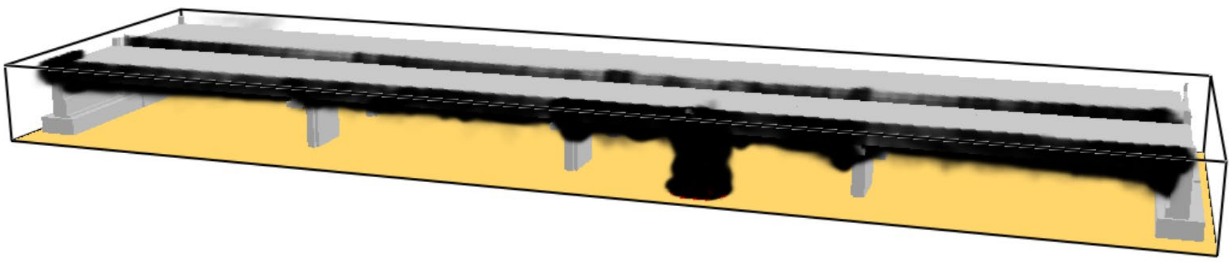
# POSSIBLE METHODOLOGY FOR PROBABILISTIC ASSESSMENT OF BRIDGE SAFETY AGAINST COLLISIONS AND FIRES



**-- Bridge Fires Report –**

**Report No. GW-02-2024**

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## EXECUTIVE SUMMARY


The overall objective of this research phase is to develop a possible stochastic methodology for quantifying the probability of bridge collapse against heavy truck collisions and the ensuing effects of fires resulting from flammable vapors with a fast-heating rate. In this work, bridge collapse implies failure to not only a single load carrying element but a drastic change in the geometry of the overall bridge that renders it unfit for future use.

In 2021, the National Bridge Inventory (NBI) had over 618,456 bridges and culverts registered in its U.S. bridge database, of which 13,963 bridges and culverts are in Virginia. Data shows that 93,000 bridges in the United States and 2,689 bridges in Virginia have one or more traffic lanes under the structure. Data for the Virginia bridges were collected and analyzed within a methodology for classifying bridges most vulnerable to heavy truck collisions and resulting structural collapses from subsequent fires. Given the on-site availability of the three specified data types, 17 bridges were selected from the commonwealth of Virginia to form a test-bed study site. Finally, stochastic models were formulated for estimating the probability of bridge collapse from subsequent fires. Research findings may interest those connected to bridge programs at the Federal, State, and local agencies.

The methodology for quantifying the probability of bridge collapse will account for the stochastic nature of the following variables:

- Individual weight and speed of heavy trucks circulating in traffic flows.
- Heavy trucks circulating in traffic flows transporting hazardous materials with flammable products.
- Frequency of heavy truck collisions at a given bridge location and its direct impact on bridge safety.
- Frequency of heavy truck collisions at a given bridge location and its direct impact on bridge safety.
- Frequency of bridge fire incidents commonly caused by crashing of vehicles and burning of flammable materials.
- Parametric impulse loading functions associated with the intensity of collisions between heavy trucks and bridge piers/girders.
- Fire curves to predict temperatures progression in bridge elements subjected to hydrocarbon fire exposure.
- Thermal gradients due to fire loading evaluated using fire dynamic simulators.
- Thermal gradients impact on structural performance of bridges
- Strain rate effects on material properties from the resulting impact loads.
- Material properties resulting from intense heat release rate (HRR).

To meet the research objective and to expand the knowledge of bridge safety against collisions with resulting fires, three main limitations remain to be addressed:

- Methodologies that jointly consider uncertainty in bridge collapse modes and traffic dynamics involving speed, vehicular type, transport of hazardous materials with flammable products, and collision distributions as a function of space, time and resulting in bridge fires.
- Bridge data in the National Bridge Inventory (NBI), such as number of pier elements, pier protection elements and condition of individual elements deterioration, along with data to model heavy truck collisions taking place under a bridge site. Collection of these data will feed into evaluation models for prediction and mitigation of collisions.
- Thermal gradient distributions on bridge elements as a function of space and time.

# ACKNOWLEDGMENTS

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**16. Abstract**


The overall objective of this research phase is to develop a possible stochastic methodology for quantifying the probability of bridge failure against heavy truck collisions which can result in fires and that can impact the safety of bridges.

In 2021, the National Bridge Inventory (NBI) had over 618,456 bridges and culverts registered in its U.S. bridge database, of which 13,963 bridges and culverts are in Virginia. Data shows that 93,000 bridges in the United States and 2,689 bridges in Virginia have one or more traffic lanes under the structure. Data for the Virginia bridges were collected and analyzed within a methodology for classifying bridges most vulnerable to heavy truck collisions and resulting structural failures from subsequent fires. Given the on-site availability of the three specified data types, 17 bridges were selected from the commonwealth of Virginia to form a test-bed study site. Finally, stochastic models were formulated for estimating the probability of bridge failure from subsequent fires. Research findings may interest those connected to bridge programs at the Federal, State, and local agencies.


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# SI* (MODERN METRIC) CONVERSION FACTORS

## APPROXIMATE CONVERSIONS TO SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| in | inches | 25.4 | millimeters | mm |
| ft | feet | 0.305 | meters | m |
| yd | yards | 0.914 | meters | m |
| mi | miles | 1.61 | kilometers | km |
| | | **AREA** | | |
| $in^2$ | square inches | 645.2 | square millimeters | $mm^2$ |
| $ft^2$ | square feet | 0.093 | square meters | $m^2$ |
| $yd^2$ | square yard | 0.836 | square meters | $m^2$ |
| ac | acres | 0.405 | hectares | ha |
| $mi^2$ | square miles | 2.59 | square kilometers | $km^2$ |
| | | **VOLUME** | | |
| fl oz | fluid ounces | 29.57 | milliliters | mL |
| gal | gallons | 3.785 | liters | L |
| $ft^3$ | cubic feet | 0.028 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.765 | cubic meters | $m^3$ |
| | | NOTE: volumes greater than 1000 L shall be shown in $m^3$ | | |
| | | **MASS** | | |
| oz | ounces | 28.35 | grams | g |
| lb | pounds | 0.454 | kilograms | kg |
| T | short tons (2000 lb) | 0.907 | megagrams (or "metric ton") | Mg (or "t") |
| | | **TEMPERATURE (exact degrees)** | | |
| °F | Fahrenheit | 5 (F-32)/9 or (F-32)/1.8 | Celsius | °C |
| | | **ILLUMINATION** | | |
| fc | foot-candles | 10.76 | lux | lx |
| fl | foot-Lamberts | 3.426 | candela/$m^2$ | cd/$m^2$ |
| | | **FORCE and PRESSURE or STRESS** | | |
| lbf | poundforce | 4.45 | newtons | N |
| lbf/$in^2$ | poundforce per square inch | 6.89 | kilopascals | kPa |

## APPROXIMATE CONVERSIONS FROM SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| mm | millimeters | 0.039 | inches | in |
| m | meters | 3.28 | feet | ft |
| m | meters | 1.09 | yards | yd |
| km | kilometers | 0.621 | miles | mi |
| | | **AREA** | | |
| $mm^2$ | square millimeters | 0.0016 | square inches | $in^2$ |
| $m^2$ | square meters | 10.764 | square feet | $ft^2$ |
| $m^2$ | square meters | 1.195 | square yards | $yd^2$ |
| ha | hectares | 2.47 | acres | ac |
| $km^2$ | square kilometers | 0.386 | square miles | $mi^2$ |
| | | **VOLUME** | | |
| mL | milliliters | 0.034 | fluid ounces | fl oz |
| L | liters | 0.264 | gallons | gal |
| $m^3$ | cubic meters | 35.314 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.307 | cubic yards | $yd^3$ |
| | | **MASS** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.202 | pounds | lb |
| Mg (or "t") | megagrams (or "metric ton") | 1.103 | short tons (2000 lb) | T |
| | | **TEMPERATURE (exact degrees)** | | |
| °C | Celsius | 1.8C+32 | Fahrenheit | °F |
| | | **ILLUMINATION** | | |
| lx | lux | 0.0929 | foot-candles | fc |
| cd/$m^2$ | candela/$m^2$ | 0.2919 | foot-Lamberts | fl |
| | | **FORCE and PRESSURE or STRESS** | | |
| N | newtons | 0.225 | poundforce | lbf |
| kPa | kilopascals | 0.145 | poundforce per square inch | lbf/$in^2$ |

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## LIST OF ABBREVIATIONS

| | |
|---|---|
| 3D | three-dimensional |
| AASHTO | American Association of State Highway and Transportation Officials |
| ASCE | American Society of Civil Engineers |
| BDS | Bridge Design Specifications |
| CFR | Code of Federal Regulations |
| CRSS | Crash Report Sampling System |
| DOT | Department of Transportation |
| EN | Eurocode |
| FARS | Fatality Analysis Reporting System |
| FDS | Fire Dynamics Simulator |
| FEM | finite element model |
| FHWA | Federal Highway Administration |
| FIRST | Fatality and Injury Reporting System Tool |
| HRR | heat release rate |
| LRFD | Load and Resistance Factor Design |
| NBI | National Bridge Inventory |
| NCHRP | National Cooperative Highways Research Program |
| NFPA | National Fire Protection Association |
| NHTSA | National Highway Traffic Safety Administration |
| NIST | National Institute of Standards and Technology |
| NSC | National Safety Council |
| NYSDOT | New York State Department of Transportation |
| RABT | Guideline for Road Tunnel Equipment and Operation (Richtlinien für die Ausstattung und den Betrieb von Straβentunneln) |
| TMRA | thermomechanical response analysis |

## LIST OF NOTATIONS

This section provides a list of notations used in this report.

| | |
|---|---|
| $\Phi_{TF}$ | truck-fire related collision involvement rate |
| $\widehat{N}_{iF}$ | number of truck-related collisions carrying flammable materials occurring on link $i$ |
| $\widetilde{N}_i$ | random variable nominal/design value |
| $\hat{V}_i$ | volume of trucks traversing link $i$ |
| $E_s$ | reinforcing steel modulus |
| $\varepsilon_{sT}$ | yield strength of steel at given temperature $T$ |
| $E_{cT}$ | concrete modulus at given temperature $T$ |
| $E_{co}$ | concrete modulus at the initial temperature of 32 °F (0 °C) |
| $E_{sT}$ | steel modulus at given temperature $T$ |
| $E_{so}$ | steel modulus at the initial temperature of 32 °F (0 °C) |
| $f'_{cT}$ | concrete compressive strength at given temperature $T$ |
| $f'_{co}$ | concrete compressive strength at the initial temperature of 32 °F (0 °C) |
| $f'_{tT}$ | concrete tensile strength at given temperature $T$ |
| $f'_{co}$ | concrete tensile strength at the initial temperature of 32 °F (0 °C) |
| $F_{yT}$ | yield strength of steel at given temperature $T$ |
| $F_{yo}$ | yield strength of steel at the initial temperature of 32 °F (0 °C) |
| $L_i$ | length of link $i$ in miles |
| $N_i$ | site-specific adjustment factor |
| $Q_{CT}$ | worst-case collision force (kip) |
| $R_{CPC}$ | critical pier component capacity |
| $T_{eff}$ | performance limit State effective period |
| $\hat{V}$ | annual truck volume traversing under the bridge |
| $W_b$ | width of bridge (feet) |
| $\hat{\lambda}$ | random variable bias factor |
| $b$ | pier width or diameter |
| $W$ | truck weight |
| $AF_{BC}$ | annual frequency of bridge collapse |
| $HVE_i$ | heavy vehicle base encroachment frequency |
| $KE$ | truck kinetic energy |
| $P(Q_{CT} > R_{CPC} \mid C)$ | probability of the worst-case collision force, $Q_{CT}$, exceeding the critical pier component capacity $R_{CPC}$ |
| $P(C \mid HVE_i)$ | probability of a collision given a heavy vehicle encroachment |
| $Pr(Q \mid C)$ | probability of bridge collapse due to a specific truck-related collision |
| $Pr(Q \mid C \mid F)$ | probability of bridge collapse due to a specific truck-related collision followed by an ensuing bridge fire. |
| $V$ | truck velocity |
| $X$ | number of truck-related collisions |
| $\lambda_F$ | expected annual number of truck-related collisions leading to fires |

# CHAPTER 1 - INTRODUCTION

## 1.1. BACKGROUND

This report presents a literature review of vehicular collisions near bridges that have resulted in fires and have impacted the safety of bridge piers or girders. Data compiled by Wardhana and Hadipriono (2003) from around the United States have shown that nearly 3.18 percent of bridge collapses have been attributed to fires. Recent research by Wright et al. (2013) showed that fires resulting from vehicular collisions are a growing concern to the safety of bridges. This results from the rapid growth in the ground transportation across the United States and an increase in the shipping of hazardous flammable materials, spontaneously combustible materials, and other dangerous materials. Wright et al. (2013) summarized the devastating impact of fires on the safety of the transportation infrastructure and the ensuing impact on the local economy due to closure of bridges. Fires resulting from hazardous materials shipped across the United States can result in very intense and explosive fires (Ahrens 2017).

This report further outlines advanced nonlinear computational tools that are often used in investigating the response of structures to fire incidents. For instance, Dai et al. (2010) investigated the response of a steel assembly and compared the experimental results against numerical simulations using the ABAQUS/Explicit solver (2020). Wright et al. (2013) also employed the ABAQUS/Explicit solver (2020) in performing the thermal analysis of bridges. In recent years, Rackauskaite et al. (2017) and Kodur et al. (2013) have used the finite element platform Ansys LS-DYNA (2022) with the explicit dynamic solver in research for structural fire analysis. More recently, researchers at the university Edinburgh in Scotland in collaboration with the University of California at Berkeley, implemented a fire beam element model in the OpenSees platform (Jiang and Usmani 2013, Jiang et al. 2015, Mazzoni et al. 2006, Usmani et al. 2012, 2023). The OpenSees platform (Mazzoni et al. 2006) was chosen for this research work as it is a powerful non-linear dynamic analysis tool, and users can simulate the disproportionate collapse of bridge systems using element removal.

Despite the consequences of fire events affecting bridge safety, current bridge design manuals do not provide appropriate fire safety requirements, and not all bridges are designed with specific fire mitigation strategies (De Silva et al. 2023). For example, the AASHTO LRFD Bridge Design Specifications (BDS), 8th Edition[1] does not explicitly address fire hazards in its bridge design load combinations or design criteria (AASHTO LRFD, 2017). Similarly, the Eurocode 1[2] Part 1-2 (CEN 2002) provisions focus mainly on buildings and does not address bridge fires. Only the National Fire Protection Association (NFPA) Report 502[3] (NFPA, 2017) provides guidelines for assessing fire hazards in bridges. However, a review of these general guidelines by Kodur and Naser (2021) reported they are mainly qualitative and are only applicable to tunnels and bridges with spans greater than 984 ft (300 m). Literature review outlined in this report

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[1] AASHTO LRFD Bridge Design Specifications, 8th Edition (2017) is incorporated by reference at 23 CFR 625.4(d)(1)(v).

[2] Use of Eurocode 1: Actions on structures is not a Federal requirement.

[3] Use of NFPA 502, *Standard for Road Tunnels, Bridges, and Other Limited Access Highways*, is not a Federal requirement.

presents information on recent bridge fire incidents and research related to post-fire assessment and feasible bridge repairs.

To develop the stochastic models, the following parameters need further evaluation:

- Modeling methodologies that can jointly consider uncertainty in structural collapse modes, traffic dynamics involving speed and vehicular type, transport of hazardous materials with flammable products, and collision distributions as a function of space and time.

- Comprehensive bridge data including number of pier elements, pier protection elements and condition of individual elements deterioration. Other relevant data to this project are heavy truck collision data near a bridge site. Combination of these data types will feed into predictive models for prediction and mitigation of collisions.

- Design charts that can be used in estimating thermal gradient distributions on bridge structural elements as a function of space and time.

## 1.2. RESEARCH OBJECTIVES

The overall objective of this research phase is to develop a possible stochastic methodology for quantifying a probabilistic bridge collapse due to fires resulting from heavy truck collisions. This will include the need to further evaluate the stochastic nature of vehicular collisions resulting in fires and its ensuing impact on the safety of bridges. Although extensive research was conducted for investigating the dynamic interaction that takes place when heavy trucks collide with bridge elements there still is the need to account for the stochastic nature of the following variables:

- Individual weight and speed of heavy trucks circulating in traffic flows.

- Frequency of heavy trucks transporting hazardous materials with flammable products.

- Frequency of heavy truck collisions at a given bridge location and its direct impact on bridge safety.

- Frequency of bridge fire incidents commonly caused by crashing of vehicles and burning of flammable materials.

- Parametric impulse loading functions associated with the intensity of collisions between heavy trucks and bridge piers/girders.

- Fire curves to predict temperatures progression in bridge elements subjected to hydrocarbon fire exposure.

- Thermal gradients due to fire loading evaluated using fire dynamic simulations.

- Thermal gradients impact on structural performance of bridges

- Strain rate effects on material properties from the resulting impact loads.

- Material properties resulting from intense heat release rate (HRR).

The work presented in this interim report leverages knowledge from both the transportation engineering and structural engineering domains, and the dynamics of fire forming events. This knowledge includes the stochastic nature of truck weight and speed distributions, the expected frequency of truck-related collisions, and the relation between bridge fire location and heat flux. To evaluate the stochastic nature of these variables, traffic detector data, collision data, and data presented in the literature was obtained to estimate the probability of bridge fires. Traffic and collision data were used jointly to develop Poisson-based probability functions for evaluating the probability of bridge collapse resulting from the combined effects of bridge collisions and fires. The proposed methodology can be used in calculating the probability of collapse due to bridge fires over a specified time period. The established Poisson-based probability functions will support estimating the likelihood of collapse using stochastic models and simulations to assess the vulnerability and mitigation of bridge elements and systems subjected to the impact of heavy vehicles and the resulting safety on the bridge from fires.

The stochastic methodology will help identify strategic solutions for prioritizing the replacement or significant rehabilitation of higher risk bridges from vehicular collisions and bridge fires and potentially increase the safety of bridges according to the following target objectives:

- Estimate the likelihood of a collision involving flammable fuel or cargo that detonates or combusts and then results in a fire event with high consequences.

- Develop a stochastic methodology for quantifying the probability of collapse of bridges subjected to heavy truck collisions as a means for assessing the vulnerability of bridges using analytical and/or experimental methods.

- Estimate thermal gradient distributions on bridge structures as a function of space and time.

# CHAPTER 2 - LITERATURE REVIEW

## 2.1. FIRES RESULTING FROM VEHICLE COLLISIONS ON BRIDGE ELEMENTS

Wright et al. (2013) conducted a review of the New York State Department of Transportation (NYSDOT) data collected from 1960 to 2013. This database documents a total of 1,746 bridge collapses in the United States, of which 50 bridge collapses were due to fire. As shown in Table 2-1, these 50 bridge fires were a result of consequences such as natural fires, arson, and vehicular collisions. Only 5 bridge fires (10 percent) were due to vehicular collisions, which indicates that 0.29 percent of this set of bridge collapses was due to fires resulting from heavy truck collisions.

**Table 2-1. NYSDOT database cause of fire incidents**

| Fire Cause | Count | Percentage |
|---|---|---|
| Unknown | 38 | 76 |
| Arson | 4 | 8 |
| Collisions | 5 | 10 |
| Explosions | 2 | 4 |
| Natural | 1 | 2 |

Data source: Wright et al. (2013).

Incidents involving heavy trucks carrying dangerous materials and colliding with bridge elements are low-probability incidents. However, due to their devastating nature they are also high-consequence incidents, which can paralyze the transportation infrastructure for long periods. This is because on average it is more difficult to detour traffic around bridges that have been affected by fires (Garlock et al. 2012). Despite the impact of bridge fires on the transportation infrastructure, bridge design codes and standards have not yet introduced design guidelines or assessment measures for bridge safety when exposed to fires following collisions. An increase in fire incidents expose the safety of bridges and renews the call for introducing fire design provisions for bridges (Garlock et al. 2012).

## 2.2. PROBABILISTIC RISK OF BRIDGE FIRES

Naser and Kodur (2015) have developed a method for classification of bridges based on fire hazard. One of the main conclusions from their research was that fire incidents in bridges are random events that follow a stochastic approach. Naser and Kodur (2015) have supported their findings based on a survey conducted by the NYSDOT over a 15-year period (1990-2005). Furthermore, data compiled by Wardhana and Hadipriono (2003) from around the United Sates have shown that around 3.18 percent of all bridge collapses have been attributed to fires.

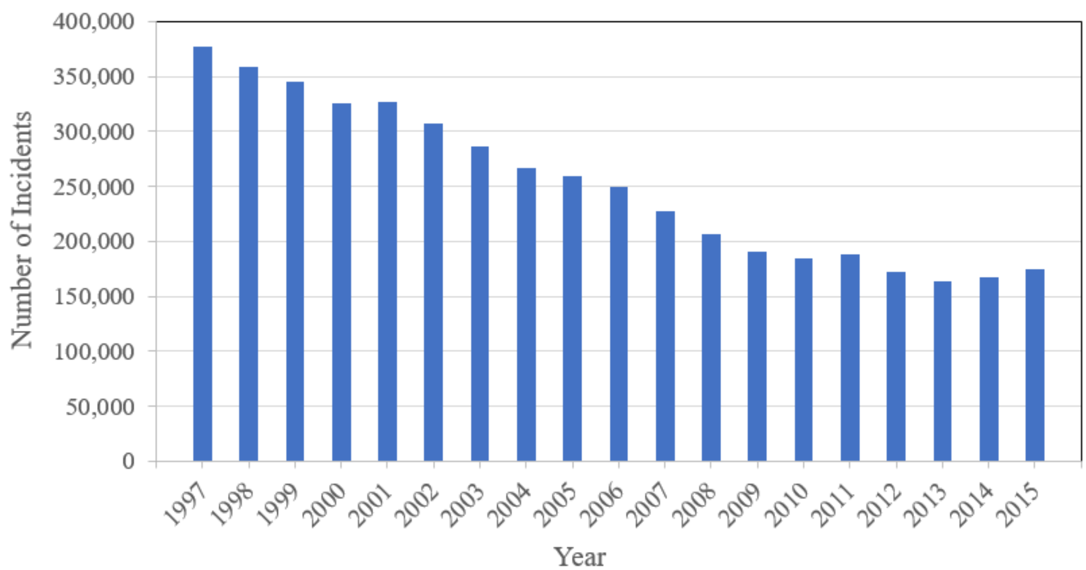
Figure 2-1 depicts the total number of highway vehicle fires by year as reported in Table 2 of the NFPA "U.S. Vehicle Fire Trends and Patterns" report in 2020 (NFPA 2020). These incidents include all fire types and not necessarily those resulting from collision of tanker trucks. Naser and Kodur (2015) conducted a further review of the NFPA vehicle fire supporting tables (NFPA 2013), and concluded that in 2011, 195,600 vehicle fire incidents occurred on all U.S. roadways and approximately 90,000 of these fire incidents occurred on highways (53,700), commercial roads (13,800), and streets (22,500). The remaining 105,600 fire incidents occurred along rural and residential driveways. As stated by Naser and Kodur (2015) these remaining vehicle fires do not impact the safety of bridges against fire hazards. Naser and Kodur (2015) calculated the fire intensity ratio on U.S. roadways as the ratio of 90,000 by 195,600 resulting in a fire intensity of $\lambda_F$=0.46 per year, which can also be expressed as the Poisson distribution mean. This further translates in a Poisson distribution for all fire incidents on U.S. roadways as:

$$P = 1 - e^{-0.46T} \qquad \textbf{(2-1)}$$

In the above equation *T* is the number of years. Naser and Kodur (2015) recognized that this distribution will relate to all fire incidents and not necessarily those that may involve bridge structures. In their work, they assumed that 5 percent of total fire incidents are assumed to occur on/underneath bridges (Naser and Kodur 2015). This further translates in a Poisson distribution for all fire incidents on/underneath bridges as:

$$P = 1 - e^{-0.023T} \qquad \textbf{(2-2)}$$

Within a one-year period this translates in a 2.3 percent probability of a fire breaking out on or underneath a bridge. This estimated probability of a fire breaking out on/underneath a bridge may not reflect how fires are a main cause leading to significant structural damage. Furthermore, the 2.3 percent probability of a fire breaking on a bridge is not necessarily related to heavy truck collisions that is likely to compromise the structural integrity of bridges.



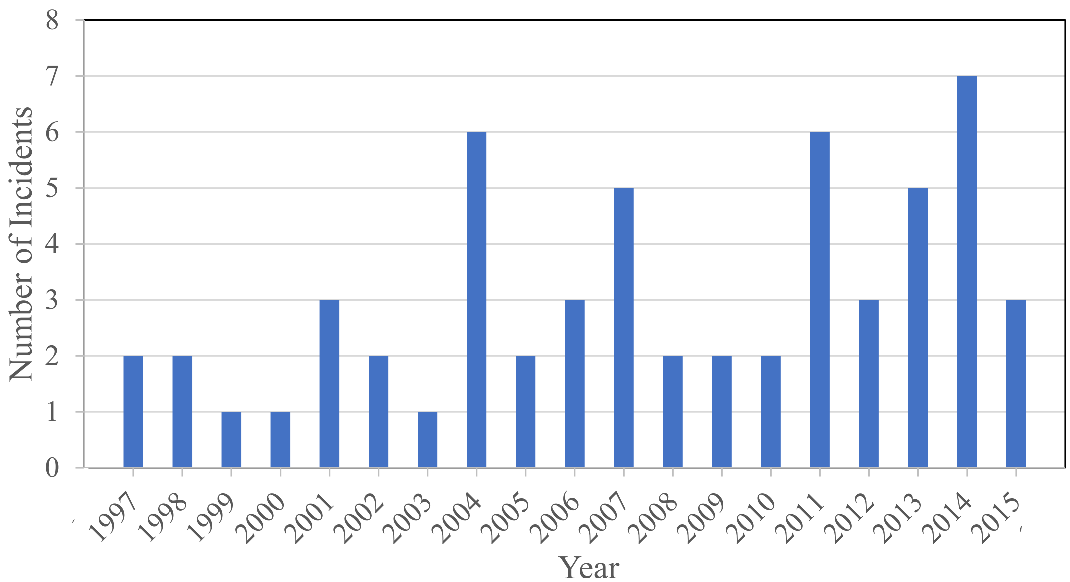

Data source: National Fire Protection Association (NFPA 2020).

**Figure 2-1. Chart. Number of highway vehicle fires by year.**

To address the impact of heavy truck collisions and the resulting fires on the structural integrity of bridges, Garlock et al. (2012) published collected and available information on 11 bridge collapses from fires. Peris-Sayol et al. (2017) expanded the dataset to include a total of 154 bridge collapses from fires. Of the 11 bridge fires investigated by Garlock et al. (2012), 10 occurred in the United States and one occurred in Germany. Data from the 154 bridge collapses reported by Peris-Sayol (2017) were collected only across the United States from bridge management authorities, literature review, and information published in the news. Of these 154 bridge collapses due to fire, 58 fire events involved tanker trucks. Figure 2-2 presents the data published by Peris-Sayol et al. (2017) and shows the distribution of fire incidents per year resulting from tanker trucks averaged three incidents per year. In Figure 2-1 the total number of highway vehicle fires in 2014 was 167,500. In 2014, Figure 2-2 shows that the total number of fires resulting from tanker trucks is 7. This results in a fire intensity of $\lambda_F$ = 4.18×10$^{-5}$, and the Poisson distribution for fire incidents on bridges resulting from tanker trucks is:

$$P = 1 - e^{-(4.18\times10^{-5})\,T} \quad \textbf{(2-3)}$$

Within a one-year period this translates in a 0.00418 percent probability of a fire breaking out on bridges resulting from tanker trucks. NFPA 551[4] (2017) categorizes a risk having a probability between 0.1 percent and 10 percent to be considered a probable risk. Probable risks are those which can occur several times during a life span of a system (50–75 years for highway bridges). This results in the probability that a tanker truck fire will occur during a 75-year period of 0.31 percent, which is a probable risk according to NFPA 551.




Data source: Peris-Sayol et al. (2017)

**Figure 2-2. Chart. Number of fire incidents involving tanker trucks per year.**

## 2.3. FIRE CURVES

Fire curves are used in assessing fire effects on structures and are formulated as a function of temperature rise versus time. Figure 2-3 shows a variety of fire curves that are relevant in assessing the impact of fire in structural applications and have been used by the engineering community worldwide. Researchers such as Kodur et al. (2010), Garlock et al. (2012), Wright et al. (2013), and De Silva et al. (2023) highlighted many bridge collapses due to fire incidents and derived fire design curves useful for assessing fire effects on bridges. The RABT-ZTV curves were developed from a series of test programs such as the EUREKA-499 FIRETUN project in

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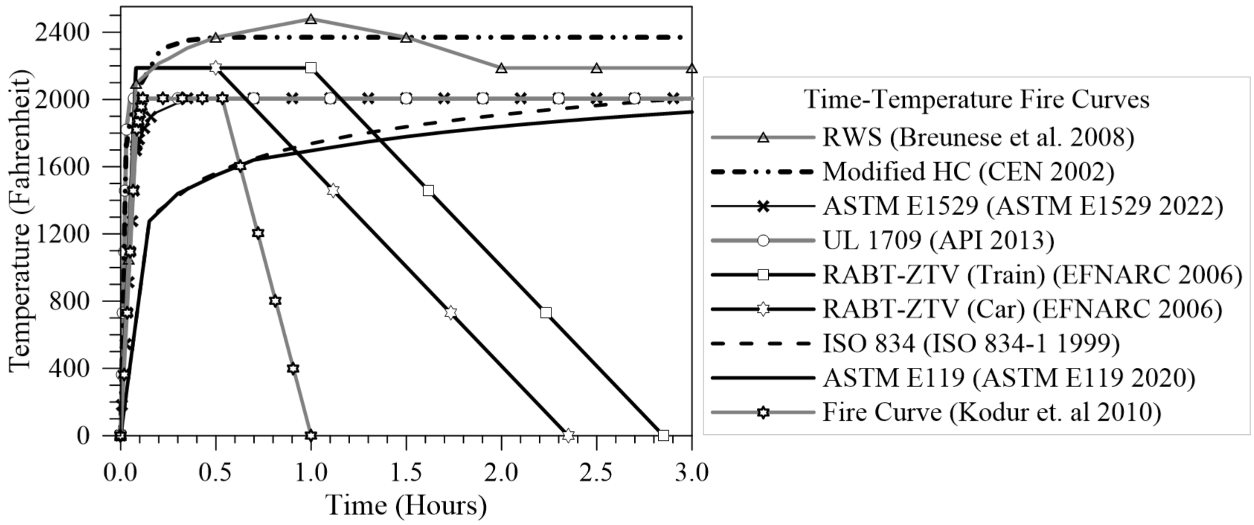
[4] Use of NFPA 551, *Guide for the Evaluation of Fire Risk Assessments*, is not a Federal requirement.

Germany. According to these two types of fire design curves, the peak temperature of 1200 °C is reached within 5 minutes (EFNARC 2006, Stahlanwendung 1995).




Data source: Wright et al. (2013).

**Figure 2-3. Graph. Standard time-temperature fire curves from flammable vapors.**

This report focuses mainly on bridge collapse from fires resulting from collisions of trucks carrying hazardous flammable materials, spontaneously combustible materials, and other dangerous materials. After a collision, combustible materials may spill and begin to vaporize, leading in potential ignition of the flammable vapor. It was noted previously that current bridge design manuals do not explicitly address fire hazards in its bridge design load combinations or design criteria. The NFPA Report 502[3] (NFPA, 2017) fire design curves identified as applicable for assessing fire hazards for bridges were developed for tunnels. Tunnels have different oxygen and ventilation conditions than bridges. Therefore, the NFPA fire curves may not directly apply to a bridge fire assessment.

As shown in Figure 2-3, fires resulting from flammable vapors have a fast-heating rate within the first few minutes after ignition. Since bridges are wide open structures, bridge fires can reach high temperatures quickly because of plentiful oxygen available to the fire. Some fire curves indicate bridge fires can reach temperatures over 1,800 °F (1,000 °C) within 4 to 5 minutes of ignition. In other fire incidents, the maximum temperature will be reached after 1 to 2 hours. Differences observed in the heating rate and peak temperature are directly related to the quantity of fuel and ventilation characteristics. Each of the fire curve models depicted in Figure 2-3 were developed using a wide range of two variables: quantity of fuel and ventilation. In Figure 2-3, the RWS (Rijkswaterstaat) fire curve is the most severe and is widely used around the world in fire tests developed for tunnel fire protection systems (Breunese et al. 2008).

Except for the two RABT-ZTV fire curves (EFNARC 2006, Stahlanwendung 1995), all other models show the temperature does not decrease within the fire duration. This might not resemble realistic bridge fires because the fuel will burn-out after a certain time duration. Kodur et al. (2010) proposed a design fire curve, which as shown in Figure 2-3 depicts a well-defined decay phase reaching nearly 0 °F after 1 hour. The fire curves depicted in Figure 2-3 will help provide a stochastic evaluation of bridges sub-system and systems following a truck collision and resulting fire events.

## 2.4. ANALYSIS OF BRIDGE STRUCTURES TO FIRE INCIDENTS

Advanced nonlinear computational tools are used to investigate the response of structures to fire incidents. In bridges, detailed investigation of key elements is essential for improving the computational accuracy when assessing a fire incident following a heavy truck collision. Two prominent finite element platforms have been successfully used by many researchers in evaluating the response of structural members to fire incidents. For instance, Dai et al. (2010) investigated the response of a restrained steel assembly in the form of a rugby-goalpost setup and compared the experimental results against numerical simulations using the ABAQUS/Explicit solver (2020). Wright et al. (2013) also employed the ABAQUS/Explicit solver (2020) in performing the thermal analysis of bridges. In their setup, one steel W-section beam and two identical steel W-section columns with identical bolted joints were investigated at both ambient and elevated temperatures. In recent years, Rackauskaite et al. (2017) and Kodur et al. (2013) have used the finite element platform Ansys LS-DYNA (2022) with the explicit dynamic solver in research for structural fire analysis. Other software packages have been developed which can be used to assess the response of bridges to fire incidents, but these have been the most prominently used in fire analysis. No research work has been published that addresses the multi-hazard resistance of bridges against the combined effects of collisions and fires.

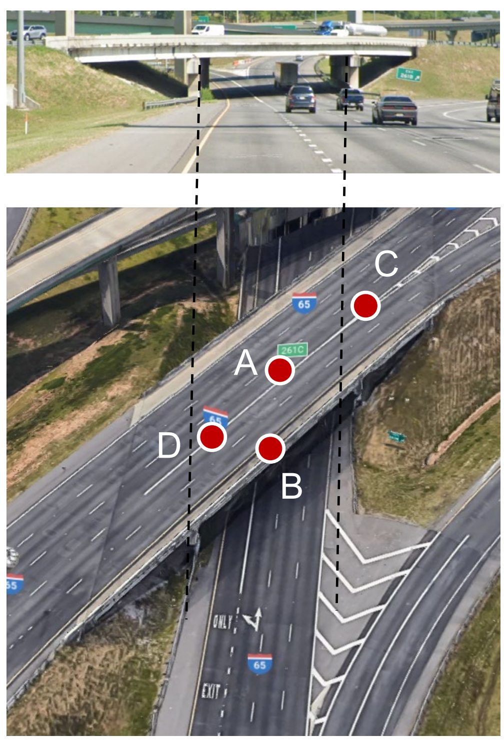
Most recently, Usmani et al. (2012, 2023) added a *Structures in Fire* module for fire modelling capability in OpenSees (Mazzoni et al. 2006). In this software platform (Usmani et al. 2023) material time-dependent temperature distributions are modelled across frame elements cross-section fibers to include temperature dependent properties. In this research, assessment of bridges following a truck collision with or without the effects of an ensuing fire are evaluated using this software platform. In thermomechanical hybrid simulations (TMHS) (Whyte et al. 2016), thermal gradients are obtained from computational fluid dynamics models which evaluate the propagation of thermal fields from the heat source to structural elements. The thermal gradient in bridge elements is developed prior to using this module.

### 2.4.1. Thermal Gradients in Bridge Structural Elements

Thermal gradients in fire analysis of bridges are considered in three-dimensional (3D) finite element simulations as input non-uniform temperature distributions. Thermal gradients are typically estimated from fire dynamic simulations. Temperature distribution result in internal stresses and distortion of structural elements, which subsequently impact the global structural behavior of bridges (Usmani et al. 2023). Thermal gradients may develop within the cross section of members, and along the longitudinal and transverse direction of bridges. Thermal gradients should also be considered in the structural assessment of bridges under fires following a collision event. Wright et al. (2013) proposed that a 3D finite element model (FEM) is needed to understand the bridge response under fires, which may lead in disproportionate collapse. Thermal gradients are established using computational fluid dynamics codes. Fire Dynamics Simulator (FDS) is a computational tool that is often used in developing thermal gradients. FDS was developed by the National Institute of Standards and Technology (NIST) in cooperation with VTT Technical Research Centre of Finland. FDS is a free software for predicting the fire parameters such as: flame height, gas temperatures, and heat flux exposure onto structural members. In this research, for fires resulting from a heavy truck collision, only 3D FEM analysis is considered in the analysis of bridge fires due to the disproportionate damage.

FDS is a computational framework which provides data in a format that is easily transferred to the thermomechanical response analysis (TMRA) in OpenSees. In this research, boundary thermal gradients from FDS are thus imported into OpenSees. For instance, Wright et al. (2013) evaluated the collapse of the I-65 Bridge in Birmingham, Alabama, under a selection of fourteen fire simulations. This bridge consists of three spans, and each of the piers is comprised of 5 circular reinforced columns and a concrete deck placed over seven longitudinal steel girders. In the I-65 Bridge fire, the fuel tanker truck swerved to avoid merging traffic and subsequently collided with one of the five pier columns. After the impact, 9,900 gallons of diesel fuel leaked from the tanker and the fire lasted approximately 45 minutes. In the central span, three of the girders immediately over the flame were exposed to extreme heat. After the fire dwindled, deflections were observed in the bridge deck, resulting in the collapse of the structure.

Wright et al. (2013) performed fourteen fire dynamic simulations to investigate thermal gradients in the bridge composite deck and girder. As outlined in Wright et al. (2013), these fourteen fire simulations consisted of placing the heat source in four different locations, two different beam materials, and four vehicle types resulting in four different heat release rates. The four different fire locations are outlined in Figure 2-4.

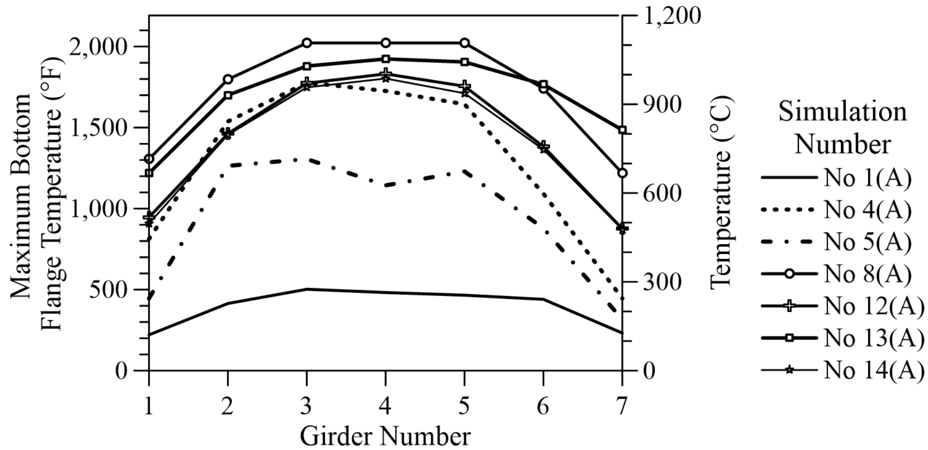



Note: Photo shows FDS fire simulations locations A, B, C, and D that were performed by Wright et al. (2013) for the I-65 bridge fire in Birmingham, Alabama.

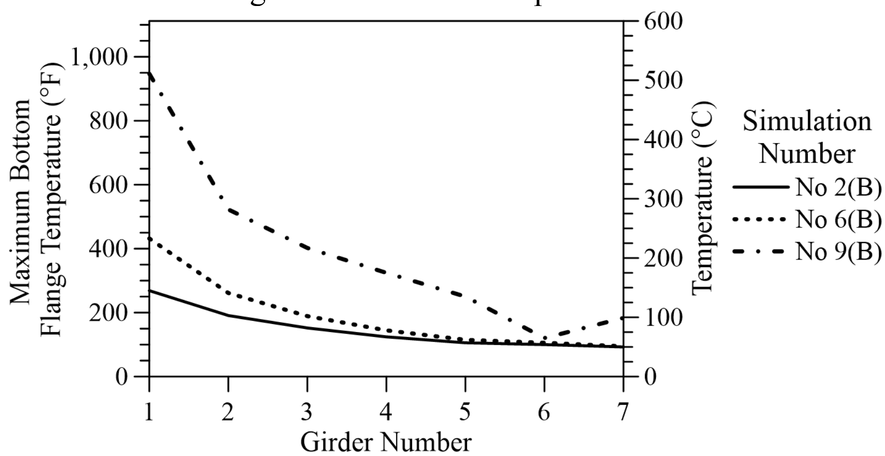
Original Photo: © 2023 Google® (see Acknowledgements section)

**Figure 2-4. Photo. I-65 Bridge fire simulations and locations.**

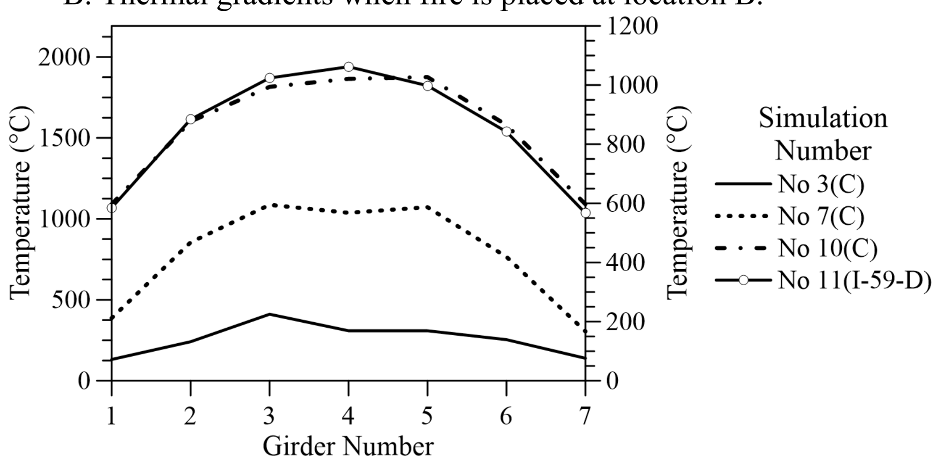
Figure 2-5 shows a sample of thermal gradients from the fourteen simulations carried out in the research by Wright et al. (2013) at locations shown in Figure 2-4. Location A is at the center of the second span below Girder 4, the center girder. Location B is at the center of the second span below Girder 1, the edge girder. Location C is next to the abutment below Girder 4.




A. Thermal gradients when fire is placed at location A.




B. Thermal gradients when fire is placed at location B.




C. Thermal gradients when fire is placed at location C.

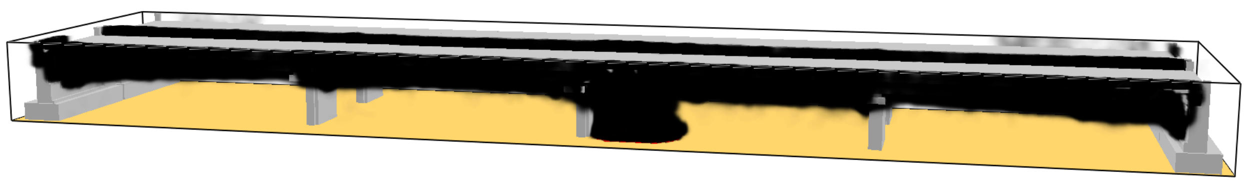
Source: FHWA

Data source: Wright et al. (2013)

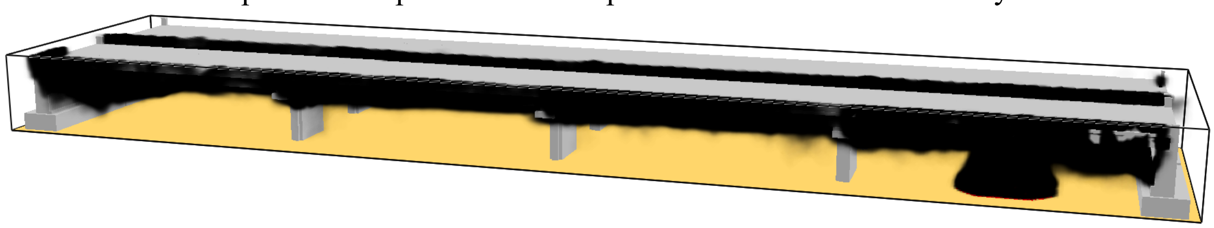
**Figure 2-5. Graph. Thermal gradients across the girders bottom flange.**

The simulation depicted as *No 11(I-59 D)* in Figure 2-5C, corresponds to a fire placed closest to the actual location of the fire event in the I-65 Bridge in Birmingham, Alabama. One of the main conclusions from the study by Wright et al. (2013) is that when the fire is below Girder 4 the maximum temperature achieved in the girders is nearly double as to when the fire is placed near the edges of the bridge, which corresponds to location B in Figure 2-4. Also, the heat gradients and profiles depicted in Figure 2-5 are directly related to the location of the heat source.

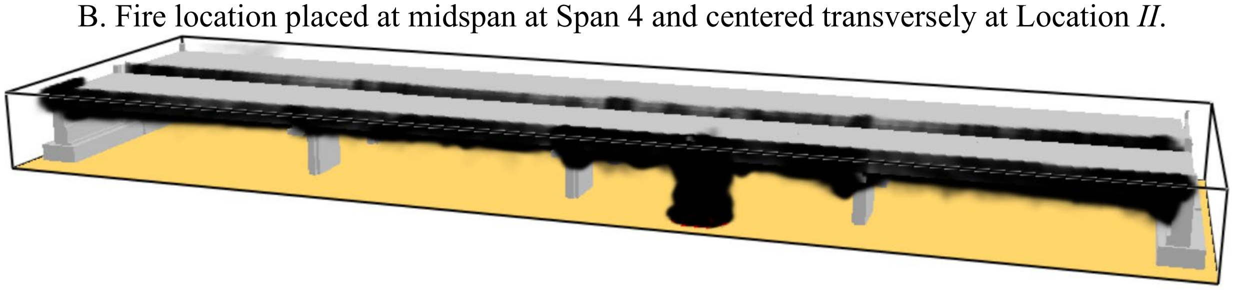
To corroborate the results from Wright et al. (2013) a parallel study was conducted in this research on the bridge prototype depicted in Figure 2-6. Fire dynamic simulations were performed according to the listed three fire locations I, II, and III. Figure 2-7 shows thermal gradients from these three simulations and as function of time. Similar to the results by Wright et al. (2013), when the fire source is placed at the center of the bridge transversely the maximum temperature achieved in the girders is nearly double to the fire simulation placed near the edges of the bridge. Furthermore, the heat gradients and profiles depicted in Figure 2-7 follow similar thermal gradients trends as those depicted in Figure 2-5.



A. Fire location placed near pier column at Span 3 and centered transversely at Location *I*.



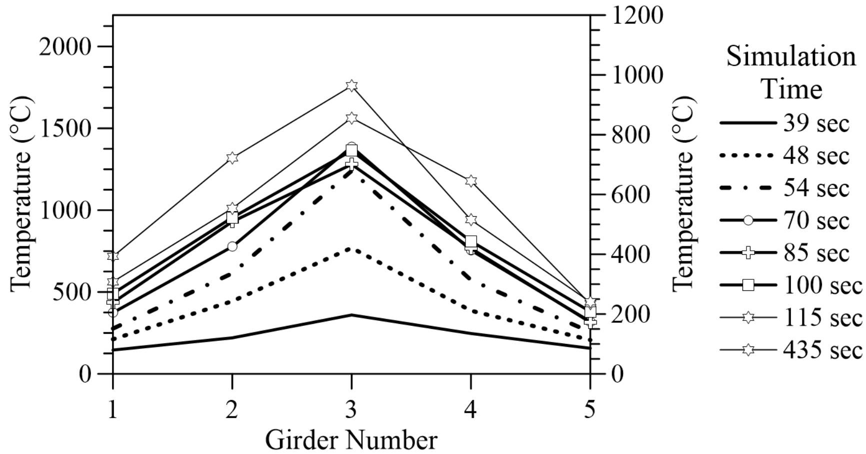
B. Fire location placed at midspan at Span 4 and centered transversely at Location *II*.



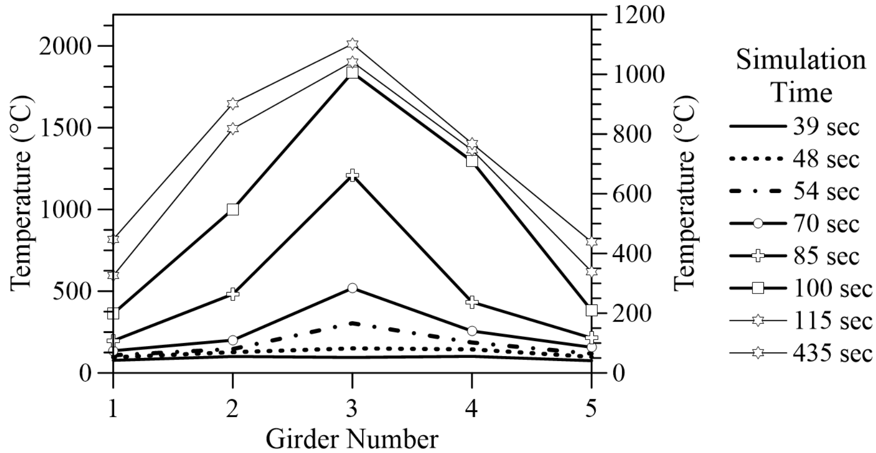
C. Fire location placed at midspan in span 3 and below Girder 1 at Location *III*.

Source: FHWA

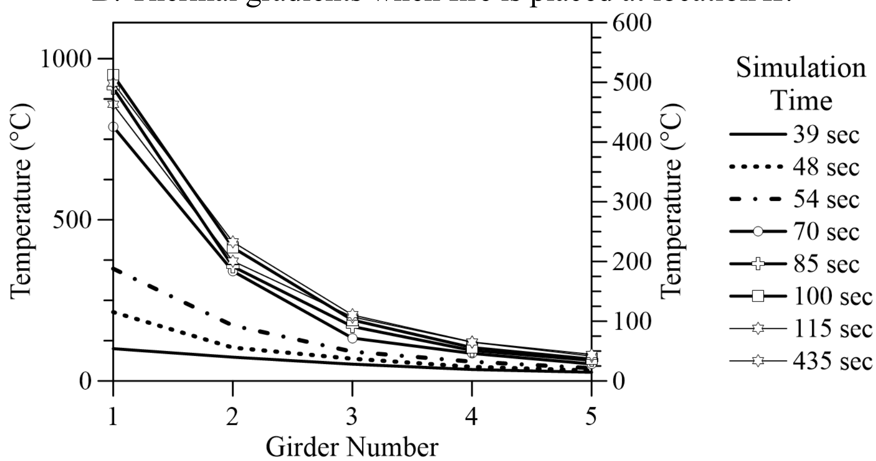
**Figure 2-6. Illustration. Prototype bridge fire locations for fire dynamic simulations.**




A. Thermal gradients when fire is placed at location *I*.




B. Thermal gradients when fire is placed at location *II*.




C. Thermal gradients when fire is placed at location *III*.

Source: FHWA

Data source: Wright et al. (2013)

**Figure 2-7. Graphs. Thermal gradients across the girders bottom flange.**

### 2.4.2. Thermal Properties of Materials

#### *2.4.2.1. Structural Steel Thermal Properties*

Research published in the literature indicate that while material properties of reinforcing steel bars differ from hot-rolled sections, high temperature properties in these two materials are nearly similar. Provisions published in the ASCE[5] (ASCE 1992) and the Eurocode[6] (CEN 2002) have deemed acceptable for all structural steel applications (Wright et al. 2013) and are reviewed in this section. Kodur et al. (2013) and Poh (2001) reports on tests to measure the strength properties of structural steel in two forms, namely: transient-state and steady-state tests. In transient-state tests, the test specimen is subjected to a constant load and then exposed to uniformly increasing temperature, similar to a fire event. Steady-state tests are not relevant to this study because the test specimens are only subjected to a steady temperature. As reported in the research by Twilt (1991) and Anderberg (1988), transient-state tests under slow heating rates were mainly used in characterizing the material properties formulations present in the Eurocode[6] (CEN 2002). Less information is provided in quantifying the types of tests that were used in deriving the ASCE[5] (ASCE 1992) material properties formulations. The mathematical formulations implemented in the OpenSees *Structures in Fire* software platform (Usmani et al. 2023) are solely based on the Eurocode[6] (CEN 2002).

Variations in the yield strength and elastic modulus of structural steel under uniformly increasing temperature and tension loads are reported in Figure 2-8. The ASCE[5] (ASCE 1992) and the Eurocode[2] (CEN 2002) indicate that both the yield strength and elastic modulus decrease as temperature increases. Previous research has shown that this decrease results from an increase of the bond length in iron atoms due to rising temperatures. Research by Dever (1972) as shown a temperature dependence on the elastic constants of single-crystal iron and has been measured from 25 °C to 900 °C. As the bond length increase there is a resulting decrease in the bond strength as thus a reduction the yield strength and elastic modulus of iron-carbon materials.

The test data plotted in Figure 2-8 was compiled by Kodur et al. (2013). The test data are compiled from various high-temperature property tests published in the literature (Outinen and Mäkeläinen 2004, Outinen et. al. 1997, Mäkeläinen et. al. 1998, Li et. al. 2003, Chen et. al. 2006, Clark 1953, and Cooke 1988). In Figure 2-8A, variations in the yield strength according to the ASCE (ASCE 1992) and the Eurocode (CEN 2005b) plots fit reasonably well with the published data. In Figure 2-8B variations in the elastic modulus according to the ASCE[5] (ASCE 1992) and the Eurocode[6] (CEN 2002) plots have a wider scatter of values against the published test data, and this scatter is more pronounced when the temperature increases beyond 800 °F (425 °C).

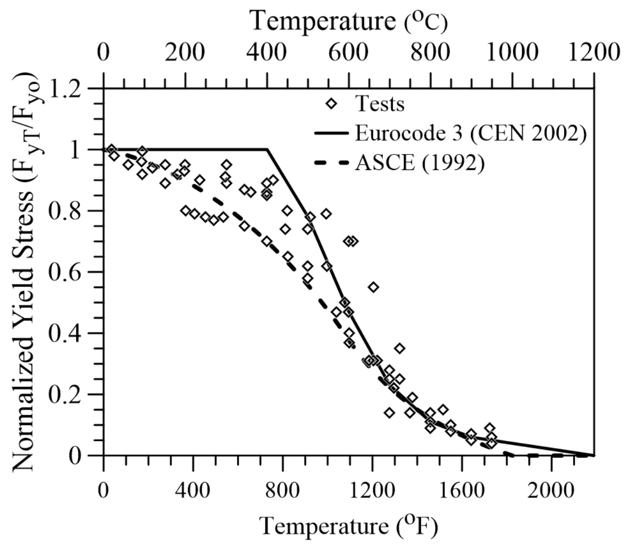
Graphs in Figure 2-9 depict the temperature-stress-strain curves from ASCE[5] (ASCE 1992) and the Eurocode[6] (CEN 2002). These graphs were developed for temperature of 68 °F (20 °C), 392 °F (200 °C), and 1112 °F (600 °C). As shown in the figures, both the stress and strain were

---

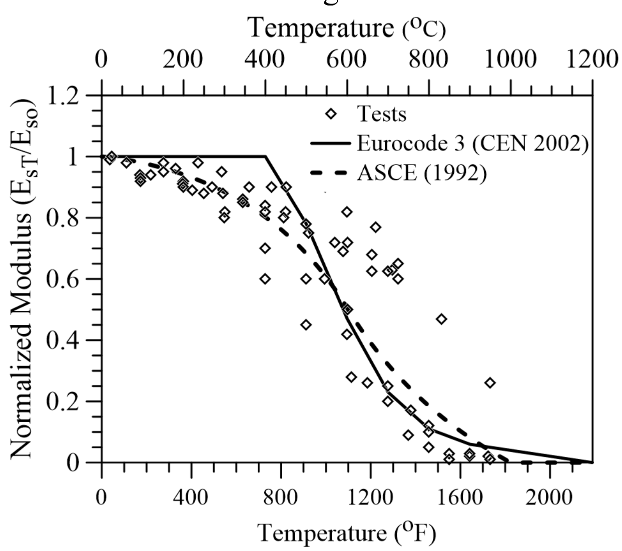
[5] Use of ASCE Manuals and Reports on Engineering Practice No. 78, *Structural Fire Protection*, is not a Federal requirement.

[6] Use of Eurocode 3: Design of steel structures is not a Federal requirement.

normalized according to the yield stress derived at a given temperature *T* (i.e. $F_{y,T}$) and the yield stress derived at the initial temperature of 32 °F (0 °C) (i.e. $F_{y,o}$).



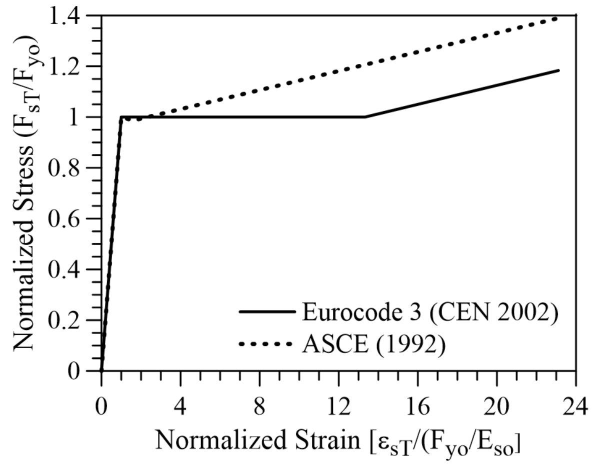

A. Yield strength of steel.



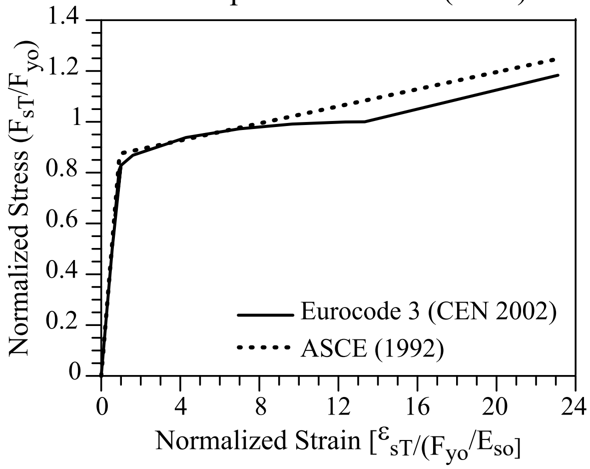

B. Elastic modulus of steel.

Source: FHWA

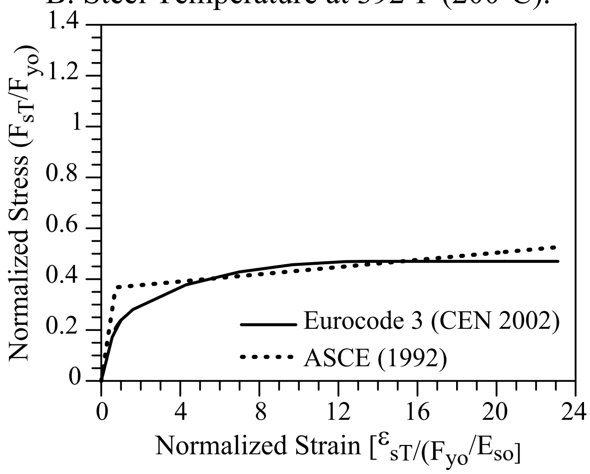
**Figure 2-8. Graphs. Temperature dependent material properties of steel.**




A. Steel Temperature at 68ºF (20ºC).




B. Steel Temperature at 392ºF (200ºC).



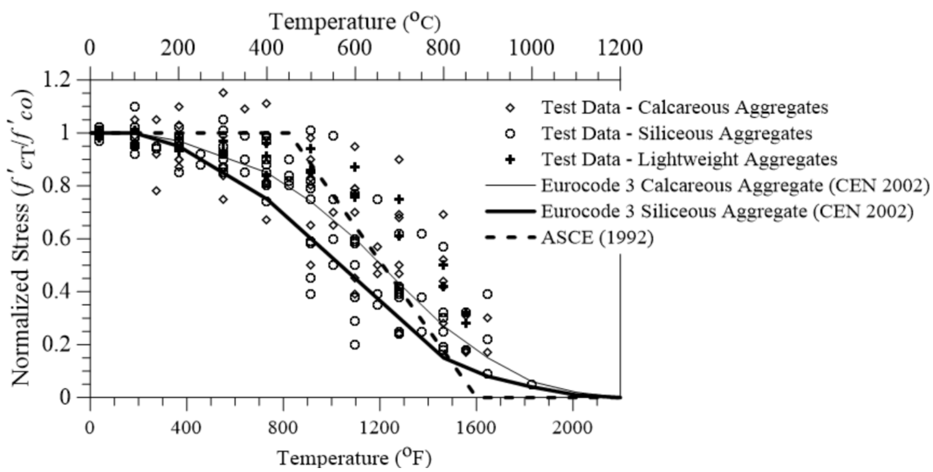

C. Steel Temperature at 1,112ºF (600ºC).

Source: FHWA

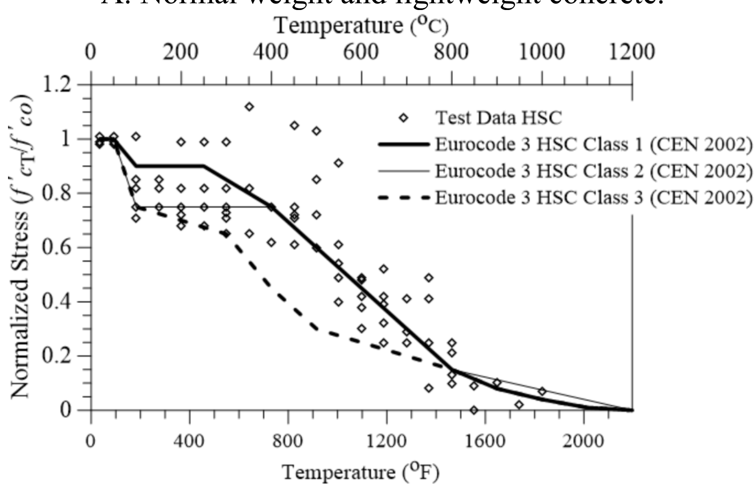
**Figure 2-9. Graphs. Temperature-stress-strain relationships for structural steel.**

### *2.4.2.2. Concrete Thermal Properties*

Mechanical properties of concrete change significantly as a function of temperature. As shown in Figure 2-10 the mechanical properties of concrete vary as a function of temperature and depend on the composition and characteristics of the aggregates. Figure 2-10A depicts the Eurocode[6] (2005) formulation for normalized concrete compressive strength for normal weight calcareous, and siliceous aggregates, and lightweight aggregates. The test data plotted in Figure 2-10 was compiled by Kodur et al. (2008) from various high-temperature property tests published in the literature. The figure shows that ASCE[5] (1992) does not distinguish between these three sets of normal weight and lightweight aggregates.




A. Normal weight and lightweight concrete.

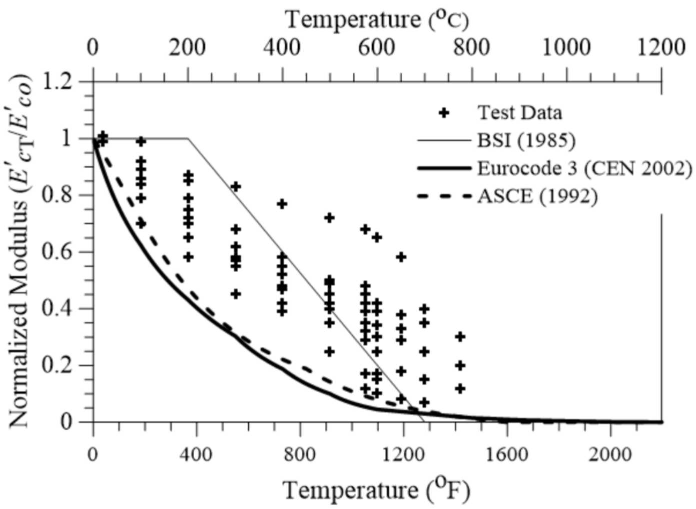



B. High strength concrete (HSC).

Source: FHWA

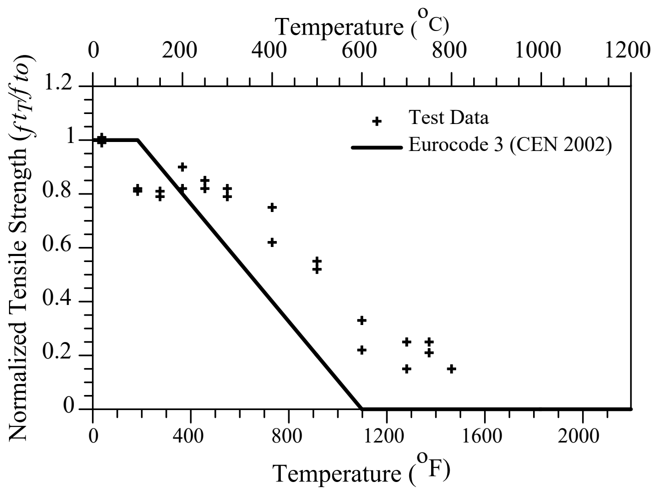
**Figure 2-10. Graphs. Temperature dependent concrete compressive strength.**

Figure 2-10B depicts the Eurocode[6] (2002) formulation for normalized concrete compressive strength for Class 1, 2 and 3 high strength concrete (HSC). ASCE[5] (1992) does not provide a formulation for HSC under elevated temperatures. As necessary this research will consider the ASCE[5] (1992) plot in Figure 2-10A to calculate the normalized concrete compressive strength under elevated temperatures. As shown in the figure, the concrete compressive strength derived at a given temperature T (i.e. $f'_{cT}$) was normalized by the concrete compressive strength at the initial temperature of 32 °F (0 °C) (i.e. $f'_{co}$).




Source: FHWA

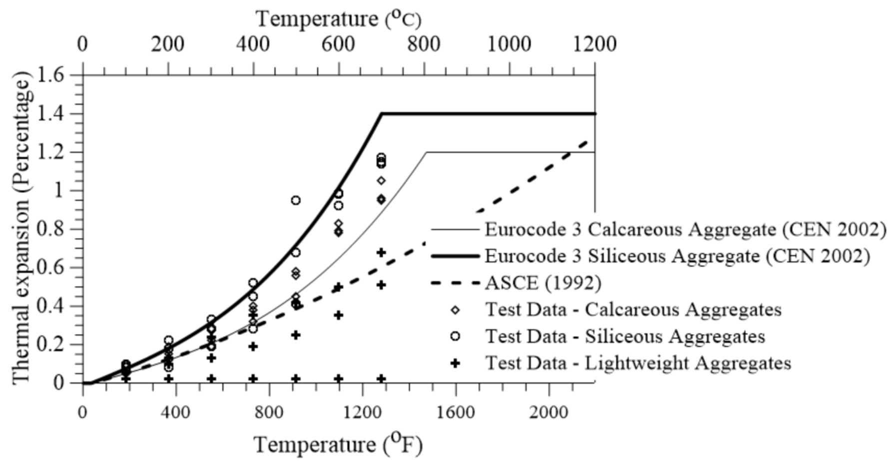
**Figure 2-11. Graph. Temperature dependent concrete elastic modulus.**




Source: FHWA

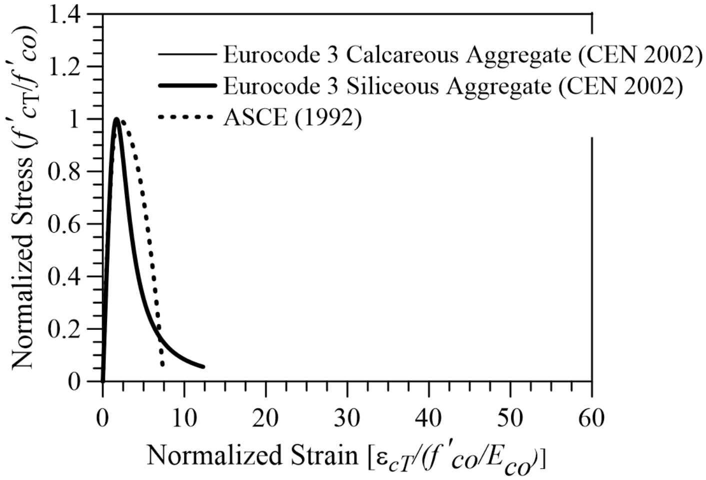
**Figure 2-12. Graph. Temperature dependent concrete tensile strength.**

Graphs in Figure 2-14 depict the temperature-stress-strain curves from ASCE[5] (ASCE 1992) and the Eurocode[6] (CEN 2002). As before, these graphs were developed for temperature of 68°F (20 °C), 392 °F (200 °C), and 1112 °F (600 °C). As shown in the figures, both the stress and strain were normalized according to the concrete compressive strength derived at a given temperature T (i.e. $f'_{cT}$) and the concrete compressive strength derived at the initial temperature of 32 °F (0 °C) (i.e. $f'_{co}$). Plots in Figure 2-14 depict the Eurocode[6] (2005) formulation for normalized concrete compressive strength of normal weight calcareous, and siliceous aggregates, and lightweight aggregates. ASCE[5] (1992) does not distinguish between these three sets of normal weight and lightweight aggregates.

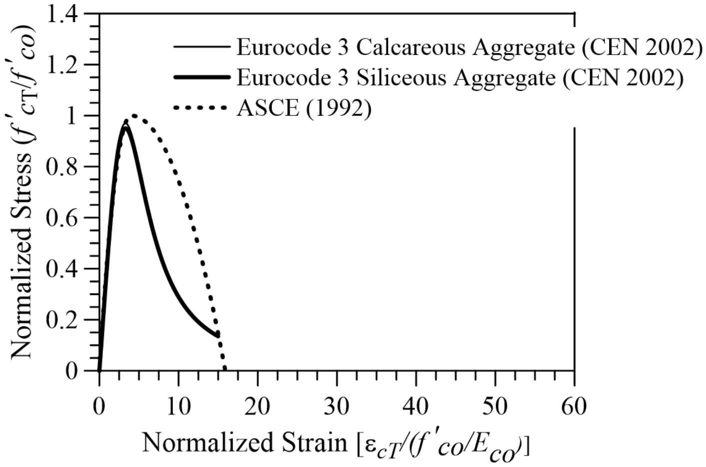



Source: FHWA

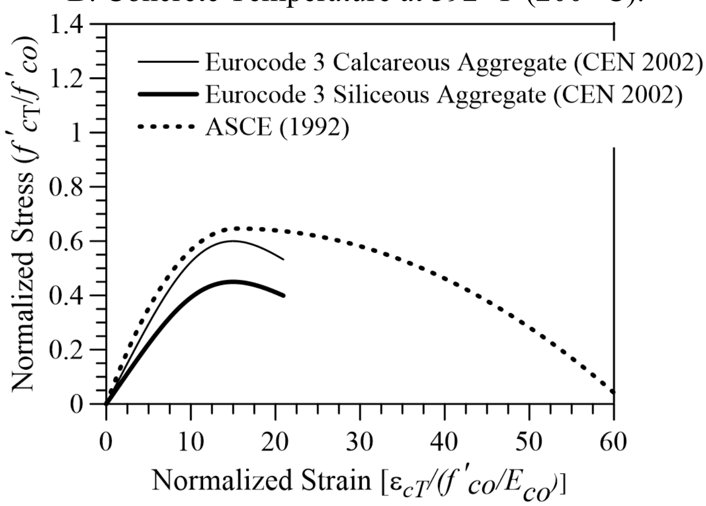
**Figure 2-13. Graph. Temperature dependent concrete thermal expansion.**




A. Concrete Temperature at 68 °F (20 °C).




B. Concrete Temperature at 392 °F (200 °C).




C. Concrete Temperature at 1,112 °F (600 °C).

Source: FHWA

**Figure 2-14. Graph. Temperature-stress-strain relationships for concrete.**

## CHAPTER 3 - DATA FROM FATALITY ANALYSIS REPORTING SYSTEM (FARS)

The Fatality Analysis Reporting System (FARS) is a nationwide census providing yearly data regarding fatal injuries suffered in motor vehicle traffic crashes (FARS 2023). The Fatality and Injury Reporting System Tool (FIRST) (2023) facilitates the data mining of FARS. FIRST is a web base query tool developed by the National Highway Traffic Safety Administration (NHTSA). FIRST allows users to customize queries for major NHTSA databases, including the Fatality Analysis Reporting System (FARS) and the Crash Report Sampling System (CRSS). Phase trends of crash statistics involving trucks with flammable materials and resulting in fires were queried and are presented in this section.

Table 3-1 shows vehicle fatal crashes queried for the United States and the Commonwealth of Virginia within the period of 2007 to 2021 and according to the listed FARS filter selection. Table 3-2 shows the results of all large truck fatal crashes queried for the United States and the commonwealth of Virginia within the period of 2007 to 2021. A total of 5 bridge collisions against fixed objects were identified from a query of FARS for large trucks carrying flammable materials. Of these crashes, 4 resulted in fires.

**Table 3-1. FIRST data on all vehicular fatal crashes for period of 2007-2021**

| [a] FIRST Crash Type Filter Selection | Unites States | Virginia |
|---|---|---|
| All vehicle crashes | 752,558 | 16,493 |
| All vehicle crashes carrying flammable materials | 1,130 | 22 |
| All vehicle crashes carrying flammable materials and resulting in fires | 187 | 6 |
| All vehicle crashes against fixed objects | 164,910 | 5,144 |
| All vehicle crashes against fixed objects and carrying flammable materials | 131 | 5 |
| All vehicle crashes against fixed objects, carrying flammable materials and resulting in fires | 113 | 4 |

Data: [a] Fatality and Injury Reporting System Tool (FIRST 2023): 2007-2020 Final File and 2021 Annual Report File (ARF). Report Generated: Monday, October 16, 2023. This data was obtained using the Fatality and Injury Reporting System Tool (FIRST) Link at: Fatality and Injury Reporting System Tool (FIRST) (dot.gov).

**Table 3-2. FIRST Tool data on all large truck fatal crashes for period of 2007-2021**

| [(a)] FIRST Crash Type Filter Selection | Unites States | Virginia |
|---|---|---|
| Large truck crashes | 64,460 | 1,416 |
| Large truck crashes carrying flammable materials | 1,129 | 22 |
| Large truck crashes carrying flammable materials and resulting in fires | 187 | 6 |
| Large truck crashes against fixed objects | 5,786 | 226 |
| Large truck crashes against fixed objects and carrying flammable materials | 131 | 5 |
| Large truck crashes against fixed objects, carrying flammable materials and resulting in fires | 36 | 4 |

Data: [(a)] Fatality and Injury Reporting System Tool (FIRST 2023): 2007-2020 Final File and 2021 Annual Report File (ARF). Report Generated: Monday, October 16, 2023. This data was obtained using the Fatality and Injury Reporting System Tool (FIRST) Link at: Fatality and Injury Reporting System Tool (FIRST) (dot.gov).

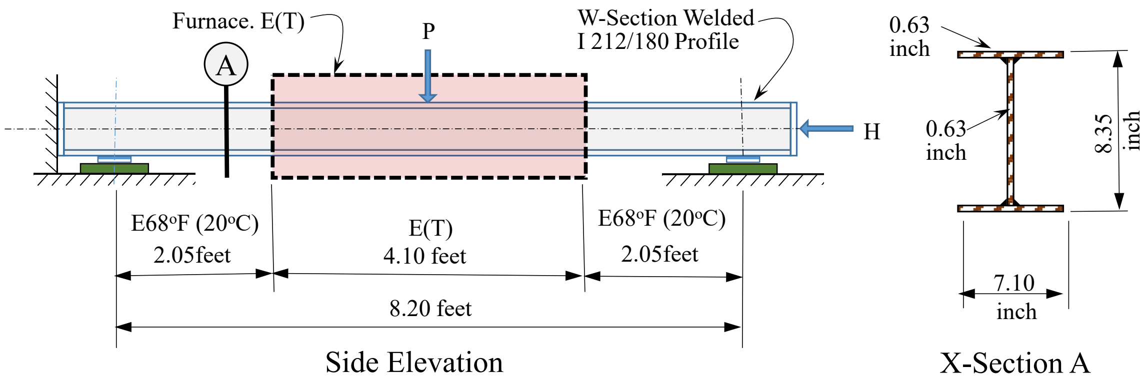
## CHAPTER 4 - FINITE ELEMENT ANALYSIS OF THERMAL EFFECTS

*OpenSees* (McKenna, 1997) is an open-source finite element software that was originally developed for structural analysis under seismic and or dynamic loads. Researchers at The University of Edinburgh and the University of California, Berkeley have since collaborated to develop *Structures in Fire*, a fire beam element model in the OpenSees platform. (Jiang and Usmani 2013, Jiang et al. 2015, Usmani et al. 2012, 2023). This platform was chosen for this research work as it is a powerful non-linear dynamic analysis tool, and provides access to the source code; thereby, allowing the development of new classes of elements and material models that take into account dynamic increase factors that members may experience under collision loads. Users in OpenSees can analyze the fire effects after truck collisions by simulating disproportionate collapse of bridge systems with element removal.

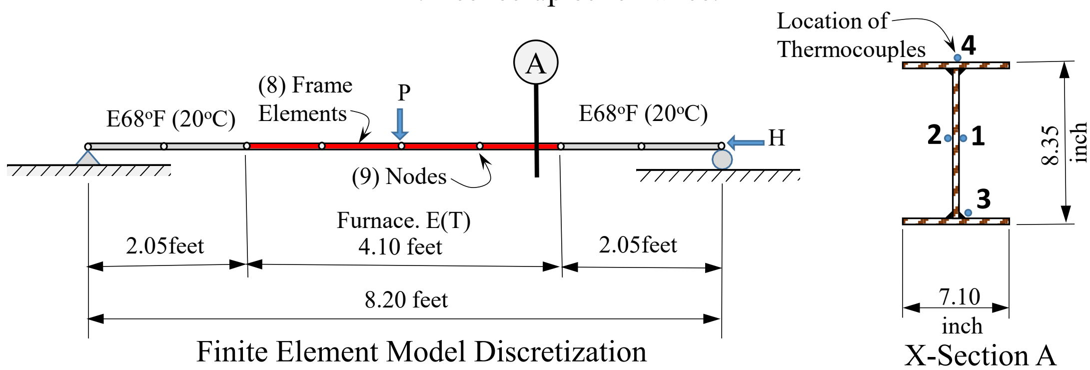
Volkmann et al. (2020) validated three benchmark case studies from the literature using the OpenSees *Structures in Fire* platform. In their validation they used the experimental fire tests investigated at COST (2014). As shown in Figure 4-1A, one of the benchmark tests consisted of testing a simply supported steel beam partially heated in a furnace and subjected to a concentrated point load, *P*, of 890 kips (200 kN) and an axial force, *H*, of 1,780 kips (400 kN). The investigated steel beam was partially heated in a furnace in the central 4.10 feet and the ends were kept at room temperature. The beam was an I-section with a flange width of 7.10 inches, a beam depth of 8.35 inches, and a web thickness of 0.63 inches. The tested yield stress, $F_y$, was 54 ksi, and the Young's modulus, *E*, was 30,000 ksi. The experimental test results were also validated by Volkmann et al. (2020) against the OpenSees analytical model depicted in Figure 4-1B. In the analytical model, the steel material model was the *SteelECThermal* model (Usmani et al. 2012, 2023), which is based on the Eurocode[2] EN 1993-1-2 (CEN 2002). The model for the eight beam elements depicted in Figure 4-1B used *dispBeamColumnThermal* frame elements (Usmani et al. 2012, 2023). The *dispBeamColumnThermal* frame element efficiently simulates thermal elongations and subsequent secondary deflections when elements are subjected to heat gradients and subjected to fixed-pinned boundary restraints (Volkmann et al. 2020).

Similar to the experimental program, a uniform temperature profile was used across the elements cross-section. The temperature profile consisted of heating the beam elements for 120 minutes at a rate of 50 °F per minute (28 °C per minute) until the temperature inside the furnace reached 1200 °F (649 °C), or the temperature at the surface of the beam elements reached a maximum of 1000 °F (538 °C). As previously stated, only the four beam elements in the central 4.10 feet were subjected to this heat profile. The elements at the ends of the beam were not subjected to this heat gradient. Further details of this benchmark test setup can be found in COST (2014) and Boko et al. (2012). Figure 4-1B illustrates the OpenSees analytical model used in validating the transient-state experimental benchmark test program. Figure 4-2 shows the analytical results temperature versus beam midspan deflections obtained from this research program against the benchmark test results presented in Volkmann et al. (2020).

The beam mid span deflection after application of the initial vertical load, *P*, of 890 kips (200 kN) was 0.20 inches. After this initial load stage, temperature gradients were applied, and as expected, the beam midspan continuously increased and follow similar gradients and values as those recorded from the test program thermocouples.




A. Test setup schematics.

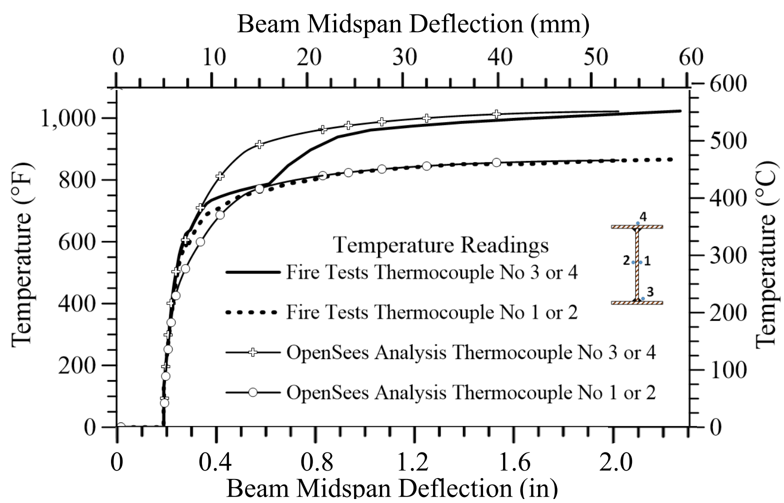



B. Finite element model schematics.

Note: Further details on the experimental program can be found at COST (2014), Volkmann et al. (2020) and Boko et al. (2012)

Source: FHWA

**Figure 4-1. Illustrations. Transient-state experimental program.**




Note: Further details on the test results can be found at Boko et al. (2012)

Source: FHWA

**Figure 4-2. Graph. Transient-state experimental vs analysis test results.**

# CHAPTER 5 - PROBABILITY OF BRIDGE COLLAPSE

In this report, bridge collapse implies failure to not only a single load carrying element but a drastic change in the geometry of the overall bridge that renders it unfit for future use. This implies that damage or failure to a single pier column/wall may or may not lead to the collapse of the structure. Previous work presented an equation for the probability of observing $k$ truck-related collisions given the expectation $\lambda$ at a specific bridge location (Silva et al. 2024). It is possible to estimate the probability of bridge collapse for a specified time duration (e.g., the service life of a bridge). The estimated probability of bridge collapse can provide a metric for evaluating vulnerability of a location-specific bridges to pier collisions from heavy trucks. The next section proposes a possible methodology for calculating the probability of observing $k$ fire incidents resulting from truck-related collisions given the expectation $\lambda$ at a specific bridge location.

## 5.1. ANNUAL NUMBER OF TRUCK RELATED COLLISIONS RESULTING IN FIRES

The data from all traffic detector stations with vehicle classification in Virginia were used to estimate the rate of overall truck-related collision resulting in fires. In this work, truck-fire involvement rate $\Phi_{TF}$ represents the number of truck related collisions which have resulted in fire incidents per million truck miles traveled as follows:

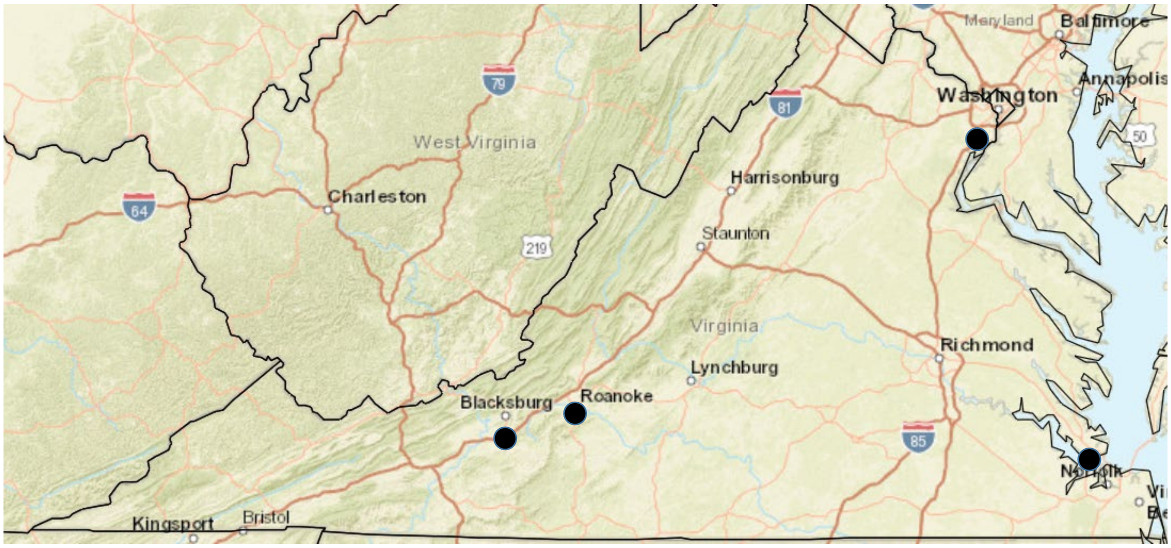
$$\Phi_{TF} = \frac{\sum \widehat{N}_{iF}}{\sum \widehat{V}_i \cdot L_i} \times 1{,}000{,}000 = \frac{4}{991{,}359{,}898} \times 1{,}000{,}000 = 0.0040 \qquad \textbf{(5-1)}$$

$\sum \widehat{N}_{iF}$ denotes the total number of truck-related collisions carrying flammable materials and resulting in fire incidents that occurred in Virginia between 2007 and 2021, $\widehat{V}_i$ denotes the volume of trucks traversing Link $i$, and $L_i$ denotes the length of Link $i$ in miles. The data queried from FARS revealed the total number of truck-related collisions with fire incidents, $\sum \widehat{N}_{iF}$, and is listed in Table 3-2. The large solid circles in Figure 5-1 illustrates the distribution of the 4 truck-related collisions with fire incidents on the 402 links. These fire incidents occurred near Christiansburg, Roanoke, Springfield, and Norfolk. Link $i$ is the roadway stretch on which the $i$th traffic detector station with vehicle classification is deployed, bounded by the nearest upstream and downstream off-ramps (i.e., exits) from the detector station. This proposed methodology assumes that traffic volumes remain constant along the 402 links.

In this work the expected annual number of truck-related collisions with resulting fire incidents that would occur under the bridge is obtained by multiplying the truck-fire involvement rate, $\Phi_{TF}$, by the width of a specific bridge, $W_b$, and by the estimated annual truck volume traversing under the bridge. The expected annual number of truck-fire collisions, $\lambda_F$, that impact bridge piers corresponding to one direction of travel is estimated by the following equation:

$$\lambda_F = \left(\frac{\widehat{V}}{1{,}000{,}000}\right)\left(\frac{W_b}{5280}\right)\Phi_{TF} \qquad (5\text{-}2)$$

Equation (5-2) does not directly provide a measure of collisions to bridge piers and the resulting subsequent fire. Table 5-1 presents the data of expected number of truck-related collisions for the seventeen study sites. Figure 5-2 presents a chart of the expected number of truck-related collisions for the seventeen study sites.

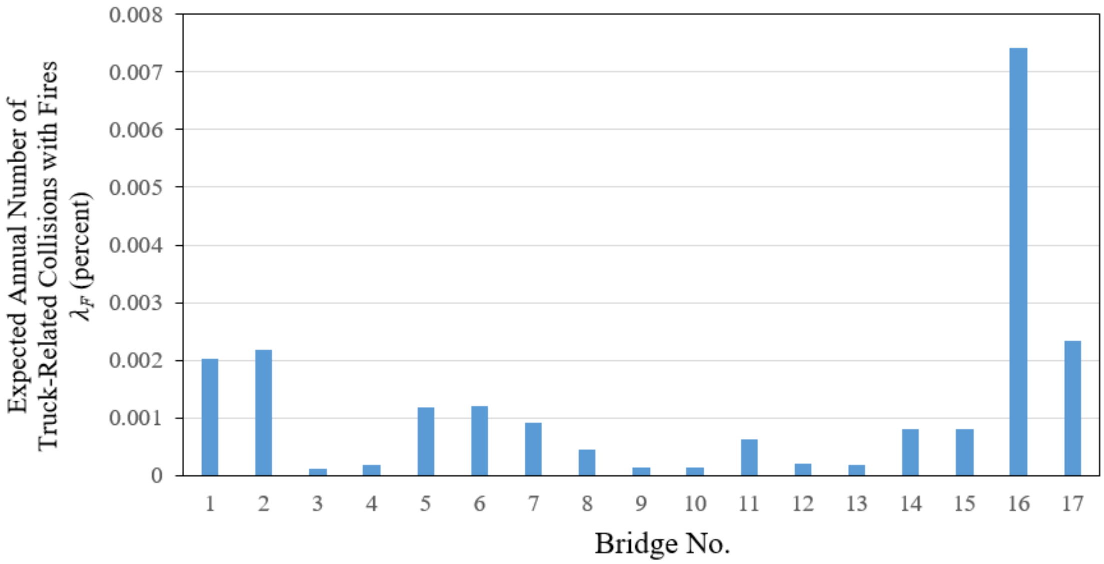



Data overlay on Original Map: © 2022 TomTom (see Acknowledgments page).

**Figure 5-1. Graph. Distribution of truck-related collisions with fire incidents.**

**Table 5-1. Expected annual number of truck-related collisions with fires for the study sites.**

| Bridge No. | Annual Truck Volume $\widehat{V}$ | Bridge Width $W_b$ (unit: feet) | Expected Annual Number of Truck-Related Collisions with Fires, $\lambda_F$ (percent) |
|---|---|---|---|
| **1** | 385,720 | 68.8 | 0.002028 |
| **2** | 414,947 | 68.8 | 0.002182 |
| **3** | 56,718 | 25.9 | 0.000112 |
| **4** | 94,087 | 25.9 | 0.000186 |
| **5** | 517,697 | 29.9 | 0.001183 |
| **6** | 406,909 | 38.4 | 0.001194 |
| **7** | 451,305 | 26.6 | 0.000917 |
| **8** | 207,065 | 27.9 | 0.000441 |
| **9** | 56,810 | 29.9 | 0.000130 |
| **10** | 61,788 | 29.9 | 0.000141 |
| **11** | 155,955 | 51.8 | 0.000617 |
| **12** | 47,623 | 58.1 | 0.000211 |
| **13** | 39,954 | 58.1 | 0.000177 |
| **14** | 303,488 | 34.4 | 0.000798 |
| **15** | 300,715 | 34.4 | 0.000791 |
| **16** | 1,429,790 | 67.9 | 0.007419 |
| **17** | 1,175,996 | 25.9 | 0.002328 |




Source: FHWA

**Figure 5-2. Chart. Study sites expected annual number of truck-fire related collisions**

## 5.2. HEAVY TRUCK COLLISIONS RESULTING IN FIRE INCIDENTS

Extending on previous work by Silva et al. (2024) the probability of observing $k$ truck-related collisions given the expectation $\lambda_F$ at a specific bridge location resulting in fire incidents, the probability of bridge collapse for a specific bridge in $T$ years with unidirectional roadway under the bridge can be formulated as follows:

$$\mathrm{Pr}_{bf} = 1 - \sum_{k} \left\{ \frac{(\lambda_F T)^k e^{-\lambda_F T}}{k!} \cdot [1 - \mathrm{Pr}(Q|C|F)]^k \right\} \quad \textbf{(5-3)}$$

Let $Pr(Q|C|F)$ denote the probability of bridge collapse due to a specific truck-related collision and resulting fire given the weight, and speed distribution of trucks, the width of bridge piers, and the heat intensity of the fire. Likewise, the probability of bridge collapse from a truck collision and resulting fire incident for a specific bridge in $T$ years with bidirectional roadway under the bridge can be formulated as follows (Silva et al. 2024):

$$\mathrm{Pr}_{bf} = 1 - \sum_{k_1} \sum_{k_2} \left( \left[ \frac{(\lambda_{1F} T)^{k_1} e^{-\lambda_{1F} T}}{k_1!} \right] \cdot \left[ \frac{(\lambda_{2F} T)^{k_2} e^{-\lambda_{2F} T}}{k_2!} \right] \cdot [1 - \mathrm{Pr}_1(Q|C|F)]^{k_1} \cdot [1 - \mathrm{Pr}_2(Q|C|F)]^{k_2} \right) \quad \textbf{(5-4)}$$

Given bridge collapses induced by collisions are low frequency events and these events may not occur for a specific bridge during the testing period, the probability $\mathrm{Pr}_{bf}$ can be estimated for an extended time duration (e.g., the service life of a bridge) and used as a metric for evaluating vulnerability of a location-specific bridge to pier collisions and a resulting fire incident.

# CHAPTER 6 - CONCLUSIONS

This report presents a literature review of fire incidents that have occurred from heavy truck collisions on bridge piers and girders. This literature review showed that fires resulting from vehicular collisions are a growing concern to the safety of bridges. This is a direct result of the rapid growth in the ground transportation across the United States and an increase in the shipping of hazardous flammable materials, spontaneously combustible materials, and other dangerous materials. Unlike other types of fire causing events, previous research demonstrated that collisions of trucks carrying hazardous material across the United States can produce very intense and explosive fires.

An extensive data mining and analysis of bridge inventory data, collision data, traffic detector data and collisions resulting in fire incidents were conducted for Virginia. Seventeen representative bridges were selected to characterize and validate the following stochastic variables:

- *Frequency of heavy truck collisions resulting in fire incidents as a function of bridge location*. Data analysis and literature review showed the stochastic frequency of heavy truck collisions on bridge piers and resulting fire follows a Poisson distribution. This is a realistic assumption since heavy truck collisions with fire incidents at a given bridge location may be assumed to occur independently of time and at a constant rate. The Poisson distribution variables of time and constant rate were formulated as the multiplication of truck volume crossing under the bridge, the width of the bridge pier, and a representative collision involvement rate for truck-related collisions with fire incidents.

- *Heat flux effects on material properties*. Material properties, including the strengths of concrete and reinforcing steel are influenced by heat flux. Material properties of concrete and steel can change significantly as a function of temperature. Material properties such as strength and elastic modulus were plotted as a function of temperature.

- *Thermal gradients on bridge system*. Thermal gradients in fire analysis of bridges are considered in 3D FEM simulations as input non-uniform temperature distributions. Thermal gradients are typically estimated from fire dynamic simulations. Temperature distribution result in internal stresses and distortion of structural elements, which subsequently impact the global structural behavior of bridges.

These stochastic variables are then used in evaluating some of the design parameters listed below:

- Structural resistance of bridge girders and pier elements necessary to prevent collapse of bridges resulting from collisions and resulting fire incidents.

- Probability of collapse of a bridge from a collision and resulting in a fire incident in one year or over a prolonged time duration. A prolonged time duration may correspond to the service life of the bridge.

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