This is a preprint draft. The published article can be found at: https://doi.org/10.1016/j.jcsr.2019.01.020

Please cite this paper as:
Kodur VK, Naser M.Z. (2019). "Designing steel bridges for fire safety." Journal of Constructional Steel Research. Vol. 156, pp. 46-53. (https://doi.org/10.1016/j.jcsr.2019.01.020).

Designing Steel Bridges for Fire Safety

V. K. Kodur[1,*], M. Z. Naser[2]

1. ABSTRACT

While bridge fires can often lead to substantial losses, current codes and standards do not specify any provisions for fire resistance of load bearing structural members in bridges. In order to bridge this knowledge gap, this study presents a practical approach to overcome fire hazard in steel bridges of critical nature. The proposed approach comprises of two components namely, analytical and numerical. In the analytical component, fire risk in a steel bridge is assessed, through a specially derived fire-based importance factor that allows estimating vulnerability of a bridge to fire hazard. The second component integrates both simplified calculation method as well as highly nonlinear numerical analysis through a coupled finite element (FE) based simulation with the purpose of developing relevant strategies for mitigating fire risk and losses. The applicability of this approach is illustrated herein through a comprehensive case study on an actual steel bridge that underwent an intense fire incident. The aim of this study is first to present engineers and designers with a practical tool to identify steel bridges vulnerable to fire hazard and secondly to guide them into developing optimum solutions to mitigate large fire losses.

***Keywords*: Fire hazard, Bridges, Design and Mitigation strategies, Finite element simulation.**

[1,*]University Distinguished Professor and Chairperson, Civil and Environmental Engineering, Michigan State University, East Lansing, MI, Email: kodur@egr.msu.edu
[2]Assistant Professor, Glenn Department of Civil Engineering, Clemson University, Clemson, SC, Email: mznaser@clemson.edu, Website: www.mznaser.com

This is a preprint draft. The published article can be found at: https://doi.org/10.1016/j.jcsr.2019.01.020

Please cite this paper as:
Kodur VK, Naser M.Z. (2019). “Designing steel bridges for fire safety.” Journal of Constructional Steel Research. Vol. 156, pp. 46-53. (https://doi.org/10.1016/j.jcsr.2019.01.020).

2. INTRODUCTION

Recent incidents have demonstrated that fire represents a critical hazard and may lead to momentous losses in buildings and bridges [1]. Generally, the adverse effects of fire in buildings can often be controlled through provision of active and passive fire protection systems as outlined in building codes. However, such guidelines may not be extendable to other infrastructure such as bridges due to fundamental differences relating to fire severity, geometric configuration and material characteristics etc. [2-4]. These facts when combined with the reality that there are no specific provisions for fire design of bridges in bridge codes and standards highlight the immediate need for developing fire mitigation strategies in bridges.

There are no specific requirements in codes and standards for designing bridges to withstand fire hazard as a result of two common assumptions, 1) likelihood of fire breakout in bridges is very small and hence it is not justifiable to fire-proof all bridges, and 2) a small percentage of bridge fires can damage bridge structural members, thus life safety of commuters is not usually at risk. While these assumptions may hold true, to some extent, property and monetary losses from bridge fires can be substantial [4-7]. Such losses include maintenance/reconstruction costs of damaged bridge components, together with indirect costs arising from delays and traffic detouring.

Fires in bridges are often characterized by intense burning reaching temperatures as high as 900-1000˚C in early stages of ignition [8, 9]. Such fires are referred to as *hydrocarbon fires* and can significantly damage integrity of steel structural systems often used in steel bridges. Due to its high strength, structural steel has lower sectional (and thermal) mass, this when combined with inherent low specific heat and high thermal conductivity of steel leads to rapid rise in temperature

Please cite this paper as:
Kodur VK, Naser M.Z. (2019). "Designing steel bridges for fire safety." Journal of Constructional Steel Research. Vol. 156, pp. 46-53. (https://doi.org/10.1016/j.jcsr.2019.01.020).

in steel members once exposed to fire. As steel strength (yield) and stiffness are highly dependent on temperatures, any rapid rise in steel temperature leads to rapid degradation in those mechanical properties. As a result, steel structural components (particularly girders) may show inferior fire resistance to concrete members which exhibit slower rise in cross-sectional temperature and moderate loss in mechanical properties due to its endothermic nature. Thus, fire-induced damage can be significant in steel bridges as documented in recent fire tests and bridge fires [10-12].

The current rise in bridge fire incidents, when combined with the fact that there is lack of appropriate approaches for mitigating fire hazard, clearly shows that there is need to develop design-oriented (practical) approaches to overcome fire hazard in bridges [13-15]. To bridge this knowledge gap, this study articulates a practical approach to mitigate bridge fires. The proposed approach embraces the application of a specifically derived importance factor for fire risk. Then, the proposed approach compliments the qualitative analysis with undertaking a highly nonlinear finite element simulation to investigate possible strategies with the prime goal of improving fire resistance of steel structural members in bridges.

3. FIRE PROBLEM IN BRIDGES

3.1 General

The open literature clearly shows that fire incidents in bridges has significantly increased over the years [16-18]. This review also shows that most of these fires occurred due to fuel (or chemical) spillage resulting from collision of fuel tankers, either with other vehicles or structural components (i.e. piers, girders, walls) in the vicinity of bridges. Hence, fires in bridges are of high intensity and are often explosive. This can be attributed to the fact that vehicle collisions or derailing of fuel tankers often happen at high speeds causing explosive and quick ignition of flammable gasoline fuels (with low flash temperature). This burning of fuel produces extreme temperatures (in the range of 700-900˚C) that may peak at 1200˚C [4, 19, 20]. Some of the recent notable fire incidents, together with the cause of fire and type of damage, on steel bridges are listed in Table 1.

3.2 Recent bridge fire incidents

In order to illustrate the magnitude of a typical bridge fires, two recent fire incidents are presented herein. One of these fire incidents occurred on July 15, 2009, at the I-75 overpass in Hazel Park, MI. This fire started as a 50,000 liters fuel tanker collided with a passing truck. This collision resulted in temperatures around 850-1000˚C and led to high degradation of strength properties of the un-proofed steel girders. This resulted in loss of capacity in the overpass steel girders and triggered the collapse of this bridge within 20 minutes of fire exposure. The collapse of this overpass caused major damages and delays and these losses were estimated at $2 million [21].

The other fire incident occurred on April 29, 2007 when a fire broke out near the I-580 freeway in Oakland, CA. This fire started as a large gasoline tanker (carrying 30,000 liters) overturned and this led to sudden and intense conflagration [16]. This fire produced temperatures in the range of 1100˚C which led to the collapse of the unprotected 25.6 m steel girders. This resulted in large deflections leading to development of significant fire induced forces in the girders, which in turn overstressed connections. Due to these high restraint forces, the bolted connections weakened and steel girders collapsed within 20-25 minutes [16]. The estimated losses in the aftermath of this fire were $9 million. This resulted in large traffic disruptions and detours in one of the busiest traffic routes in the US.

The worst bridge fire to occur in Germany broke out at the Wiehltalbrücke Bridge in 2004 due to car crashing a fuel tanker (transporting 33,000 liters of gasoline). The steel bridge is 30.25 m wide and 705 m in length. Due to this collision, the fuel tanker fell 30 m through a guardrail and then exploded. Due to this explosion, a rapidly rising fire developed reaching temperatures of 1200°C [22]. As a result of this intense heat, the steel deck of this bridge weakened and deformed over 60 m. Fortunately, this bridge did not collapse. This fire has caused significant damaged to the bridge, as a 20 m × 31 m segment of the steel bridge needed to be replaced. This damage was estimated at €32 million.

3.3 Lack of provisions for fire safety

Above discussed fire incidents clearly show how fires in bridges can be very intense, unlike building fires which burn at much lower intensity. This is due to number of differences in characteristics between buildings and bridges as shown in Table 2. In general, the problem of fire hazard in buildings is overcome to a great extent through implementation of active fire protection systems i.e. water sprinklers. These systems help mitigate fire while still in early stage. Still, bridges do not incorporate any active fire protection systems mainly due to major installation (practical) challenges and cost implications. Further, current design codes and standards still do not require installation of passive fire protection (insulation) measures to main structural members in bridges [23].

In buildings, combustible materials typically comprise of cellulose based fuels (e.g., wood) which gradually burn when ignited. Cellulose based fuels are often represented through ASTM

Please cite this paper as:
Kodur VK, Naser M.Z. (2019). "Designing steel bridges for fire safety." Journal of Constructional Steel Research. Vol. 156, pp. 46-53. (https://doi.org/10.1016/j.jcsr.2019.01.020).

E119 standard fire curve where fire temperature reaches 1000°C within two hours. However, gasoline-based fuels commonly, associated with bridge fires, burn at more rapid rate producing hydrocarbon fires. Such fires can reach a temperature of 1050°C within the first 5-10 minutes of ignition. Another key difference arises due to variation in ventilation characteristics between buildings and bridges. For instance, buildings are often designed with compartmentation features and as a result, there is limited supply of fuel and oxygen for burning. However, bridges are in large and open spaces which provide unlimited supply of oxygen. When combined with large amount of fuel available (in fuel tankers), this provides ideal conditions for quick burning and fire growth (and spread).

In addition to fire and ventilation characteristics, there are major differences in features of structural members used in buildings and bridges. For example, structural shapes (steel structural elements) used in buildings are of compact sections. However, in bridges, structural systems often utilize slender sections (ex. plate girders) due to performance requirements and cost considerations. Slender members, although can satisfy load capacity requirements under ambient conditions, are vulnerable to fire-induced instabilities as noted in recent fire incidents and laboratory fire tests [10, 24].

4. PROPOSED APPROACH TO OVERCOME FIRE HAZARD IN STEEL BRIDGES

Findings of above review clearly show that it is not feasible or practical to design all bridges to withstand effects of fire. However, certain steel bridges can be critical from the fire point of fire safety and for such bridges appropriate fire mitigation strategies is to be developed to enhance fire resistance. In order to design these bridges for fire actions, this paper proposes as approach for overcoming fire threats and this approach comprises of two steps. In the first step, the magnitude of fire hazard in the selected bridge is analytically quantified by applying a newly derived fire-based importance factor (IF). In case fire risk for this bridge is found to be high, then appropriate strategies for mitigating fire are to be developed as part of the second step. Thus, in the second step, a refined investigation is carried out in which load bearing members are examined using either simplified calculation and/or a 3D nonlinear finite element analysis as to evaluate their fire performance. The outcome of this analysis is then used to arrive at optimum strategies to enhance fire resistance in the bridge. Figure 1 illustrates the chronological steps associated with the proposed procedure.

As part of the first step, relevant data is collected on features (parameters) of the bridge. Such characteristics include susceptibility (fire vulnerability) of a bridge which encompasses geometrical features of structural members, materials used in their construction, loading and support conditions of structural members and fire intensity, critical nature (i.e. location, size, number of vehicle served etc.) from the point of traffic functionality and flow as well as accounting for any installed fire mitigation strategies. Through examination of this collected data, a fire importance factor can be assigned. This fire-based importance factor is similar to that used for evaluating occupancy type or snow loading in the design of buildings and hence comprises of number of parameters covering various aspect of steel bridge geometry, traffic density etc.

The developed fire-based importance factor is calculated using a weightage factor approach. In this approach, weightage factors are assigned to various parameters or characteristics of the bridge (i.e. material type, type of load supporting system etc.) on a scale from 1 to 5. Larger weightage factors are assigned to represent higher vulnerability of a bridge to fire i.e. metropolitan bridges are of higher importance to transportation network than rural bridges and hence are assigned a higher weightage factor of 3 (as oppose to 1 for rural bridges). In a similar manner, bridges that serve large volume of commuters (> 50,000 vehicles per day) are assigned a weightage factor of 5 as oppose to 2 for bridges that serve lesser number of vehicles per day (in the range of 1,000-5,000). A list of recommended weightage factors for all classes and various parameters can be found elsewhere [2].

Once weightage factors are assigned to all parameters, a class factor can then be calculated as:

$$\psi_x = \frac{\sum \varphi_{x(\max)}}{\varphi_{total}} \tag{1}$$

where, $\varphi_{x(max)}$ is the maximum weightage factor of each parameter in class (x), φ_{total} is the summation of maximum weightage factors of all parameters in the fire classes.

Finally, an overall class coefficient (λ), calculated using a set of mathematical expressions that utilize weightage factors, is used to assign a fire risk grade for a bridge, such that:

$$\lambda = \sum \Delta_x \psi_x \tag{2}$$

where, Δ_x is a class coefficient calculated as the ratio of the summation of selected weightage factors of sub-parameters in class (x), i.e. geometry of the selected bridge, to the summation of the maximum weightage factors of the same parameters in that class.

This overall class coefficient is then compared against numerical scores representing four fire-based risk grades namely low, medium, high and critical with scores of <0.2, 0.2-0.5, 0.51-0.94, and ≥0.95, respectively. Each risk grade is associated with a value of importance factor being 0.8, 1.0, 1.2, and 1.5 for low, medium, high and critical risk grade, respectively. Thus, if a bridge is to fall under "low" (IF = 0.8) or "medium" (IF = 1.0) risk grade, then this bridge is considered to be less vulnerable to fire damage and may not require supplementary actions to enhance fire safety. However, if a bridge is found to have a "high" (IF = 1.2) or "critical" (IF = 1.5) risk grade, then such a bridge is vulnerable to fire induced damage.

Kodur and Naser [2] found that if a bridge that falls under "high" or "critical" risk grade, then this bridge often has fire resistance of less than one hour. Thus, these researchers recommended designers to develop suitable strategies to enhance the fire safety aspects of such a bridge so as to reduce the risk grade to "medium" or preferably "low". Fire safety of a bridge can be enhanced through implementing practical strategies to enhance fire resistance (FR) of its main components. One strategy can be the use of fire protection to insulated main structural members (i.e. girders) of a steel bridge. With the applied fire protection, if fire resistance of main structural members of the selected bridge is increased to 60-90 minutes the vulnerability of the bridge to fire hazard can be significantly improved. This is based on observation from recent bridge fire which have showed how steel girders can lose much of their strength and collapse within 20-30 min of severe fires [17, 18]. When fire resistance of girders in a bridge is known to be more than 60 to 90 minutes, then such a bridge may not require additional safety measures. But, when fire resistance of girders turn out to be less than that of the required resistance, then suitable fire mitigation strategies, such as installation of insulation, foam/water (or extinguishing agents) flooding systems, need to be implemented to enhance fire performance.

As part of the second step, simplified or advanced analysis is to be performed to determine fire resistance of structural members in that particular bridge. As an illustration, in the case of a simply-supported steel girder, fire resistance can be evaluated at the critical section by applying a simplified approach to evaluate degrading moment capacity at a given point in time (say 60

Please cite this paper as:
Kodur VK, Naser M.Z. (2019). "Designing steel bridges for fire safety." Journal of Constructional Steel Research. Vol. 156, pp. 46-53. (https://doi.org/10.1016/j.jcsr.2019.01.020).

minutes). First, temperature in steel girder at a given fire exposure time can be determined using simplified expression such as *best-fit method* as shown herein:

$$T = 0.54\, t \left({}^{F}/_{V}\right)^{0.6} + 50 \quad \text{- for uninsulated sections} \tag{3a}$$

$$T = \frac{t}{40\left[\frac{\frac{d_i}{k_i}}{\frac{F}{V}}\right]^{0.77}} + 140 \quad \text{- for insulated sections} \tag{3b}$$

where, F is the surface area of unit length (m^2), V is the volume of steel in unit length (m^3), t is the time to reach a limit temperature, k_i = conductivity of insulation (w/mK), and d_i = thickness of insulation (mm).

Knowing steel temperature, the reduced moment capacity, M_T, of the girder at the given fire exposure time can then be evaluated by extending room temperature capacity equations with due consideration to accommodate temperature-induced degradation to strength properties of the steel (and concrete, if present), such that:

$$M_T = k_{y,T}\, f_y\, Z \tag{4}$$

where, f_y is the yield strength of steel at room temperature, MPa, Z_x is the plastic section modulus of the section, mm^3, $k_{y,T}$ is the reduction factor of yield strength of steel at steel temperature T which can be evaluated through simplified relations as given in applicable fire design codes or standards.

If reduced moment capacity (M_T) falls below level of bending moment (arising from applied load), then failure occurs. In order to evaluate fire resistance of this girder, a layer of fire protection can be applied on the steel girder. Steel temperature is recalculated with the addition of fire protection material. The reduced moment capacity at that particular steel temperature is again re-evaluated and checked against moment due to applied loading to determine failure. The analysis

Please cite this paper as:
Kodur VK, Naser M.Z. (2019). "Designing steel bridges for fire safety." Journal of Constructional Steel Research. Vol. 156, pp. 46-53. (https://doi.org/10.1016/j.jcsr.2019.01.020).

is continued until a selected insulation thickness leads to a fire rating of 60-90 minutes, which can be sufficient in most bridges applications.

In lieu of above simplified calculation method, more complex finite element analysis can be applied to evaluate fire resistance of steel bridges. In this advanced analysis, both mid-span deflection history as well as sectional capacity can be evaluated as a function of fire exposure time. Similar to simplified analysis, if steel girder was found to prematurely fail (in less than 60 minutes), then a layer of fire protection is applied on the girder and the analysis is re-iterated. In case the applied fire protection is not sufficient to enhance fire response of steel girders, then the finite element analysis is to be repeated with thicker fire insulation until required fire resistance is achieved and the fire risk grade of the bridge reduces to "medium" or "low" risk category. It should be noted that adopting FE analysis could prove beneficial in post-fire investigation as such analysis gives information relating to damage modes (i.e. through providing insights into stress/strain levels, magnitude of deformation) as well as capturing realistic failure (occurrence of shear buckling etc.). As a result, advanced analysis is one-step ahead of simplified calculation methods and its applications will be illustrated through a case study.

5. APPLICABILITY OF PROPOSED APPROACH

This section illustrates applicability of above approach to a bridge that experienced actual fire.

5.1 Selection of a bridge

The bridge selected for this case study, is the one on I-65 interchange in Birmingham, Al USA. This bridge is made of 36.6 m steel girders spanning over three simply supported spans and

Please cite this paper as:
Kodur VK, Naser M.Z. (2019). "Designing steel bridges for fire safety." Journal of Constructional Steel Research. Vol. 156, pp. 46-53. (https://doi.org/10.1016/j.jcsr.2019.01.020).

carried by reinforced concrete piers. These steel girders have experienced significant structural damage due to fire and thus considered as most critical structural members from the point of fire hazard. Based on the available data of this bridge, the features of this bridge, along with other details of fire incident, were obtained from published records. Then, the above discussed procedure is applied to evaluate the susceptibility of this bridge to fire hazard and then to enhance fire resistance of steel girders in this bridge as to minimize its vulnerability to fire.

5.2 Description of bridge fire incident

The I-65 bridge caught fire on January 5, 2002 when a 37,000 liters gasoline tanker overturned. This bridge encompassed welded plate girders, heavily strengthened with closely spaced steel stiffeners, and made of Grade 350 MPa steel and. The steel girders were made of plates of 457 mm width and 28 mm thickness comprising flanges, and one plate of 1344 mm depth and 12 mm thickness for the web. The steel girders were also stiffened with intermediate stiffeners at a spacing of 1.1 m along the span length and with thickness of 12 mm, while bearing stiffeners of 25 mm thickness were placed at the support locations. These girders were carrying a 170 mm thick reinforced concrete slab that has an effective width of 2.15 m and made of concrete of grade 40 MPa. The resulting fire generated intense temperatures reaching 900-1100˚C. This intense heat led to rapid rise in steel temperature degrading strength and stiffness properties of girders and causing them to sag 3 m (Barkley and Gary 2002). In the aftermath of this fire, the I-65 bridge was shut and as a result, travelers were detoured to nearby routes. It is worth noting that the bridge was re-commissioned for operation after 54 days of extensive repairs [5].

5.3 Assessing fire risk through importance factor

The above discussed approach is applied to evaluate vulnerability of the selected steel

Please cite this paper as:
Kodur VK, Naser M.Z. (2019). "Designing steel bridges for fire safety." Journal of Constructional Steel Research. Vol. 156, pp. 46-53. (https://doi.org/10.1016/j.jcsr.2019.01.020).

bridge to fire hazard. From fire safety point of view, un-proofed steel girders generally display lower fire resistance than concrete piers, thus the likelihood of damage/loss of capacity to occur in steel girders is high compared to other components of this bridge. In other words, the fire based importance factor for the selected bridge is governed by the performance of steel girders under effect of fire since loss of steel strength and stiffness properties with temperature is much faster than that of concrete. Hence, concrete members normally show signs of higher fire resistance as compared to steel members. Following the recommendation and procedure outlined by Kodur et al. [25], the fire-based importance factor for selected bridge turns to be 1.2 (i.e. "high" risk grade).

5.4 Evaluating inherent fire resistance of bridge steel girder

As shown above, the I-65 bridge is categorized to be of "high" risk and thus this bridge is highly susceptible to damage in case of a fire incident. Thus, suitable strategies are to be developed to minimize fire risk on this bridge. For this, the first step is to evaluate fire resistance of the bridge girders using simplified analysis and finite element simulation as discussed above. The analysis can be carried out on steel girder in main span no. 7 that experienced the highest level of damage. Girder No. 7 is analyzed as a simply supported independent girder as the main span is separated by expansive joints (side approach spans). Using Eq. 3, temperature rise in steel girders can reach about 600°C within 30 minutes of fire exposure to a standard fire. At this temperature, the available moment capacity, calculated using Eq. 4, reduces to about 3,000 kN.m which corresponds to 50% of sectional capacity at ambient conditions. It can be inferred that this girder would fail around 30 minutes which is much lower than that recommended fire resistance (60-90 minutes). As a result, installing fire insulation to this girder is required to ensure better performance during fire incident.

In lieu of simplified analysis, a finite element analysis can be carried out. For this purpose,

Please cite this paper as:
Kodur VK, Naser M.Z. (2019). "Designing steel bridges for fire safety." Journal of Constructional Steel Research. Vol. 156, pp. 46-53. (https://doi.org/10.1016/j.jcsr.2019.01.020).

3D finite element model, capable of handling coupled and uncoupled nonlinear thermo-mechanical phenomena, and that can integrate temperature-dependent material properties can be carried out. To simulate this bridge fire incident, two sets of discretization models were developed for undertaking thermal and mechanical analysis [25]. The discretization of girder into elements is shown in Fig. 2. Full details on the development of the finite element model can be found elsewhere [10, 25].

The developed finite element model was applied to evaluate the fire resistance of I-65 steel bridge girder under ISO834 as well as Hydrocarbon fire scenario and applied gravity loading. Results from thermal analysis of uninsulated I-65 girder section are shown in Fig. 3 to exemplify sectional temperature progression in the composite girder. Plotted data clearly show that the temperature in top flange is much lower as compared to the bottom flange which can be attributed to the insulating effect of the concrete slab which tend to absorbs heat from the hotter top flange (i.e. heat sink). It can be also seen that the temperatures in the web are also higher as compared to that in bottom flange and this is due to the fact that the web is slender (thinner) and has larger surface area which also produces rapid rise in sectional temperature.

The structural response of I-65 bridge girder is illustrated in Fig. 3e and f, wherein mid-span deflection is plotted as a function of fire exposure time. This mid-span deflection increases linearly until yielding occur in steel. The uninsulated girder experiences rapid rise in sectional temperatures which leads to rapid rise in deflection resulting in early failure; within 28 and 12 min of exposure to ISO 834 and hydrocarbon fire, respectively. The failure time matches that obtained by tracing degradation in moment capacity as a function of fire exposure, which can be seen in Figs. 3e and f. In this particular bridge, tracing temperature-induced degradation of moment

Please cite this paper as:
Kodur VK, Naser M.Z. (2019). "Designing steel bridges for fire safety." Journal of Constructional Steel Research. Vol. 156, pp. 46-53. (https://doi.org/10.1016/j.jcsr.2019.01.020).

capacity was prioritized as the steel bridge was simply supported and heavily stiffened in shear. Hence, anticipated failure mode is to occur through flexure. This anticipated failure mode matches that which occurred in the bridge fire as can be seen in Fig. 4.

5.5 Arriving at optimum strategies for enhancing fire resistance

The analysis shows that the uninsulated steel girder fails within 28 minutes, thus the fire performance of this girder is poor as fire is severe and can lead to considerable damage and/or collapse of the bridge. As discussed above, the vulnerability of steel girders to fire hazard can be minimized by applying fire insulation. In order to arrive at appropriate thickness and scheme to fire protection, finite element analysis is carried out in ANSYS [26] to trace the realistic response of a fire exposed bare steel girder under two fire scenario namely ISO834 and hydrocarbon fire. Based on this analysis, a gypsum fire insulation (of conductivity of 0.15 W/m.K) of 18 mm thick is applied to the steel girder. The finite element analysis is also carried out on the insulated girder to quantify the positive impact of fire protection on the thermal and structural response of this steel girder. Figure 4 shows predicted temperature progression and compares mid-span deflection as well as degradation in moment capacity in uninsulated and insulated steel girders under ISO 834 and hydrocarbon fires. It is worth noting that results obtained from advanced analysis matches with that obtained from simplified analysis (using Eq. 3b) which gives average temperature rise across the steel section to be close to 400°C at 60 minutes of exposure to the ISO834.

Figure 4 shows that temperature rise in insulated I-65 bridge girder seem to follow similar characteristics of that in the uninsulated steel girder, but with lower rise in temperature. As a result, the deflection of insulated girder slowly rises in magnitude and at slower rate than that in bare steel girder. It can be seen from Fig. 3e and 3f that mid-span deflection was much more significant in

Please cite this paper as:
Kodur VK, Naser M.Z. (2019). "Designing steel bridges for fire safety." Journal of Constructional Steel Research. Vol. 156, pp. 46-53. (https://doi.org/10.1016/j.jcsr.2019.01.020).

uninsulated steel girder as compared to insulated steel girder under both fire scenarios. For example, under ISO 834 fire, bare and insulated steel girders fail in 28 and 118 minutes, respectively. In the case of steel girder exposed to hydrocarbon fire, bare and insulated steel girders fail in 28 and 118 minutes, respectively. This enhanced fire resistance of 118 minutes is greater than 60-90 minutes of fire resistance needed to mitigate adverse impact of fire on a bridge [27, 28].

The finite element analysis is also carried out on bare and insulated steel girder when exposed to a hydrocarbon-based fire (see Fig. 4). Since hydrocarbon fires are more severe than ISO384 standard fire curve, the bare and insulated steel girder fail at earlier times than that observed in steel girders exposed to ISO834 fire scenario. The bare and insulated steel girders, when exposed to hydrocarbon fire scenario, fail at 12 and 80 min, respectively. It can be seen that using an 18 mm insulation thickness can improve fire resistance of the girder (to 60 minutes) even when exposed to a hydrocarbon fire and this can significantly lower the risk of collapse/damage to bridge. This is of utmost importance since average respond time for firefighters can take up to 15-20 min to arrive at fire incident location and start firefighting protocol [13].

5.6 Re-assessing fire risk based importance factor

Following prediction from 3D nonlinear analysis, it can be seen that using an 18 mm thick fire protection seem to delay rise in temperature across the steel girder which enhances fire resistance to 60 minutes. To take the applied of fire insulation into consideration, the fire importance factor is re-evaluated and was found to be 1.0 and hence this bridge falls under "medium" fire risk category. Table 3 further lists values of importance factor, risk grade, mid-span deflection and failure time in steel girders when exposed to ISO834 and hydrocarbon fires.

This is a preprint draft. The published article can be found at: https://doi.org/10.1016/j.jcsr.2019.01.020

Please cite this paper as:
Kodur VK, Naser M.Z. (2019). "Designing steel bridges for fire safety." Journal of Constructional Steel Research. Vol. 156, pp. 46-53. (https://doi.org/10.1016/j.jcsr.2019.01.020).

6. PRACTICAL AND DESIGN IMPLICATIONS

This paper outlines application for a rational and practical approach for assessing vulnerability of steel bridges for mitigating fire hazard in steel bridges is outlined in. Thu the case study illustrated herein is for a bridge that is susceptible to high fire risk under "high" risk category, the proposed approach can be extended to any bridge with different structural systems, fire scenarios etc. The presented approach can also be used to assess fire risk in existing bridges (for upgrading or strengthening purposes) and also to develop suitable strategies to enhance fire safety in new constructions (while in design stage). Some of the proposed strategies include limiting access to high-risk fuel tankers to travel on certain routes (away from bridges), and use of specifically designed active fire protection systems (such as heavy-duty deluge systems, sprinklers or water curtain similar to that used in tunnels). Also, integrating structural fire design principles into the structural design of bridge components can significantly enhance inherent fire resistance of bridges. When these strategies are applied, fire performance can be enhanced in key bridges that are classified to be of "high" or "critical" fire risk grade. The reader should note that application of insulation/fire protection is highlighted herein due to its suitability in actual scenarios as shown in recent fire tests and experiments [29].

7. CONCLUSIONS

Based on the information presented, the following conclusions can be drawn:

- Fire is destructive force and represents major threat especially to steel bridges. In severe fire incidents, fire can lead to significant damage (and collapse in certain scenarios).

Please cite this paper as:
Kodur VK, Naser M.Z. (2019). “Designing steel bridges for fire safety.” Journal of Constructional Steel Research. Vol. 156, pp. 46-53. (https://doi.org/10.1016/j.jcsr.2019.01.020).

- The presented approach of evaluating fire risk in a steel bridge combines qualitative and quantitative measures (i.e. through 3D nonlinear FE simulation) as to develop appropriate strategies in order to optimally overcome fire in bridges.
- Steel girders in a bridge can collapse within 20-30 minutes under severe fire conditions. Provisions of 60-90 minutes of fire rating can mitigate early failure in most critical bridges.
- The proposed approach can be used to quantify fire risk in existing or new bridges through developing optimum fire safety strategies for overcoming fire.

REFERENCES

[1] Department of Transportation, Federal Highway Administration, Highway Statistics, 1995-2010: Ibid, Highway Statistics.

[2] Kodur, V.K.R., and Naser, M.Z. (2013). “Importance Factor for Design of Bridges Against Fire Hazard.” Engineering Structures, 54, 207-220. https://doi.org/10.1016/j.engstruct.2013.03.048

[3] Kodur, V.K.R., Naser, M.Z. (2015). “Effect of Local Instability on Capacity of Steel Beams Exposed to Fire.” Journal of Constructional Steel Research 111, 31-42. https://doi.org/10.1016/j.jcsr.2015.03.015

[4] Peris-Sayol, G., Paya-Zaforteza, I., Balasch-Parisi, S., and Alós-Moya, J. (2017). “Detailed Analysis of the Causes of Bridge Fires and Their Associated Damage Levels.” Journal of Performance of Constructed Facilities, 10.1061/(ASCE)CF.1943-5509.0000977

[5] Barkley, T., and Gary, S. Bridge Rebuilt on The Fast Track. United States Department of Transportation - Federal Highway Administration, 2002.

Please cite this paper as:
Kodur VK, Naser M.Z. (2019). “Designing steel bridges for fire safety.” Journal of Constructional Steel Research. Vol. 156, pp. 46-53. (https://doi.org/10.1016/j.jcsr.2019.01.020).

[6] Bennetts, I., and Moinuddin, K. (2009). “Evaluation of the impact of potential fire scenarios on structural elements of a cable-stayed bridge.” J. Fire Prot. Eng., 19(2), 85–106

[7] Gong, X., and Agrawal, A. K. (2016). “Safety of Cable-Supported Bridges during Fire Hazards.” Journal of Bridge Engineering, 21(4), http://dx.doi.org/10.1061/(ASCE)BE.1943-5592.0000870

[8] Garlock, M., Paya-Zaforteza, I., Kodur, V.K.R., and Gu, L. (2012). “Fire hazard in bridges: Review, assessment and repair strategies.” Engineering Structures, 35, 89-98.

[9] Guthrie, D., Goodwill, V., and Hicks, M. (2009). “Tanker fire shuts down I-75, collapses Nine Mile bridge.” The Detroit News.

[10] Naser, M. Z. (2016). Response of steel and composite beams subjected to combined shear and fire loading. PhD thesis, Michigan State University, East Lansing, US.

[11] Naser, M.Z., Kodur, V.K.R. (2017). “Comparative Fire Behavior of Composite Girders under Flexural and Shear Loading.” Journal of Thin-Walled Structures 116, 82-90. https://doi.org/10.1016/j.tws.2017.03.003

[12] Naser, M.Z., Kodur, V.K.R. (2017). “Response of Fire Exposed Composite Girders under Dominant Flexural and Shear Loading.” Journal of Structural Fire Engineering. https://doi.org/10.1108/JSFE-01-2017-0022

[13] Giuliani, L., Crosti, C., and Gentili, F. (2012). “Vulnerability of bridges to fire.” In Proceedings of the 6th International Conference on Bridge Maintenance, Safety and Management, 8-12.

[14] Marjanishvili, S., Mueller, K., and Fayad, F. (2017). “Robust bridge design to blast, fire, and other extreme threats.” Bridge Structures, 13(2-3), 93-100.

Please cite this paper as:
Kodur VK, Naser M.Z. (2019). “Designing steel bridges for fire safety.” Journal of Constructional Steel Research. Vol. 156, pp. 46-53. (https://doi.org/10.1016/j.jcsr.2019.01.020).

[15] Quiel, S. E., Yokoyama, T., Bregman, L. S., Mueller, K. A., and Marjanishvili, S. M. (2015). “A streamlined framework for calculating the response of steel-supported bridges to open-air tanker truck fires.” Fire Safety Journal, 73, 63-75.

[16] Bai, Y., Burkett, W., Nash, P. (2006). “Rapid Bridge Replacement under Emergency Situation: Case Study.” J. Bridge Eng. 11, 266–273.

[17] Bajwa, C.S., Easton, E.P., Dunn D.S. (2009). “The MacArthur Maze Fire: How Hot Was It?” U.S. Nuclear Regulatory Commission, WM2009 Conference, 1-5 March, Phoenix, AZ.

[18] Battelle. (2004). “Comparative risks of hazardous materials and non-hazardous materials truck shipment accidents/incidents.” Washington D.C. (USA): Federal Motor Carrier Safety Administration.

[19] Alos-Moya, J., Paya-Zaforteza, I., Hospitaler, A., and Rinaudo, P. (2017). “Valencia bridge fire tests: Experimental study of a composite bridge under fire.” Journal of Constructional Steel Research, 138, 538-554, https://doi.org/10.1016/j.jcsr.2017.08.008.

[20] Liu, X., Zhang, L., Guo, S., and Fu, M. (2017). “A simplified method to evaluate the fire risk of liquid dangerous chemical transport vehicles passing a highway bridge.” Journal of Loss Prevention in the Process Industries, 48, 111-117.

[21] National Steel Bridge Alliance. (2010). Steel bridge news, Chicago.

[22] Eisel, H., Palm, N., Prehn, W., and Sedlacek, G. (2007). “Brandschaden und Instandsetzung der Wiehltalbrücke im Zuge der A4, Köln–Olpe.” Stahlbau, 76, 94-104.

[23] NFPA 502 Standard for road tunnels, bridges, and other limited access highways, 2008. Quincy (MA).

[24] Aziz, E. M., Kodur, V. K., Glassman, J. D., and Garlock, M. E. M. (2015). “Behavior of steel bridge girders under fire conditions.” Journal of Constructional Steel Research, 106, 11-22.

[25] Kodur, V.K.R., Aziz, E.M. and Naser, M.Z. (2017). “Strategies for Enhancing Fire Performance of Steel Bridges.” Engineering Structures, 131, 446–458. https://doi.org/10.1016/j.engstruct.2016.10.040

[26] ANSYS. Finite element computer code. Version 14. Canonsburg (PA): ANSYS, Inc.; 2011.

[27] Kodur, V.K.R., and Naser, M.Z. (2017). “Strategies for mitigating fire hazards in transportation infrastructure.” IFireSS 2017 – 2nd International Fire Safety Symposium, Naples, Italy.

[28] Naser, M.Z., and Kodur, V.K.R. (2015). “A probabilistic assessment for classification of bridges against fire hazard.” Fire Safety Journal, 76, 65–73. https://doi.org/10.1016/j.firesaf.2015.06.001

[29] Aziz, E.M., and Kodur, V.K.R. (2013). “An approach for evaluating the residual strength of fire exposed bridge girders.” Journal of Constructional Steel Research, 88, 34-42.

Please cite this paper as:
Kodur VK, Naser M.Z. (2019). "Designing steel bridges for fire safety." Journal of Constructional Steel Research. Vol. 156, pp. 46-53. (https://doi.org/10.1016/j.jcsr.2019.01.020).

List of Tables:

This is a preprint draft. The published article can be found at: https://doi.org/10.1016/j.jcsr.2019.01.020

Please cite this paper as:
Kodur VK, Naser M.Z. (2019). "Designing steel bridges for fire safety." Journal of Constructional Steel Research. Vol. 156, pp. 46-53. (https://doi.org/10.1016/j.jcsr.2019.01.020).

Table 1 Notable fire incidents in steel bridges

Bridge location	Date of fire incident	Cause of fire	Material type used in structural members	Damage description
I-375 bridge over I-75 in Detroit, MI, USA	May 24, 2015	A tanker carrying 9,000 gallons of gasoline crashed and caught into fire.	Composite bridge (steel girders + reinforced concrete slab).	Concrete deck was significantly damaged by fire. Also, the steel girders experienced some damage.
I-15 at Cajon, Hesperia, CA, USA	May 5, 2014	Workers cutting rebar with blowtorches spread the fire into the "falsework" of the bridge.	Composite bridge (steel girders + reinforced concrete slab).	Bridge collapsed due to burning of falsework.
Bridge over I-75 near Hazel Park, MI, USA	July 15, 2009	A gasoline tanker struck an overpass on I-75.	Composite bridge (steel girders + reinforced concrete slab).	Complete collapse of the bridge to the freeway below.
Big Four Bridge, Louisville, KY, USA	May 7, 2008	Fire started due to electrical short circuit in bridge lighting system.	Steel truss bridge	Minor structural damage resulting in large amount of debris on the bridge
Brooklyn-Queens Expressway 06, NYC, US	January 16, 2006	Fire started due to fuel tanker collision.	Steel bridge	The bridge was under construction.
Rio–Antirrio bridge, Greece	January 25, 2005	One of the cable links of the bridge snapped after a lightning strike in one of the cables.	Cable stay composite bridge	Cable failed after 40 minutes into fire. The bridge was reopened to traffic after cable

This is a preprint draft. The published article can be found at: https://doi.org/10.1016/j.jcsr.2019.01.020

Please cite this paper as:
Kodur VK, Naser M.Z. (2019). "Designing steel bridges for fire safety." Journal of Constructional Steel Research. Vol. 156, pp. 46-53. (https://doi.org/10.1016/j.jcsr.2019.01.020).

				replacement.
Wiehltalbrücke Bridge, Germany	August 26, 2004	Collision between car and fuel tanker transporting 33,000 litres of fuel.	Steel bridge	Major damages that costed €7.2 million
Mungo River Bridge, Cameron	July 1, 2004	A petrol tanker, transporting about 15,000 litres derailed over the bridge	Steel truss bridge	Bridge collapse and fell to Mungo river.
I-95 Howard Avenue Overpass in Bridgeport, CT, USA	March 26, 2003	A car struck a truck carrying 8,000 gallons of heating oil near the bridge	Composite bridge (steel girders + reinforced concrete slab)	Collapse of the girders of southbound lanes and partial collapse of the northbound lanes
I-65 Birmingham bridge, Al, USA	January 5, 2002	A 37,000 liters gasoline tanker overturned	Composite bridge (steel girders + reinforced concrete slab)	Steel girders failed and sagged 3 m
Chester Creek Bridge, PA, USA	May 24, 1998	A tank truck loaded with 8,700 gallons of gasoline derailed over the bridge	Composite bridge (steel girders + reinforced concrete slab)	Steel girders buckled because of the fire and needed major repair.
Thruway Overpass, NYC, US	October 9, 1997	Collision between car and fuel tanker loaded with 8,800 gallons of gasoline.	Composite bridge (steel I-girders + reinforced concrete slab)	Collapse of the bridge costed $7 million and took 155 days to replace

This is a preprint draft. The published article can be found at: https://doi.org/10.1016/j.jcsr.2019.01.020

Please cite this paper as:
Kodur VK, Naser M.Z. (2019). "Designing steel bridges for fire safety." Journal of Constructional Steel Research. Vol. 156, pp. 46-53. (https://doi.org/10.1016/j.jcsr.2019.01.020).

Table 2 Key differences in characteristics of buildings and bridges

Scenario		Building	Bridge
Fuel source		Wood/plastic based material	Hydrocarbon based
Ventilation		Restricted supply of Oxygen	Unlimited supply of Oxygen
Fire severity		ASTM E119/Natural fire	Hydrocarbon fire
Enclosure		Compartmentation	Open area
Fire protection features		Active and passive systems	None
Structural members	Failure limit state	Flexural	Flexural/Shear
	Connections	Web and/or the flange	Bearing of the bottom flange
	Sectional slenderness	Web slenderness (50)	Web slenderness (150 with no stiffeners)
	Loading	DL+%LL	DL+ (very little LL)
	Exposure conditions	Interior environment (lower humidity)	Outdoor environment (i.e. high humidity, hot temperature etc.)

This is a preprint draft. The published article can be found at: https://doi.org/10.1016/j.jcsr.2019.01.020

Please cite this paper as:
Kodur VK, Naser M.Z. (2019). "Designing steel bridges for fire safety." Journal of Constructional Steel Research. Vol. 156, pp. 46-53. (https://doi.org/10.1016/j.jcsr.2019.01.020).

Table 3 Importance factor and finite element predictions for cases of bare and insulated steel girder

Case	**Fire scenario**	**Insulation thickness (mm)**	**IF**	**Risk Grade**	**Failure time (min)**	**Deflection at failure (m)**
Bare steel girder	ISO834	-	1.2	High	28	3.0
	Hydrocarbon	-	1.2	High	12	3.2
Insulated steel girder	ISO834	18	1.0	Medium	118	1.2
	Hydrocarbon	18	1.0	Medium	80	1.2

This is a preprint draft. The published article can be found at: https://doi.org/10.1016/j.jcsr.2019.01.020

Please cite this paper as:
Kodur VK, Naser M.Z. (2019). "Designing steel bridges for fire safety." Journal of Constructional Steel Research. Vol. 156, pp. 46-53. (https://doi.org/10.1016/j.jcsr.2019.01.020).

List of Figures:

This is a preprint draft. The published article can be found at: https://doi.org/10.1016/j.jcsr.2019.01.020

Please cite this paper as:
Kodur VK, Naser M.Z. (2019). "Designing steel bridges for fire safety." Journal of Constructional Steel Research. Vol. 156, pp. 46-53. (https://doi.org/10.1016/j.jcsr.2019.01.020).

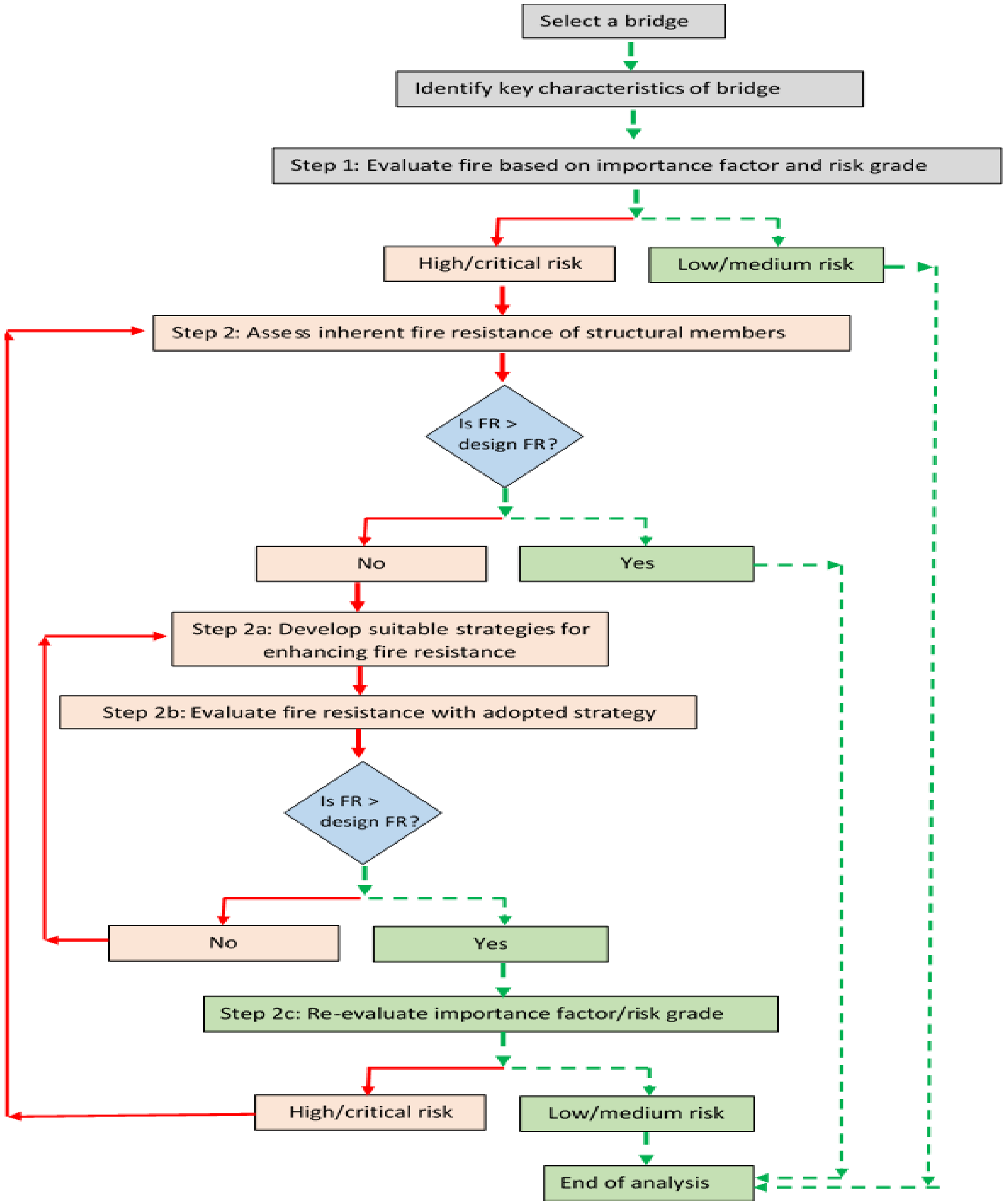


Fig. 1 Flow chart of the proposed approach for mitigating fire hazard in bridges

This is a preprint draft. The published article can be found at: https://doi.org/10.1016/j.jcsr.2019.01.020

Please cite this paper as:
Kodur VK, Naser M.Z. (2019). “Designing steel bridges for fire safety.” Journal of Constructional Steel Research. Vol. 156, pp. 46-53. (https://doi.org/10.1016/j.jcsr.2019.01.020).

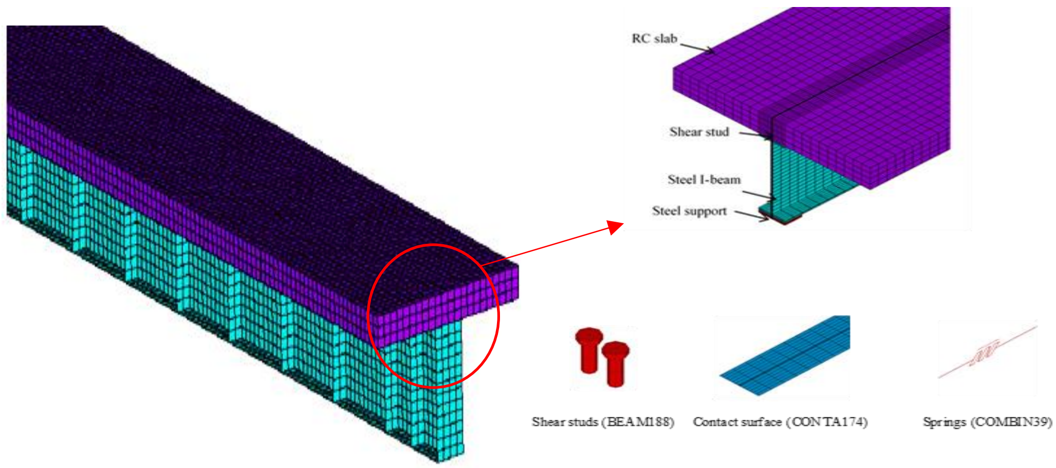
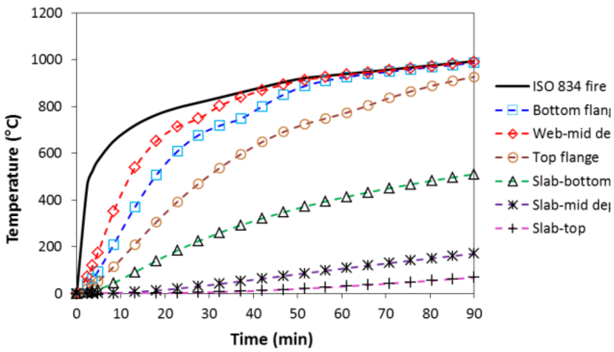


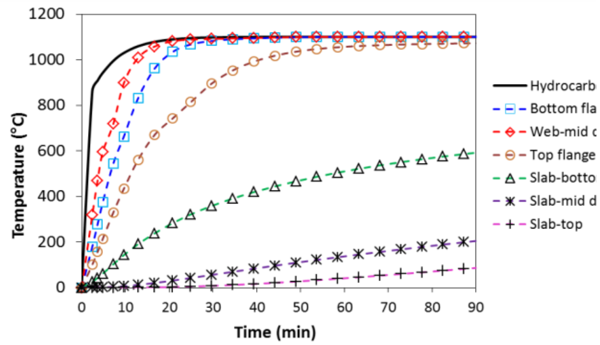
Fig. 2 Discretization of I-65 bridge girder for nonlinear FE analysis

This is a preprint draft. The published article can be found at: https://doi.org/10.1016/j.jcsr.2019.01.020

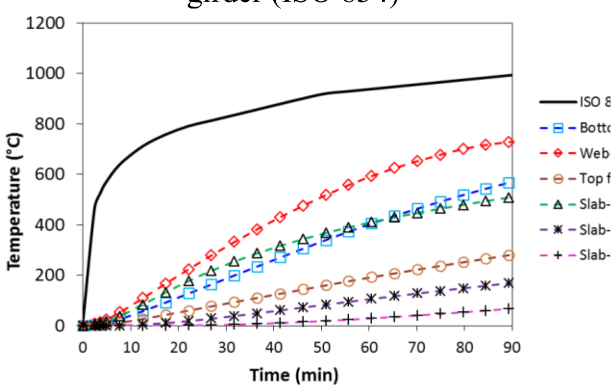
Please cite this paper as:
Kodur VK, Naser M.Z. (2019). "Designing steel bridges for fire safety." Journal of Constructional Steel Research. Vol. 156, pp. 46-53. (https://doi.org/10.1016/j.jcsr.2019.01.020).



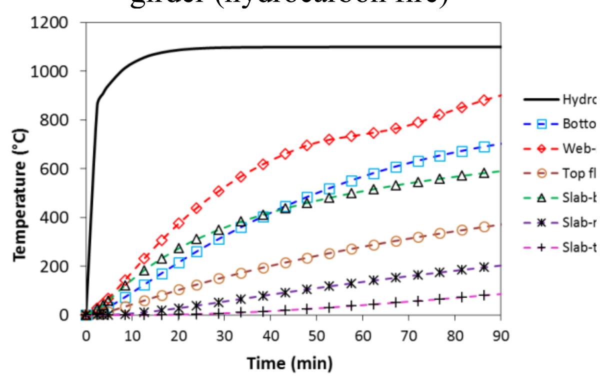
(a) Temperature progression in uninsulated girder (ISO 834)



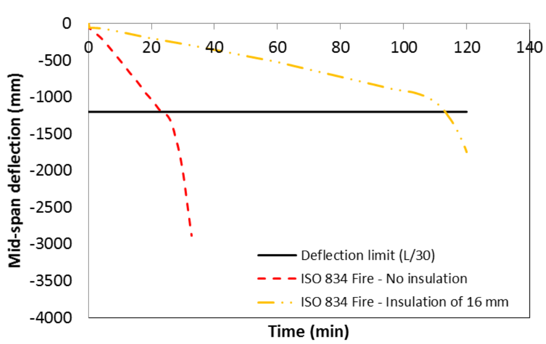
(b) Temperature progression in uninsulated girder (hydrocarbon fire)



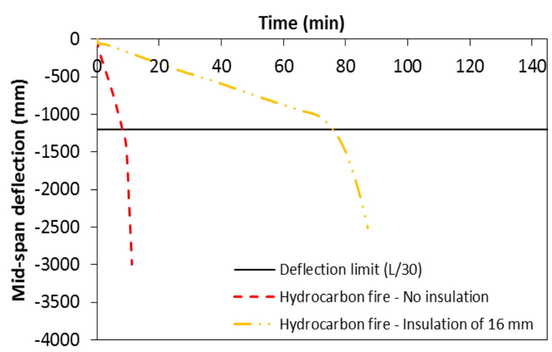
(c) Temperature progression in insulated girder (ISO 834)



(d) Temperature progression in insulated girder (hydrocarbon fire)



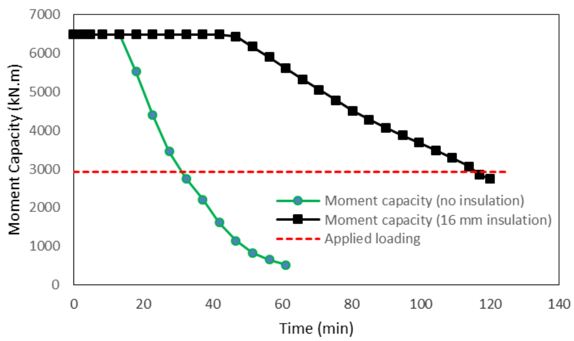
(e) Mid-span deflection (ISO 834)



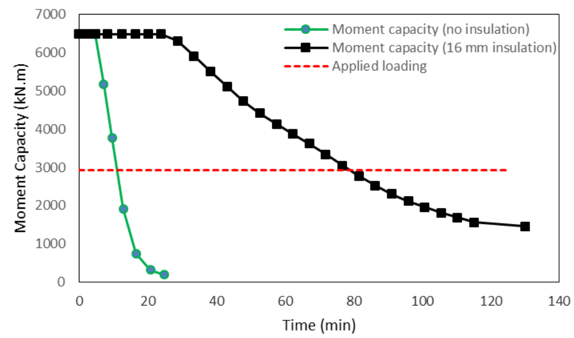
(f) Mid-span deflection (hydrocarbon fire)

This is a preprint draft. The published article can be found at: https://doi.org/10.1016/j.jcsr.2019.01.020

Please cite this paper as:
Kodur VK, Naser M.Z. (2019). "Designing steel bridges for fire safety." Journal of Constructional Steel Research. Vol. 156, pp. 46-53. (https://doi.org/10.1016/j.jcsr.2019.01.020).



(g) Degradation in flexural capacity (ISO 834)



(h) Degradation in flexural capacity (hydrocarbon fire)

Fig. 3 Thermal and structural response in uninsulated and insulated steel girder under different fire exposures

This is a preprint draft. The published article can be found at: https://doi.org/10.1016/j.jcsr.2019.01.020

Please cite this paper as:
Kodur VK, Naser M.Z. (2019). "Designing steel bridges for fire safety." Journal of Constructional Steel Research. Vol. 156, pp. 46-53. (https://doi.org/10.1016/j.jcsr.2019.01.020).

Fig. 4 Failure of I-65 bridge (courtesy of ALDOT)