duration. The longer, thinner footprint of Scenario 1 (with a smaller overall area) provides greater exposure to a larger number of cables along the length of the bridge and will result in a longer fire duration than Scenario 2. Note that the HRR and fire height in Scenario 1 will be capped according to the aforementioned 2:1 aspect ratio provision. With a larger fire footprint and an aspect ratio less than two, Scenario 2 provides a larger fire height and a more severe HRR. Though the fire in Scenario 2 will be shorter in duration, it will have higher intensity and potentially affect more cables where they are significantly inclined (such as locations furthest from the towers) due to the increased fire height. The HRR time histories for both fire scenarios are plotted in Fig. 3.

**Determining the Extent and Amount of Mitigation**

Acceptance criteria for fire-exposed performance must first be established before the extent and amount of stay cable fire protection needed to mitigate the effects of these fire scenarios can be determined. Based on the assumed service load for each stay cable, “failure” of a cable for this bridge is assumed when the 2% yield strength for cold drawn steel strand according to Hertz (2004) is reduced to 50% MUTC. Current stay cable bridges are typically designed with adequate redundancy to withstand the loss (i.e. “failure”) of at least one stay cable (Zoli and Steinhouse 2008). This study will therefore consider the “failure” of two or more cables due to any fire scenario to produce an unacceptably high potential for total and/or progressive collapse of the bridge. For some cases, however, it may not be possible to provide a reasonably constructible amount of fire protection to prevent more than two cables from failing. For this study, it is assumed that firefighting efforts will be able to respond to the fire within 50 minutes of its ignition – if no more than one cable fails within the first 50 minutes of the fire duration, then the mitigation scheme will be considered to have successfully resisted that fire scenario.

To determine the required extent and amount of fire protection, the two aforementioned scenarios were analysed for a suite of locations along the length of the bridge. For the initial phase of analysis, the stay cables were modelled as unprotected. The fire was placed along the length of the bridge at 7.6-meter (25-foot) increments (Fig. 2). A critical fire location is selected based on the spatial distribution of the peak heat flux on the cables and their resulting strength loss. For the scenario 1 and scenario 2, the critical location is determined to be 137 meters (450 feet) and 130 meters (425 feet), respectively, from the tower (Fig. 4). Time histories of the heat flux
experienced by the stay cable as well as the resulting temperature increase and strength decrease are shown in Figs. 6 through 8 for the most severely affected cables in each case. These plots show a different spatial distribution and intensity of fire effects between the two scenarios, emphasizing the need for parametric analysis to determine the controlling locations and scenarios for the tanker truck fire on the bridge deck. A rapid burst of temperature increase (and corresponding strength decrease) is shown for the steel strand bundles in both fire scenarios during the rapid combustion of both the outer HDPE pipe and the HDPE strand sheaths (see Figs. 1b and 1c).

A closer look at the maximum height of 50% strength loss for all cables helps determine how high the cable protection must to reach to achieve the design objective. By allowing the loss of a single cable for any fire scenario, the critical protection height is governed by the cable that has a 50% strength reduction at the second highest elevation. For scenarios 1 and 2, this location occurs at 12.2 meters (40 feet) and 14.3 meters (47 feet), respectively, above the road surface.

Figure 4 – Peak heat flux for Scenario 1 (L) and Scenario 2 (R)

Figure 5 – Resulting strength reductions for Scenario 1 (L) and Scenario 2 (R)

Subsequent suites of analyses were then performed to show the effects of a selected mitigation strategy. For these analyses, fire protection was applied to the exterior face of the outer HDPE pipe over a specified height of each cable (upward from the deck) to meet the aforementioned performance conditions. Fire resistance is based on the thicknesses of a commercially available spray-applied fire resistive material (SFRM) (Isolatek International 2015). As a simplification, the SFRM is modelled as having constant material properties (i.e. not as a function of temperature) using published values at room temperature. Note that SFRM is not an appropriate material for use on stay cables due to its high vulnerability to weathering and vibration, and other technologies such as concrete or steel encasement and intumescent paint would be realistically implemented to provide stay-cable fire protection. However, many of these technologies are proprietary, and material properties may be obtained only on a project-to-project basis. Rather, SFRM is used here to calculate a representative fire protection benchmark. SFRM thermal properties are publicly available for comparison, their performance can be easily correlated to prescriptive fire ratings, and analytical calculations for determining their fire resistance are well established (Buchanan 2002).
Fig. 9 shows the yield strength time history with fire protection applied on the second most critical cable for scenario 2. Note again that the most critical cable can be neglected because a single cable failure is acceptable. The curves in Fig. 9 show that the fire mitigation can delay the degradation of the steel strength for the critical second cable past the 50-minute mark, and meet the performance criteria set forth previously.
Comparisons with the UL 1709 Standard Fire

The UL 1709 hydrocarbon fire curve is typically used to obtain fire resistance ratings for a variety of construction products. UL 1709 has been referenced by bridge projects as the design fire load as a worst-case approximation. A major drawback in using the hydrocarbon curve is that it cannot be used to calculate the spatial distribution of fire effects nor the realistic variation in the magnitude of heat transfer to the structure. As shown in Figs. 6 thru 8, the UL 1709 curve provides a conservative time history for all cables for the scenarios examined; however, this high exposure magnitude may be overly conservative for most cases.

The major mitigation and cost savings of explicit modelling result from the ability to model the spatial effects of the fire and by limiting the height to which the mitigation needs to be applied. Mitigation and cost savings are also achieved by reducing the required SFRM thickness, as shown in Fig. 9. When the fire is explicitly modelled via the MDSF model, an SFRM thickness of 25 mm is needed to delay the failure of the second critical cable past 50 minutes, while the UL 1709 curve requires a thickness of 38 mm to achieve the same objective.

CONCLUSIONS

The authors have demonstrated the structural fire mitigation design process for a cable-stayed bridge by using a streamlined framework for calculating the effects of a tanker truck fire. Due to its efficiency, this approach was used to capture over 50 fire scenarios (2 fire footprints and 25 fire locations). Once the fire effects were enveloped and the governing design fire scenarios were identified, the spatial distribution of the fire protection as well as the thickness of fire protection were designed based on a set of performance criteria. The fire protection obtained via the streamlined framework was compared to the fire protection obtained using the UL1709 standard hydrocarbon fire curve. The results demonstrated that explicitly modeling the fire via the streamlined framework better quantifies the extent of fire effects on the cables and reduces the required fire protection thickness.

REFERENCES


