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Strategies for Enhancing Fire Performance of Steel Bridges

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Abstract

Bridge fires can lead to significant economic and public losses; however, there are no provisions in current codes and standards for fire resistance design of structural members in bridges. This paper presents an approach for developing strategies to mitigate fire hazard in critical bridges. The proposed approach comprises of two steps; namely estimating fire risk in a bridge, and then developing strategies for minimizing fire hazard on a critical bridge. As part of the first step, an analytical procedure is employed to derive a fire-based importance factor to assess the vulnerability of a bridge to fire. When the bridge is susceptible to likely fire damage, the second step involves a sequential finite element analysis to develop alternate strategies for minimizing the consequences of fire hazard on that bridge. The applicability of this approach is demonstrated through case studies on two major steel bridges that experienced failure due to fire incidents in recent

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years. It is shown that the proposed approach can be used as a practical tool for identifying critical bridges from the point of fire hazard and then developing solutions to overcome fire hazard in such critical bridges.

Keywords: Bridge fires; Steel girders; Fire performance; Fire induced bridge collapse, Strategies, Importance factors, Finite element analysis.

1. Introduction

In recent years, bridge fires are becoming a growing concern due to rapid urbanization and increased ground transportation of hazardous materials (flammable and spontaneously combustible materials). The most common cause in many of bridge fire incidents is due to crashing of fuel transporting trucks, and burning of gasoline in the vicinity of a bridge. These bridge fires are typically characterized by high intensity burning, with peak temperatures reaching as high as 1000˚C within the first few minutes of ignition [1, 2]. Such intense fires, referred to as hydrocarbon fires, can cause significant structural damage or even collapse of the bridge, which can lead to large economic and public losses. These losses include maintenance or reconstruction costs of fire damaged bridge, in addition to indirect costs arising from delays resulting from traffic detouring to nearby routes.

Steel is widely used in bridge construction due to number of advantages steel possesses, including; higher strength, ductility, and cost considerations. However, steel structural members exhibit lower fire resistance due to rapid rise in steel temperatures

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resulting from high thermal conductivity, low specific heat, and lower sectional mass of steel. Further, mechanical properties (strength and modulus) of steel are highly sensitive to elevated-temperatures and steel structural members can lose their load carrying capacity rapidly under fire conditions. Therefore, steel bridges can be vulnerable to fire induced collapse.

Fire hazard in steel structural members in buildings is minimized through the provisions of active and passive fire protection systems prescribed in codes and standards. These provisions may not be directly applicable to bridges due to major differences in key factors such as fire severity, member characteristics and design objectives [5]. To date, there are no specific requirements in codes and standards for designing bridges to withstand fire hazard. This is due to the common assumption that probability of fire occurring on a bridge is rare and hence it is not practical to design all bridges for fire hazard. Further, only few of the bridge fires grow into larger size fires that can affect the structural members of a bridge. In addition, unlike in buildings, life safety of commuters is not severely at risk as bridges are often open structures.

There have been several bridge fire incidents in recent years [1-5]. The adverse consequences of fire on a bridge can be illustrated by looking at one such bridge fire incident which occurred on 9-mile road overpass at the I-75 expressway near Hazel Park, MI, USA. This fire incident occurred on July 15, 2009, when a fuel tanker transporting 50,000 liters of flammable fuel crashed into a passing truck close to the bridge. This collision initiated severe fire, which burned rapidly with temperatures exceeding 1000˚C.

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These high temperatures lead to rapid degradation of strength and stiffness properties in unprotected steel girders, leading to loss of capacity in the overpass steel girders; which in turn induced collapse of these girders within 22 minutes into fire. The collapse of the overpass caused significant losses and major traffic delays. The losses were estimated at 2 million US dollars and it took several weeks to repair the fire damaged bridge [3, 6].

Due to the increasing number of bridge fires, there is a need to develop practical approaches for evaluating vulnerability of critical bridges to fire hazard. Currently, there are lack of approaches and strategies for overcoming fire hazard in bridges. This paper presents a practical approach for mitigating fire hazards in bridges. The approach comprises of application of a fire-based importance factor for classification of a bridge based on fire risk and then undertaking detailed finite element analysis to develop relevant strategies for enhancing fire resistance of structural members, thereby minimizing vulnerability of a bridge to fire.

2. Proposed Approach for Mitigating Fire Hazard in Bridges

Although fire represents a significant hazard to bridges, it is still of a rare occurrence in the life span of a typical bridge. As a result, it is not economical or practical to design all bridges for fire hazard. Only bridges that are at high risk from the point of fire hazard should be designed for fire safety. Enhancing fire resistance of structural members is key to mitigate such fire hazard on bridges. Of all the different structural members, girders are more vulnerable since they are made of steel unlike bridge piers or abutments that are made of reinforced concrete. It has been well established that steel girders have lower fire performance when compared to concrete members [1-3]. This is due to the higher thermal conductivity and lower specific heat of steel.

2.1 General approach

The proposed approach for mitigating fire hazard in a bridge comprises of two main steps. In the first step, magnitude of fire hazard on a selected bridge is quantified analytically through the application of a fire-based importance factor. If the analysis indicate that fire risk to the bridge under consideration is high, then relevant strategies for mitigating fire hazard in that bridge is developed. For this purpose, in the second step, structural members of the selected bridge are analyzed under thermal and structural loading effects to evaluate inherent fire resistance. If the structural members (such as girders) have low fire resistance and cannot withstand adverse effects of fire, then the configuration of bridge structural members is to be modified, through measures such as providing fire insulation, to enhance fire resistance. The modified structure is reanalyzed till bridge structural members can withstand a design fire hazard. The analysis is carried out under various scenarios to develop optimum strategy for enhancing fire resistance of structural members. The associated steps in this approach are illustrated through a flow chart shown in Fig. 1.

2.2 Evaluating fire risk (*Step 1*)

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As part of the first step, the magnitude of fire risk to a bridge is to be quantified. This can be done by calculating a fire based importance factor for a given bridge [2, 4]. Relevant data on characteristics of the selected bridge is to be collected and analyzed. These characteristics take into account the degree of vulnerability of a bridge to fire, the critical nature of a bridge from the point of traffic functionality, and fire mitigation strategies adopted for that bridge. Using this data, a fire based importance factor for selected bridge is determined through an approach recently proposed in literature [2]. Based on the value of this fire-based importance factor, the bridge is grouped into one of the four risk grades namely low, medium, high and critical. If the bridge falls under "low" or "medium" risk grade, then the bridge is considered to be less susceptible to fire damage or collapse, and thus no additional measures may be needed to enhance fire safety of such a bridge. However, if the bridge falls under "high" or "critical" risk grade, then the bridge is deemed to be somewhat or highly susceptible to fire induced damage/collapse, and thus additional measures are needed to minimize fire hazard on that bridge.

In general, structural members in steel bridges that fall under "high" or "critical" risk grade often have inherent fire resistance (failure time) of much less than 45 minutes in a typical bridge fire [2, 4]. Thus, suitable strategies are to be developed to bring down the fire risk of these bridges to "low" or "medium" risk grade, so as to survive typical bridge fire exposure. This can be done through developing relevant strategies to enhance fire resistance (FR) of main structural members of a bridge. One such practical strategy is

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through the application of fire protection (insulation) to main structural members of a steel bridge. The applied fire protection should provide 60-120 minutes of fire resistance to main structural members of the selected bridge, since previous bridge fire incidents have shown that steel girders in a bridge can fail in 20-30 minutes under intense fire exposure and in many cases, open air fires gets controlled, in 60-120 minutes, through firefighting or reaching burn out conditions [1, 6, 8]. Thus, enhancing the fire resistance of structural members to 60-120 minutes through application of fire insulation to structural members can significantly lower the risk of collapse/damage to bridge. Full details on enhancing fire-based importance factors, including assessing weightage factors for various types of bridges, is given by Kodur and Naser [2].

2.3 Fire resistance analysis (*Step 2*)

As part of the second step, a finite element analysis is carried out to quantify inherent fire resistance of a selected bridge. Of the different structural members, steel girders in bridges are much more susceptible to fire induced damage, since other members (piers, abutments, and deck slab) are often made of concrete. Further, girders or decks experience the impact of fire exposure to a much higher degree than piers or abutments. Therefore, fire safety of a selected steel bridge can be enhanced by increasing fire resistance of girders. However, similar analysis can be carried out for any selected bridge structural member and relevant strategies can also be developed.

For evaluating fire resistance of such steel girders, detailed fire resistance analysis is required in Step 2. For this, a finite element analysis can be carried out utilizing a three dimensional nonlinear finite element model that is capable of handling thermo-mechanical problems and integrating nonlinear temperature-dependent material properties. To evaluate fire resistance of steel bridge girders, two sets of discretization models are to be developed for undertaking thermal and structural analysis [9, 10]. The discretization adopted for modeling heat transfer and structural analysis of the steel bridge girder is shown in Fig. 2. Full details on discretization of structural members, high temperature properties of concrete and steel and failure modes to be considered in undertaking fire resistance analysis is given by Kodur et al. [6].

After evaluating inherit fire resistance, if the resulting fire resistance of bridge (girder) is higher than required (design) fire resistance (generally of 60 to 120 minutes), then no additional measures may be needed to enhance fire safety of such a bridge. However, if fire resistance of bridge is less than the required fire resistance, then suitable fire mitigation strategies are to be developed to enhance fire resistance of structural members.

2.4 Deriving optimum fire protection strategies (*Steps 3, 4* and *5*)

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As discussed above, through the application of fire protection (insulation) to steel bridge girders, fire resistance of main structural members can be enhanced and overall fire hazard on a bridge can be minimized. The enhanced fire resistance of reconfigured (fire insulted) steel bridge can be evaluated through finite element analysis. If the applied fire protection enhances the fire resistance of vulnerable members to meet design requirements (60-120 minutes), then the importance factor of the girders is re-assessed, taking into account the applied fire protection. If the fire risk grade of the structural member decreases to "medium" or "low" risk grade, this indicates that the fire risk to bridge is minimized. At this point, the analysis is completed and the needed fire protection system is arrived at.

If the fire resistance of the structural members is still less than the needed fire resistance and/or if the bridge still falls under "critical" or "high" fire risk grade, then a repeated strategy, such as incorporating thicker fire insulation, is to be adopted and the above steps are to be repeated till the fire risk grade of the bridge decreases to "medium" or "low" risk category. The step-by-step procedure for undertaking above discussed proposed approach is shown in Fig. 1.

3. Case Studies

The applicability of the above discussed approach to two practical situations is illustrated by selecting two steel bridges that experienced damage due to fire hazard in recent years. It should be noted that these bridges were designed and built without any special consideration to fire safety (resistance) provisions.

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3.1 Case Study 1: I-65 Birmingham Bridge

3.1.1 Description of bridge fire incident

On January 5, 2002, a tanker truck carrying 9,900 gallons of diesel fuel collided with the pier of the I-65 overpass at the I-20, I-59 and I-65 junction near Birmingham, Alabama, USA. The intense heat from the burning of flammable fuel reached about 1100°C and this high-temperature resulted in degradation of capacity and stiffness of steel girders causing the main span (steel girder number 7) to sag about 3 m. After this fire incident, the bridge had to be shut down and commuters were detoured to alternative highway routes. The repairs costed about $1.325 million and the bridge was re-opened for traffic after 54 days of necessary repairs [11].

3.1.2 Characteristics of bridge

This steel bridge comprised of three simply supported spans (main span and two side approach spans). The middle (main) span, over the highway, was of 36 m length, while the side approach span was of 25 m on both sides of the main span. Each span consisted of seven girders, spaced equally at a transverse spacing of 2.15 m and supported laterally with cross "X" bracing.

The bridge comprised of steel girders (built-up sections), supporting a concrete slab of 170 mm thickness with an effective width of 2.15 m. The flange plates are 457 mm width and 28 mm thickness, and the web plate has dimensions of 1344 mm depth and 12 mm thickness. The steel girders are 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. The girders are made of steel of yield strength of 350 MPa, while the concrete used in slab had a compressive strength of 40 MPa [10, 12].

3.1.3 Evaluating fire risk based on importance factor (*Step 1*)

The various characteristics of this bridge and details of the above described fire incident were collected from literature [11]. Then, the above discussed "fire based importance factor" approach was applied to evaluate vulnerability of this bridge to fire. Since the unprotected steel girders generally exhibit much lower fire resistance than reinforced concrete piers or concrete decks, probability of fire induced damage or failure to steel girders is much higher than that to concrete piers/concrete decks. Hence, the fire based importance factor for this bridge is governed by the fire performance of steel girders. This is due to the fact that loss of strength and stiffness properties of steel with temperature is at a much faster pace than that of concrete. Hence, concrete members generally exhibit higher fire resistance as compared to steel structural members. Following the outlined procedure and shown in Fig. 1 (Step 1), the fire-based importance factor for this bridge works out to be 1.2, which places this bridge under "high" risk grade [2]. Detailed calculation for evaluating importance factor is given in Appendix A.

3.1.4 Evaluating inherent fire resistance of steel members (*Step 2*)

Since I-69 bridge falls under "high" risk category, this bridge is highly vulnerable to fire hazard. To evaluate inherent fire resistance of the girder through numerical simulation, finite element analysis was undertaken as part of Step 2, full details of which are given in reference [7]. Steel girder number 7 of the main span (that has a length 36 m) of I-69 bridge, which experienced the most damage in fire is selected for fire resistance analysis. This girder is analyzed independently since the main span is simply supported and separated by expansion joints from the adjacent spans. The fire resistance analysis is carried out under the combined effect of fire exposure (two fire scenarios i.e., ISO 834 and hydrocarbon fire) and applied service loading [13-15]. The applied loading comprised of self-weight of girder (steel section) and that contributed from the tributary area of the concrete slab and wearing surface.

Results from thermal analysis on I-65 girder under both hydrocarbon and ISO 834 fires are plotted in Fig. 3 to illustrate temperature distribution in steel-concrete composite girder as a function of time. It can be seen that the temperature in top flange is much lower than that in the bottom flange in the girder. This is mainly due to the insulating effect of the concrete slab in which heat gets dissipated from the top flange to the concrete slab. Also, the temperatures in the web are higher as compared to that in bottom flange and this is because the web is much more slender (lower thickness), has larger exposed surface area than the flanges, and this produces rapid rise in web temperatures. It should be noted that

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hydrocarbon fires are much more severe than standard fire scenario (ISO 834) since these fires are characterized by high intensity fires with peak temperatures reaching as high as 1000 °C within first few minutes of fire.

The large difference in temperatures between the web and mid-depth of the slab leads to significant thermal gradients across the girder-slab cross section. These thermal gradients are primarily influenced by the type of fire scenario. In general, higher thermal gradients produce higher thermal strains at the bottom of the steel girder (and in web), as compared to that in concrete slab, leading to significant curvature (thermal bowing) in the girder.

The structural response of I-65 bridge girder is illustrated in Fig. 4, where mid-span deflection is plotted as a function of fire exposure time under ISO 834 and hydrocarbon fire scenarios. At the early stage of fire, mid-span deflection increases linearly up to yielding of steel girder. Most of the deflections at the early stage of fire exposure (when steel temperature is below 400°C) are mainly due to thermal curvature resulting from high temperature gradients that develop along the girder section. Therefore, steel girders experience different magnitude of deflection depending on thermal gradients arising due to different fire severity under two fire scenarios. Hence, the girder in the case of hydrocarbon fire experiences much higher deflections at the early stage of fire exposure as compared to that of ISO 834 fire exposure.

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The deflection increases with fire exposure time due to rise in temperature in the steel girder, and this increase is much more predominant in the case of hydrocarbon fire, as compared to ISO 834. This results in deterioration in strength and stiffness properties of steel and spread of plasticity in the section. At this stage, the web starts to experience some level of instability due to local buckling resulting from high temperature rise in the slender web [16, 17].

During the final stages of fire exposure, the rate of deflection increases significantly due to spread of plasticity in to bottom flange and further buckling of the web that result from faster strength and stiffness degradation of steel at high temperature (and also due to the effects of high temperature creep). Finally, the steel girder experiences run-away failure due to loss of flexural capacity resulting from rapid degradation of strength and stiffness properties, excessive web buckling and mid-span deflection.

Results plotted in Fig. 4 show that fire resistance (failure time) of a steel girder is highly influenced by the fire exposure scenario (level of fire severity). I-69 bridge girder exposed to hydrocarbon fire fails in just 9 minutes, while this steel girder survives for 24 minutes under ISO 834 fire exposure. This variation can be attributed to severity of fire intensity in the case of hydrocarbon fire that is much higher as compared to that of ISO 834 fire exposure.

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3.1.5 Developing strategies for enhancing fire resistance (*Step 3*)

Since the uninsulated steel girder fails early into fire exposure, the fire performance of this girder is deemed poor and can lead to substantial damage/complete collapse of this bridge in the event of fire. To minimize the vulnerability of this steel bridge to fire hazard, strategies has to be developed to enhance fire resistance of this girder; as outlined in Step 3 of Fig. 1. One such strategy is through the provision of fire insulation to girders.

In this study, a gypsum based spray applied fire insulation (SFRM) is applied on the steel girder. In order to arrive at an optimum fire protection thickness and insulation scheme, finite element analysis of I-69 bridge girder is carried out in ANSYS [18] utilizing various thicknesses of SFRM including 7 mm, 12.7 mm, 14 mm, 16 mm, 18 mm, 20 mm, 25 mm and 30 mm. For each insulation thickness, the steel girder was analyzed under two fire scenarios (ISO 834 and hydrocarbon) and corresponding fire resistance is evaluated.

Figure 5 shows predicted temperature progression in the insulated (reconfigured) I-69 bridge girder corresponding to 16 mm SFRM thickness on steel girders. The thermal response of the insulated steel girder follows a similar trend of that observed in the uninsulated girder, but with much lower rise in sectional temperatures, as can be seen by comparing temperatures in Figs. 3 and 5. Similarly, mid-span deflection in insulated girder increases at a slower rate than that in the case of bare steel girder, that can be seen by comparing deflections in Figs. 4 and 6. This is due to the effect of applied fire insulation on girder that produce slower rise in steel temperatures.

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It can be seen in Fig. 6 that mid-span deflection decreased significantly due to applied SFRM on steel girders as a result of slower progression of temperatures in the steel section. Fire resistance of this girder with 16 mm thick insulation increases from 24 minutes to 113 minutes under ISO 834 fire exposure, while the corresponding increase in fire resistance of this girder is from 9 minutes to 76 minutes under hydrocarbon fire conditions. Similarly, fire resistance of this girder with 18 mm thick insulation increases to 124 minutes under ISO 834 fire exposure, while the corresponding increase in fire resistance of this girder is 120 minutes under hydrocarbon fire conditions.

This enhanced fire resistance to 60 minutes or higher can significantly lower the risk of fire-induced (collapse or damage) since bare steel girders can fail within 20-30 minutes of fire. Typically the average response time for firefighters to arrive at a fire incident can be 20-30 minutes. Provision of fire resistance of 60 to 120 minutes can give sufficient time to fight the fire or for the fire to burn out on its own in most scenarios [2, 6].

3.1.6 Re-evaluating fire risk based importance factor (Step 5)

Predictions from finite element analysis indicate that applying 18 and 30 mm thick fire protection in I-69 bridge girder can delay temperature progression within steel girders and enhance fire resistance to about 120 minutes (for ISO 834 and hydrocarbon fire scenarios) depending on fire exposure scenario. To account for this added fire protection on girder, the fire-based importance factor is re-evaluated by considering all characteristics

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of the bridge (as in Step 1), including added fire protection to the girder. The revised importance factor was evaluated to be 1.0, indicating that this bridge falls under "medium" fire risk category. This indicates that the bridge is less susceptible to fire damage/collapse and no additional measures may be needed to enhance fire safety of this bridge. Detailed calculations illustrating the computation of revised importance factor (Step 5 of flow chart in Fig. 1) is given in Appendix. Table 1 summarizes importance factor, risk grade, and failure times of I-69 bridge, with and without fire insulation, under ISO 834 and hydrocarbon fire scenarios.

3.2 Case Study 2: I-80/880 MacArthur Maze Bridge

To further illustrate the applicability of the above approach, a second bridge that experienced a recent fire incident is analyzed using the above developed methodology. Only main highlights and findings for this bridge is presented here.

<u>3.2.1 Description of bridge fire incident</u>

A fire incident occurred on MacArthur Maze bridge (I-80/880 interchange) in Oakland, California on April 29th, 2007. The fire started when a tanker truck carrying 8,600 gallons of gasoline overturned on a connector ramp of I-80/880, underneath I-580 expressway. The firefighters responded to the incident within 14 minutes, but the intense fires from the accident resulted in fire temperatures reaching 1100^{o}C. This intense heat led to deterioration of strength and stiffness properties in the steel box support girder leading

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to collapse of two I-580 spans. The first span of the overpass collapsed in about 17 minutes following the start of the fire, and a second adjacent span also collapsed about 5 minutes after the first collapse. This incident costed $9 million to repair the bridge, economic impact of $6 million per day, and took a month to finish the repairs and retrofitting.

3.2.2 Characteristics of bridge

MacArthur Maze bridge comprised of six steel girders (built-up section), supporting a concrete slab of 19.7 mm thickness and effective width of 2.0 m. The first span that collapsed under fire was 25.6 m length, while the second collapsed span was 23.5 m long. The dimensions of the top flange plate are of 304.8 mm width and 25.4 mm thickness, while the bottom flange has same width as top flange but 50.8 mm thickness. The web plate has dimensions of 1080 mm depth and 12.7 mm thickness. The steel girders are stiffened with intermediate stiffeners at spacing-to-depth ratio of 1.0 along the span, and a thickness of 12 mm. The steel girders are made of yield strength of 345 MPa, while the concrete used in slab has a compressive strength of 24.8 MPa [20].

3.2.3 Evaluating fire risk based on importance factor (*Step 1*)

The various characteristics of the bridge and details of fire incident was collected from available data in literature. Following the outlined procedure in literature [2, 4] and as in case study 1, the fire-based importance factor for this bridge works out to be 1.2, which places this bridge under “high” risk grade. Bridges in this category can experience

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partial/complete collapse of main structural elements, partial shutdown of operation with possible human injuries/losses when exposed to fire conditions [4].

3.2.4 Evaluating inherent fire resistance of steel members (*Step 2*)

This bridge is analyzed to evaluate fire response through finite element analysis. The developed finite element model is applied to evaluate fire resistance of I-80/880 bridge girder. A typical girder of this bridge is analyzed with simply supported end conditions under effects of ISO 834 (as well as hydrocarbon fire scenarios) and applied service loading.

Results from analysis are utilized to evaluate inherent fire resistance of steel girder. As expected, the temperature profile of I-80/880 bridge follows similar trend as I-69 bridge, but increases at a slightly lower rate. This is due to thicker flanges and lower web slenderness in I-80/880 bridge girder, as compared to girders in that in I-69 bridge girder (case study 1). The structural response of I-80/880 bridge, girders girder is illustrated in Fig. 7, where mid-span deflection is plotted as a function of fire exposure time under ISO 834 and hydrocarbon fire scenarios. Results presented in this figure show that I-80/880 bridge girder fails in about 12 minutes under hydrocarbon fire as compared to 35 minutes for ISO 834 fire exposure. Also, it can be seen that I-80/880 bridge girder exhibit higher fire resistance than I-69 bridge girder. This is attributed to lower web slenderness and shorter span of I-80/880 bridge as compared to I-69 bridge girder.

3.2.5 Developing strategies for enhancing fire resistance (*Step 3*)

The above results clearly infer that this bridge experienced substantial damage and collapse under fire due to the lower fire resistance of the girder in the event of fire. Also, it can be inferred that the bridge could have performed better if the fire resistance of girders were higher. In order to enhance fire resistance, the girders were provided with supplemental fire insulation. Further, to optimize fire protection thickness and insulation scheme, finite element analysis of steel girder is carried out in ANSYS utilizing varying thicknesses of fire insulation including 7 mm, 12.7 mm, 14mm, 16 mm, 20 mm, 22 mm and 25 mm. For each insulation thickness, the steel girder was analyzed and the corresponding fire resistance is evaluated.

A summary of results from numerical analysis is shown in Fig. 8 for various fire insulation thicknesses on girder. The structural response of this girder with insulation thickness of 12.7 mm (for 60 minutes fire rating), 14 and 22 mm (for 120 minutes fire rating for ISO834 and hydrocarbon fire scenarios) is selected as optimum insulation thickness to enhance fire resistance. It can be seen from Fig. 8 that mid-span deflection decreases significantly due to supplemental fire insulation on steel girder. This results in slower progression of temperatures in the steel section. The use of this insulation thickness enhanced fire resistance of girder from 35 minutes to 111 and 120 minutes under ISO 834 fire exposure, while the fire resistance of same girder increase from 12 minutes to 75 and 122 minutes under hydrocarbon fire condition.

Following finite element analysis predictions, it can be seen that provision of a 12.7 mm thick fire insulation on I-80/880 bridge girders could have delayed temperature progression within steel girders and enhanced its fire resistance to 75 minutes based on fire exposure scenario. While the use of a 14 and 22 mm thick fire insulation on the same bridge girders could have enhanced its fire resistance to 120 and 122 minutes for ISO 834 and hydrocarbon fire exposure.

3.2.6 Re-evaluating fire risk based importance factor (Step 5)

To illustrate the lower fire risk with added fire insulation, after applying fire protection, fire-based importance factor is re-evaluated. The fire based importance factor of unprotected bridge with insulated girder works out to be 1.0 and the modified bridge configuration falls under "medium" fire risk category, which infers the bridge to be less susceptible to fire damage. Table 2 summarizes importance factor, risk grade, and failure time in steel girders under different fire scenarios.

4. Practical Implications

This paper presents the application of a rational methodology for assessing fire risk in a bridge and then developing relevant strategies to overcome such fire hazard on a given bridge. The two case studies illustrated here are for a bridges that fall under "high" risk category. It should be noted that the approach can be extended to piers and abutments, bridges with different structural systems, as well as different structural members, and fire scenarios. Also, this approach can be applied to quantify fire risk in new or existing bridges,

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and to develop optimum fire mitigation strategies to enhance fire performance of bridges. Further details on the derivation of importance factor, different case studies, and rationale behind key characteristics used in evaluating importance factor can be found in references [2, 4]. Similarly, further details on finite element analysis to evaluate fire resistance of structural members in bridges can be found in references [9, 10]. Overall, the proposed approach can be a practical tool for developing relevant strategies for mitigating fire hazard in bridges.

5. Conclusions

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

1. Fire represents a severe hazard to structural members in bridges and can induce significant damage or collapse in certain adverse fire scenarios.

2. The proposed approach for mitigating fire hazard comprises of estimation of fire risk in a bridge and then undertaking detailed finite element analysis to develop relevant strategies for evaluating fire resistance of structural members in bridges.

3. It should be noted that the proposed importance factor (or fire risk) is derived by considering a wide range of parameters to take into account various bridge characteristics and importance of the bridge.

4. Steel structural members in a bridge can experience failure in 20-30 minutes under severe fire conditions. Provision of fire insulation in girders can enhance

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failure time to 60-120 minutes and this can mitigate fire hazard on most critical bridges.

5. The proposed approach can be applied to quantify fire risk in existing and new bridges and to develop suitable strategies for overcoming fire hazard in bridges.

6. References

[1] Department of Transportation, Federal Highway Administration, Highway Statistics, 1995-2010: Ibid, Highway Statistics (Washington, DC: Annual Issues). 2010.

[2] Kodur V, Naser M. Importance Factor for Design of Bridges Against Fire Hazard. Engineering Structures 2013;54:207-220.

[3] Garlock M, Paya-Zaforteza I, Kodur VK, and Gu L. Fire hazard in bridges: Review, assessment and repair strategies, Engineering Structures 2012;35:89-98.

[4] Naser MZ, Kodur VK. A probabilistic assessment for classification of bridges against fire hazard. Journal of Fire Safety 2014;76:65–73.

[5] Kodur VK, Gu L, Garlock M. Review and Assessment of Fire Hazard in Bridges. Transportation Research Record 2010;2172: 23-29.

[6] Kodur VK, Aziz E, Dwaikat M. Evaluating Fire Resistance of Steel Girders in Bridges. J. Bridge Eng. 2013;18(7):633–643.

[7] Protect

[8] Aziz E., Kodur VK. An approach for evaluating the residual strength of fire exposed bridge girders. Journal of Constructional Steel Research 2013;88:34-42.

Please cite this paper as:

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[9] Aziz E.. Response of Fire Exposed Steel Bridge Girders. (Ph.D. dissertation) submitted to Department of Civil and Environmental Engineering, at Michigan State University, East Lansing, USA. 2015.

[10] Aziz E., Kodur VK. Glassman J, Garlock M. Behavior of Steel Bridge Girders under Fire Conditions. Journal of Constructional Steel Research 2015;(106):11-22.

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

[12] Wright W, Lattimer B, Woodworth M, Nahid M, Sotelino E. Highway Bridge Fire Hazard Assessment. Virginia Polytechnic Institute and State University, Blacksburg, VA. 2013.

[13] ISO834-1975: Fire resistance tests – elements of building construction, International Organization for Standardization, 1975.

[14] ASTM E119a. "Standard Methods of Fire Test of Building Construction and Materials." American Society for Testing and Materials, West Conshohocken, PA. 2008.

[15] ASTM Test Method E1529. Standard test methods for determining effects of large hydrocarbon pool fires on structural members and assemblies. American Society for Testing and Materials, West Conshohocken, PA. 1993.

[16] Naser MZ, Kodur VKR. Factors Governing onset of Local Instabilities in Fire Exposed Steel Beams. Journal of Thin-Walled Structures 2016;98:48-57.

[17] Kodur VKR, Naser MZ. Effect of Local Instability on Capacity of Steel Beams Exposed to Fire. Journal of Constructional Steel Research 2015;111:31-42.

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

[19] Choi J. Concurrent Fire Dynamics Models and Thermo-mechanical Analysis of Steel and Concrete Structures. (Ph.D. dissertation), Georgia Institute of Technology, Atlanta, GA, USA. 2008.

[20] Quiel S, Yokoyama T, Bregman L, Mueller K, Marjanishvili S. A Streamlined Framework for Calculating the Response of Steel-Supported Bridges to Open-Air Tanker Truck Fires. J. of Fire Safety 2015;73:63–75.

Appendix

Example illustrating calculations of importance factor for I-65 Birmingham bridge

The developed approach is used to quantify importance factor (fire risk) for I-65 Birmingham bridge. This bridge experienced damage due to a fire hazard in 2002. It should be noted that this bridge was designed and built without any special consideration to fire safety (resistance) provisions. The following steps highlight the procedure used in utilizing the developed importance factor approach.

*** Collecting data and statistics**

- Such information can be collected from the open literature i.e., journal articles, conference proceedings, design reports, news articles, construction and design firms as well as governmental databases.

**** Assigning weights (φ) for different parameters (from tables presented in Refs. [2, 4])**

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- These weightage factors as assigned for the different characteristics of the bridge such as Geometrical features, material properties and design characteristics Hazard (fire) likelihood, Traffic demand, Economic impact, Expected fire losses and Fire mitigation strategies used/available in the bridge.

Step 1: Evaluate fire based importance factor and risk grade

Hence, the individual class coefficients (Δ) are as follows:

$$\Delta_x = \frac{\sum \varphi_{i,x}}{\sum \varphi_{x(\max)}}$$

where,

$\varphi_{i,x}$ is the weightage factor of sub-parameter (i) in class (x)

$\varphi_{x(max)}$ is the maximum weightage factors of each parameter in class (x)

$$\Delta_g \frac{3+3+3+1+1+1+4+5}{5+4+5+4+3+4+5+5} = \frac{25}{35} = 0.60$$

$$\Delta_h = \frac{1+1+1+4}{5+3+3+5} = \frac{7}{16} = 0.44$$

$$\Delta_t = \frac{3+2}{5+3} = \frac{6}{8} = 0.63$$

$$\Delta_e = \frac{1+1+2}{3+3+3} = \frac{4}{9} = 0.44$$

$$\Delta_f = \frac{1+1}{3+3} = \frac{3}{6} = 0.33$$

Calculation of overall class coefficient (λ)

Then, the overall class coefficient (λ) is given by:

$$\lambda = \Delta_g \times \psi_g + \Delta_h \times \psi_h + \Delta_t \times \psi_t + \Delta_e \times \psi_e + \Delta_f \times \psi_f$$

$$\lambda = 0.60 \times 0.47 + 0.44 \times 0.22 + 0.63 \times 0.11 + 0.44 \times 0.12 + 0.33 \times 0.08 = 0.53$$

Obtaining risk grade and Importance factor (IF)

Risk grade for the bridge is "high" and associated importance factor is 1.2.

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Steps 2, 3 and 4 are conducted numerically

- These steps are conducted using the developed finite element analysis. The analysis is continued until an optimum fire mitigation strategy (i.e., fire insulation thickness) is arrived at.

Step 5: Re-evaluating importance factor and risk grade based on numerical analysis

$$\Delta_{fms}=\frac{0+0+3}{4+4+5}=\frac{3}{13}=0.23$$

Calculation of updated overall class coefficient (λ_u)

Then, the updated overall class coefficient (λ_u) is given by:

$$\lambda_u = \Delta_g \times \psi_g + \Delta_h \times \psi_h + \Delta_t \times \psi_t + \Delta_e \times \psi_e + \Delta_f \times \psi_f - \Delta_{fms} \times \psi_{fms}$$

$$\lambda_u = 0.60 \times 0.47 + 0.44 \times 0.22 + 0.63 \times 0.11 + 0.44 \times 0.12 + 0.33 \times 0.08 - 0.23 \times 0.18$$

$$\lambda_u == 0.49$$

Obtaining risk grade and Importance factor (IF),

Risk grade for the bridge is "medium" and associated importance factor is 1.0.

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Fig. 5. Cross-sectional temperatures progression in insulated (with 16 mm insulation thickness) I-69 bridge girder

Fig.6. Mid-span deflection in insulated I-69 bridge girder under various fire scenarios

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Fig. 8. Mid-span deflection in insulated I-80/880 bridge girder under various fire scenarios

Table 1: Summary results of case study on evaluating fire risk in I-65 Birmingham bridge

Case study	Girder Condition		Fire scenario	Insulation thickness (mm)	Importance factor	Risk grade	Failure time (minutes)
			ISO 834	-	1.2	High	24

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I-69 Birmingham Bridge	Without fire insulation strategy	Bare steel girder	Hydrocarbon	-	1.2	High	9
	With fire insulation strategy	Insulated steel girder	ISO 834	16	1	Medium	113
			ISO 834	18	1	Medium	124
			Hydrocarbon	16	1	Medium	76
			Hydrocarbon	30	1	Medium	120

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Table 2: Summary results of case study on evaluating fire risk in I-80/880 MacArthur Maze bridge

Case study	Girder Condition		Fire scenario	Insulation thickness (mm)	Importance factor	Risk grade	Failure time (minutes)
I-80/880 MacArthur Maze Bridge	Without fire insulation strategy	Bare steel girder	ISO 834	-	1.2	High	35
			Hydrocarbon	-	1.2	High	12
	With fire insulation strategy	Insulated steel girder	ISO 834	12.7	1	Medium	111
			ISO 834	14	1	Medium	120
			Hydrocarbon	12.7	1	Medium	75
			Hydrocarbon	22	1	Medium	122

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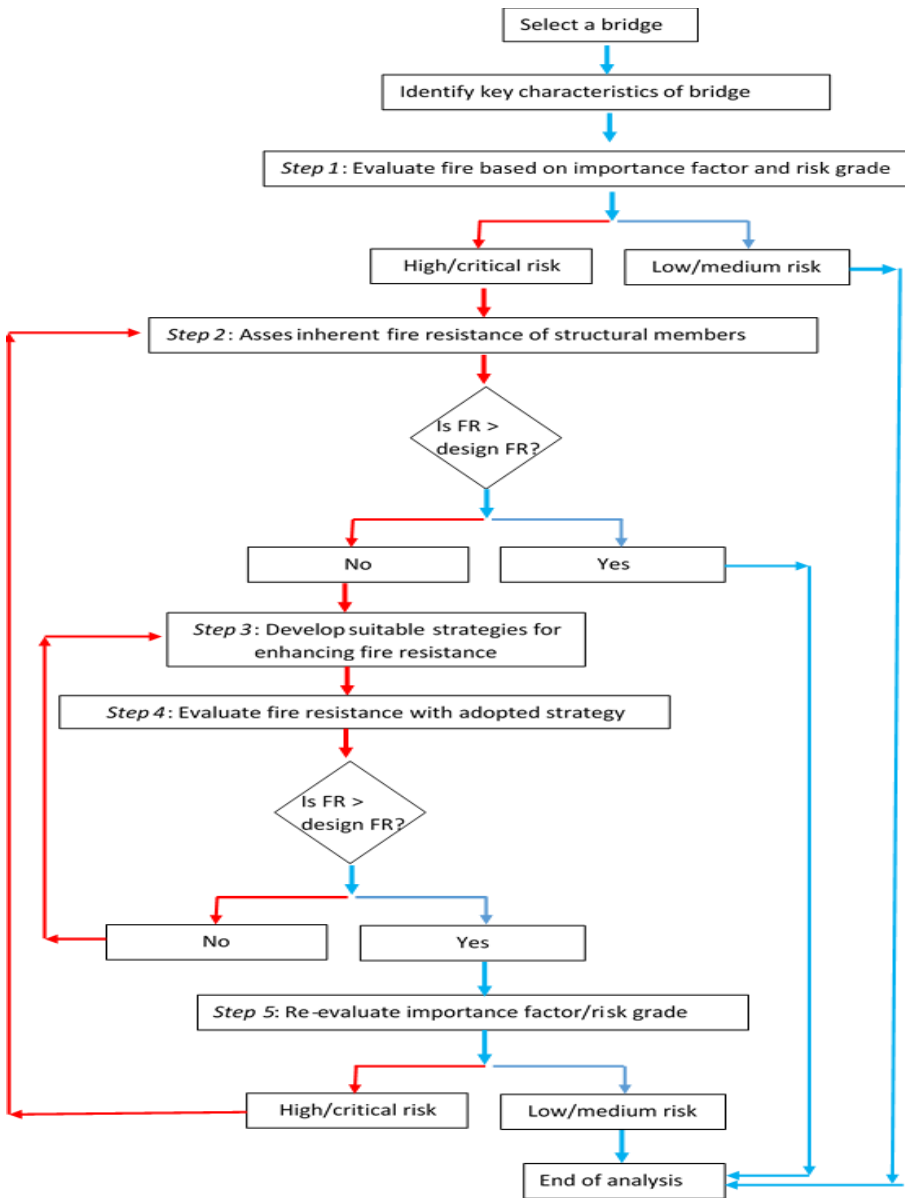

Fig. 1. Flow chart of the proposed approach for mitigating fire hazard in bridges [7]

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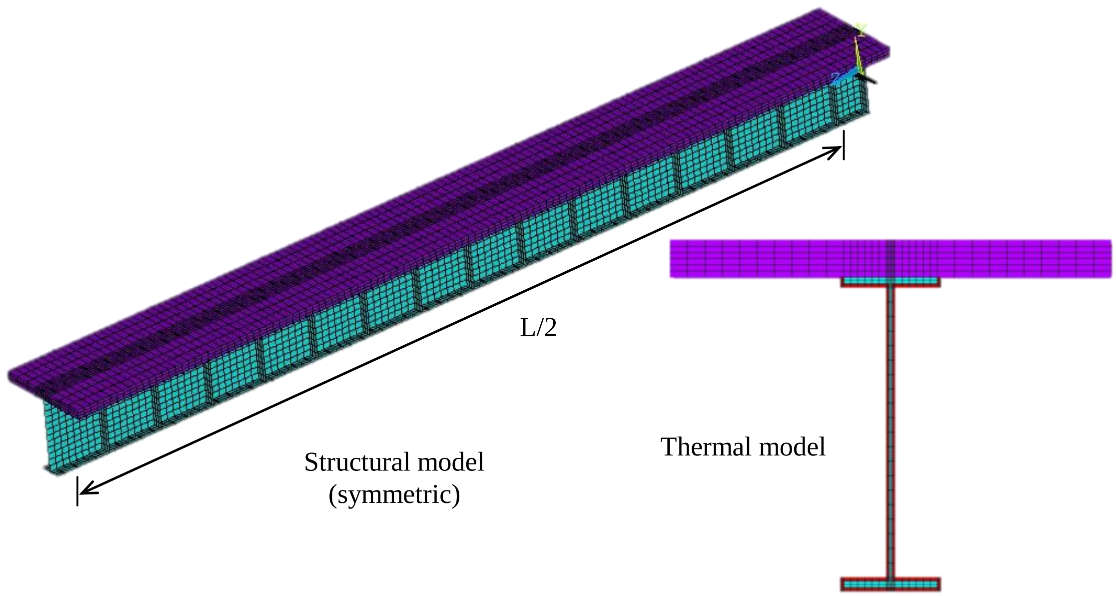

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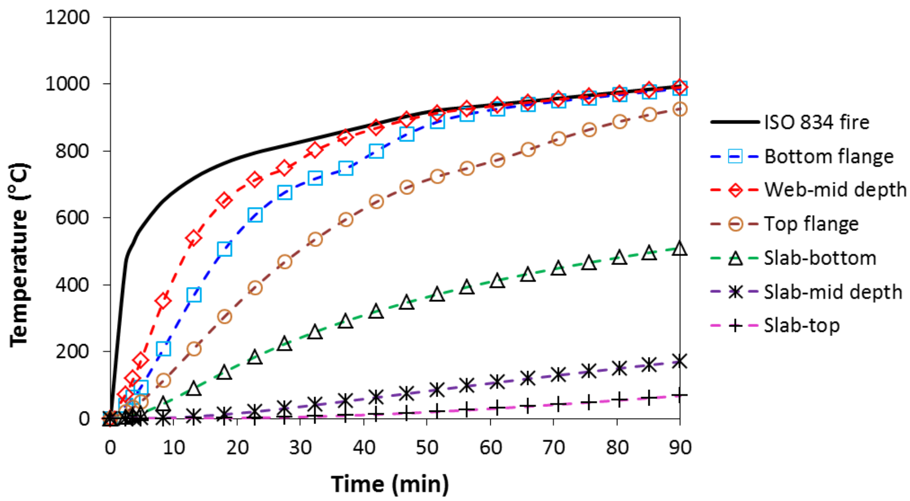

(a) ISO 834 fire

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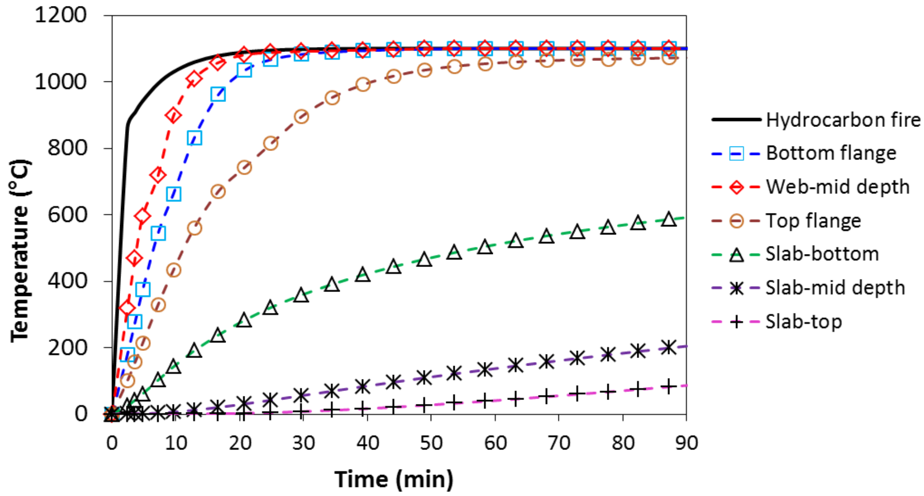

(b) Hydrocarbon fire

Fig. 3. Cross-sectional temperatures progression in bare I-69 bridge girder

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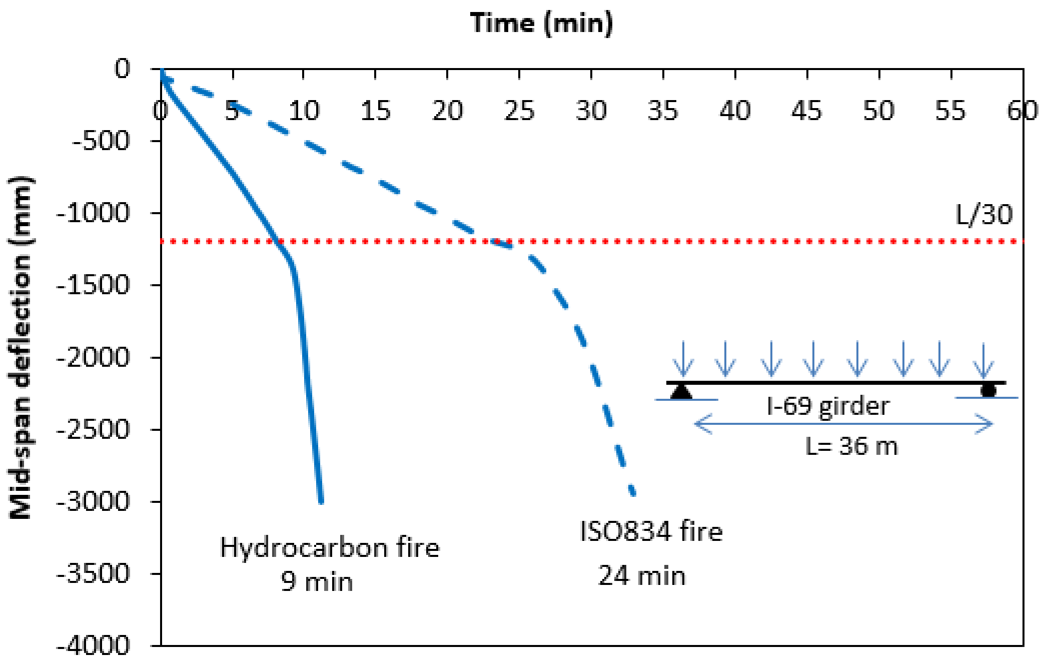

Fig.4. Mid-span deflection in uninsulated I-69 bridge girder under various fire scenarios

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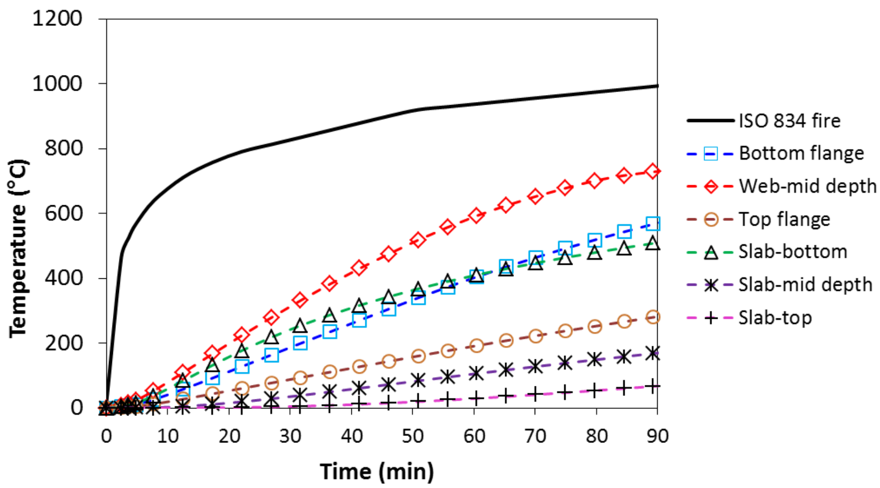
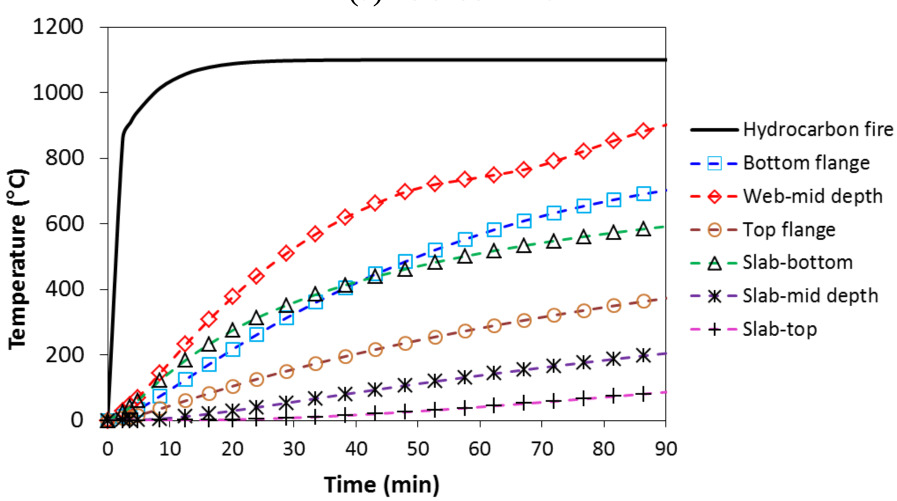


(a) ISO 834 fire



(b) Hydrocarbon fire

Fig. 5. Cross-sectional temperatures progression in insulated (with 16 mm insulation thickness) I-69 bridge girder

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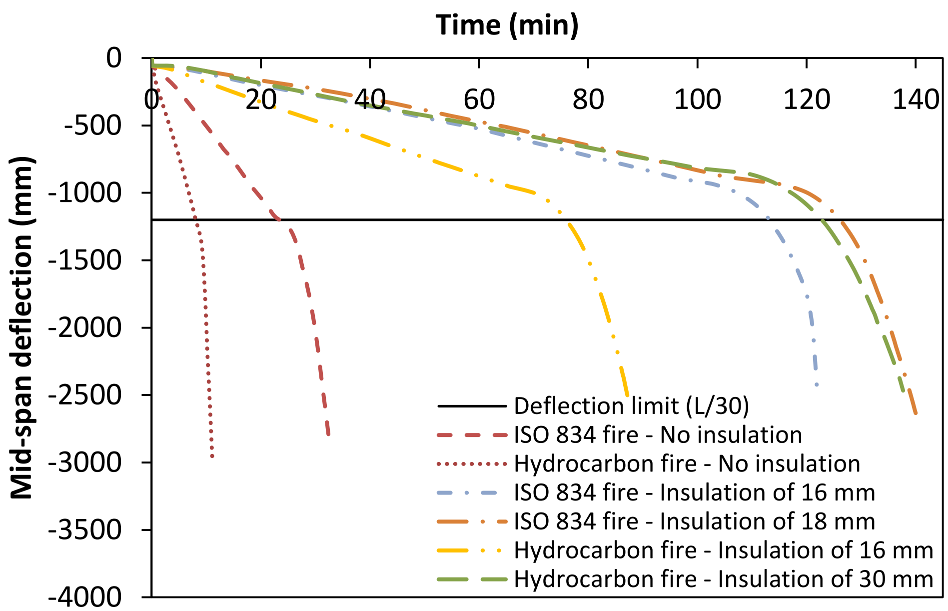

Fig.6. Mid-span deflection in insulated I-69 bridge girder under various fire scenarios

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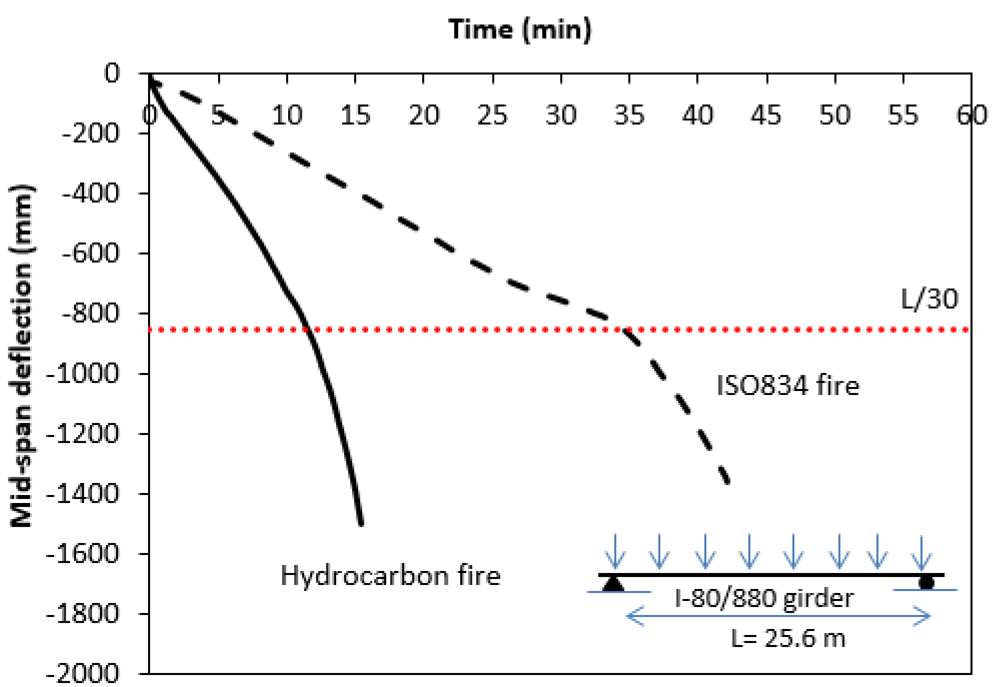

Fig.7. Mid-span deflection in uninsulated I-80/880 bridge girder under various fire scenarios

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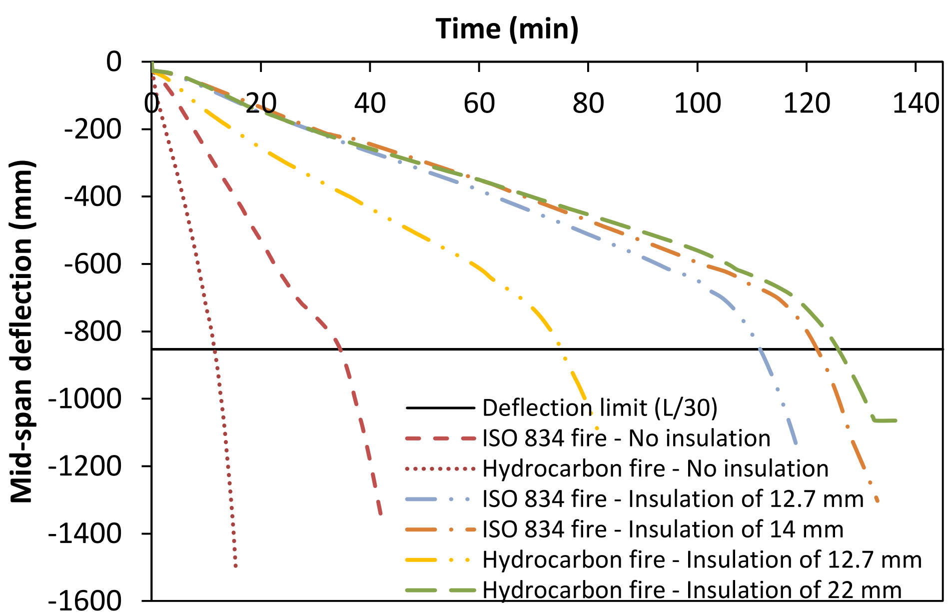

Fig. 8. Mid-span deflection in insulated I-80/880 bridge girder under various fire scenarios