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Evaluating fire resistance of prestressed concrete bridge girders

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Abstract. This paper presents an approach for evaluating performance of prestressed concrete (PC) bridge girders exposed to fire. A finite element based numerical model for tracing the response of fire exposed T girders is developed in ANSYS. The analysis is carried out in three stages, namely, fire temperature calculation, cross sectional temperature evaluation, and then strength, deformation and effective prestress analysis on girders exposed to elevated temperatures. The applicability of the computer program in tracing the response of PC bridge girders from the initial preloading stage to failure stage, due to combined effects of fire and structure loading, is demonstrated through a case study, and validated by test data of a scaled PC box girder under ISO834 fire condition. Results from the case study show that fire severity has a significant influence on the fire resistance of PC T girders and hydrocarbon fire is most dangerous for the girder. The prestress loss caused by elevated temperature is about 10% under hydrocarbon fire till the girder failure, which can lead to the increase in deflection of the PC girder. The rate of deflection failure criterion is suggested to determine the failure of PC T girder under fire.

Keywords: bridge fires; fire resistance; PC girders; FEM analysis; failure criterion; fire scenario

1. Introduction

Fire hazard in bridges is a low probability event; however consequences of such fires on a bridge can be disastrous. In recent years, bridge fires have become a growing concern due to excessive transportation of hazardous materials such as deflagration materials and flammable materials. Bridge fires can cause serious economic and property losses, and in some cases even loss of life. Following the fire, there can be congestion and chaos in surrounding traffic network, and is usually hard to detour. Further, a severe fire may lead to significant damage or even collapse of a bridge.

There have been numerous bridge fire incidents in recent years and these incidents have been documented in the literature (Kodur and Naser 2013, Garlock and Paya-Zaforteza 2012). A review of literature indicates that many of these bridge fire incidents are frequently caused by collision of trucks and burning of gasoline in the vicinity of a bridge. Such gasoline fires, also referred to as hydrocarbon fires, are usually much more severe than building fires. The burning of these fires is rapid and violent, and high peak temperatures of more than 1000℃ can be generated within the first few minutes. In some cases, such severe fires can pose a serious threat to structural components of a bridge and might induce partial or full collapse of structural members.

Adverse consequences of such fires on bridges can be minimized through provision of suitable fire resistance to structural members, such as girders and piers (Kodur and Naser 2013). Fire resistance is the duration during which a structural member exhibits resistance to destructive impact of fire exposure. Fire resistance can be achieved through proper selection of construction materials and detailing provisions of structural members. At present, there are still a number of gaps relating to these fire-resistance provisions for bridge structural members. This is due to lack of test data and validated numerical models for evaluating response of bridge structural members under fire exposure.

In recent years, some studies have focused on developing numerical models to evaluate fire resistance of structure members in bridges (Kodur and Naser 2013). Finite element based computer programs, such as ANSYS (ANSYS 2013), were often applied to evaluate fire response of girders under different fire scenarios. Most of these studies focused on steel bridge girders (Aziz and Kodur 2013), while a few studies concentrated on reinforced concrete beams (Balaji and Aathira 2016, Capua and Mari 2007, Dwaikat and Kodur 2008, Hitesh and Tarvinder 2014). There are nearly no studies on the fire performance of prestressed concrete (PC) bridges, actually PC is widely used in bridges (Kim and Laman 2014, Zhu and Chen 2014). This paper presents an approach for evaluating fire resistance of PC bridges with T girders.

2. Fire hazard in prestressed concrete bridges

A fire occurring in the vicinity of a bridge can spread to the bridge structure if significant fuel is available. While the intuition may be that it is highly improbable that a PC bridge can collapse under fire, a recent China-wide survey has shown that bridge fires are a serious concern, and more bridges were damaged due to fire incidents than

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earthquakes during 2005-2014 periods (Hou 2014). This is similar to US experience where another survey has indicated fire related accidents in bridges to be of the major causes for bridge collapses (New York State Department of Transportation 2008, Garlock and Paya-Zaforteza 2012). The review further revealed that in some cases, bridge fires can produce significant damage or collapse of structural members leading to major traffic delays, detours and costly repairs. The following fire incidents illustrate the magnitude of fire problem that is specific to PC bridges.

On August 16, 2008 a major fire broke out on a three span PC bridge (Borui Yanjiang bridge) on Jinliwen expressway along a river in Zhejiang, China. A fuel tanker transporting 29,762 litres of stearic acid experienced a sudden tire puncture leading to spilling and ignition of stearic acid. Flames spread rapidly, and burned for eighty five minutes before it was extinguished. The burning of this highly combustible fuel led to intense heat, producing extremely high temperatures. Due to rapid rise in temperatures resulting from rapid burning of stearic acid, this high intensity fire caused a large deformation in girders and piers, with the mid-span deflection in a girder reaching 40 mm. Following the fire, and based on inspection, two spans of the bridge (a total of 8 girders) and a pier on this bridge had to be replaced (see Fig.1a). Traffic disruption resulting from fire damage and reconstruction lasted for about five months and the total losses were estimated at $7 million (Hou 2014).

Another major bridge fire occurred on August 2, 2011 at the Caogou bridge, Shaanxi, China. This PC bridge was comprised of three spans, each having a length of 30 m. The super structure was constructed of prestressed concrete girders. A tanker carrying 33,103 litres of gasoline was hit by another truck coming from the opposite direction leading to spilling and ignition of gasoline. Flames spread rapidly resulting in explosions, and seven trucks in the vicinity of the bridge caught up in this fire. The fire lasted for three hours and the peak temperatures reached about 1100℃. The high intensity of fire initiated obvious deflection in PC girders (see Fig. 1(b)). Following the fire, girders in this span had to be removed and traffic in both directions had to be detoured. The rebuilding of this fire damaged bridge and the traffic detouring lasted for more than one month leading to significant economic losses (Hou 2014).

In U.S., a major bridge fire occurred at the Bill Williams River Bridge, AZ, on July 28, 2006. The bridge was comprised of fourteen spans, each having a length of 23.2 m. The super structure was constructed of prestressed concrete girders underneath a cast-in-place concrete slab. A fuel tanker carrying 28,700 litres of diesel overturned near the bridge (Davis and Tremel 2007). The fire lasted for few hours and affected span numbers 8, 9 and 10. The fire also spread to surrounding wildlife area and burned for two weeks. The post-fire bridge inspection showed spalling of concrete in the prestressed concrete girders. Following this inspection, the concrete girders were declared to be damaged by the fire and subsequently repaired, but it was not necessary to replace any of the girders.

The above incidents clearly infer that fires can pose significant threat to PC bridges. This is because the concrete and prestressing strands may suffer severe degradation in strength and stiffness properties due to high temperature exposure. Especially, the tensile strength and modulus of prestressing strands is quite sensitive to high temperatures. In addition, thin-walled (T, box, or I) girders are quite frequently used as flexural members in PC bridges, which are highly vulnerable to fire damage due to reduced mass (thin web and flanges). Thus, PC bridges are vulnerable to damage under severe fire exposure as experienced in bridge fires.

(a) Borui Yanjiang bridge

(b) Caogou bridge

Fig. 1 Illustration of fire induced damage in PC bridges

3. Approach for modeling fire response in bridge girders

To illustrate the applicability of finite element models for fire resistance analysis, a typical PC bridge with T girders is analyzed under the combined effects of fire and structural loading.

3.1 General approach

A numerical model for tracing fire response of PC bridge girders is developed in ANSYS. This finite element model utilizes coupled thermo-mechanical analysis to trace the behavior under fire conditions, and the analysis is carried out at incrementing fire steps, till failure occurs in the girder (Kodur and Dwaikat 2008, Dwaikat and Kodur 2008). At each time step, the analysis is undertaken in three steps: computation of transient temperature field on structural members resulting from fire exposure; heat transfer analysis to evaluate temperature distribution within the girder cross section; and then calculation of strength/deformation response due to combined effects of thermal and mechanical loading.

3.2 Fire temperatures

The temperatures resulting from fire exposure are calculated by assuming that web and flanges of a PC girder are exposed to heating resulting from a fire, whose temperature follows that of hydrocarbon fire (ASTM 2014) or any other fire exposure, such as ISO834 (ISO 1999). For design fires, the time-temperature relations specified in SFPE (SFPE 2004) is built into the model. Also, to simulate external fire scenarios, the time-temperature relations specified in literature (Kodur and Dwaikat 2008) can be incorporated into the model.

3.3 Thermal analysis

The fire temperature at various fire stages is supplied as input (data) to carry out heat transfer analysis. For this analysis thermal properties of the constituent materials are needed to determine temperature profile within the cross section of girder. A 3-D finite element method is applied to perform heat transfer analysis. The girder is discretized into a number of hexahedral elements and temperature rise at each node within elements of the girder is evaluated. The heat transfer model is capable of predicting temperature distribution of cross section in girder with any boundary conditions. The governing equation for transient heat conduction in an isotropic material is given as (Kodur and Dwaikat 2008)

$$k\nabla^2 T + Q = \rho c \frac{\partial T}{\partial t} \tag{1}$$

where k =thermal conductivity; ρc = heat capacity; T=temperature; t=time; and Q=internal heat generation.

The heat transfer from fire zone to girder is through convection and radiation (Capua and Mari 2007), and follows the relation

$$q = \alpha_{\mathrm{c}}\left(T - T_f\right) + \varepsilon\delta\left(T^4 - T_f^4\right) \tag{2}$$

where q=heat flux; α_{c}=coefficient of convection heat transfer; T_f =fire temperature; ε=emission factor; and δ=Stefan-Boltzmann radiation constant.

3.4 Strength/deformation analysis

Following the heat transfer analysis, temperatures generated from thermal analysis are applied as a thermal-body-load on structural elements of the girder to simulate conditions of fire exposure on PC bridge girder. The temperature dependent mechanical properties (stress-strain relationships) of prestressing strands and concrete are assumed to follow provisions given in literature (Zhang and Zheng 2007, CEN 2004) and these relations are supplied as input into ANSYS.

For structural analysis, it is assumed that no bond-slip occurs between prestressing strands and the concrete at elevated temperatures, due to the fact that reliable interface bond is ensured by duct grouting, and that the thermal expansion coefficient of prestressing strands and concrete is close. Fire-induced spalling is not considered in the analysis since the spalling is a major concern only in structural members made of high strength concrete (Kodur and Dwaikat 2008).

As part of strength analysis, the deformation under applied loading at room temperature is evaluated at initial (first) time step. For the subsequent time steps, the temperature dependent stress-strain relationships are input according to temperature within elements. At each iteration within a time step, Newton-Raphson solution technique is applied to reach convergence. Resulting mid-span deflections, together with temperature in strands and capacity of girder, are checked against the limiting values to assess the failure state of the girder at that time step. The time increments continue until failure occurs in the girder, under any of the limiting values.

4. Case study

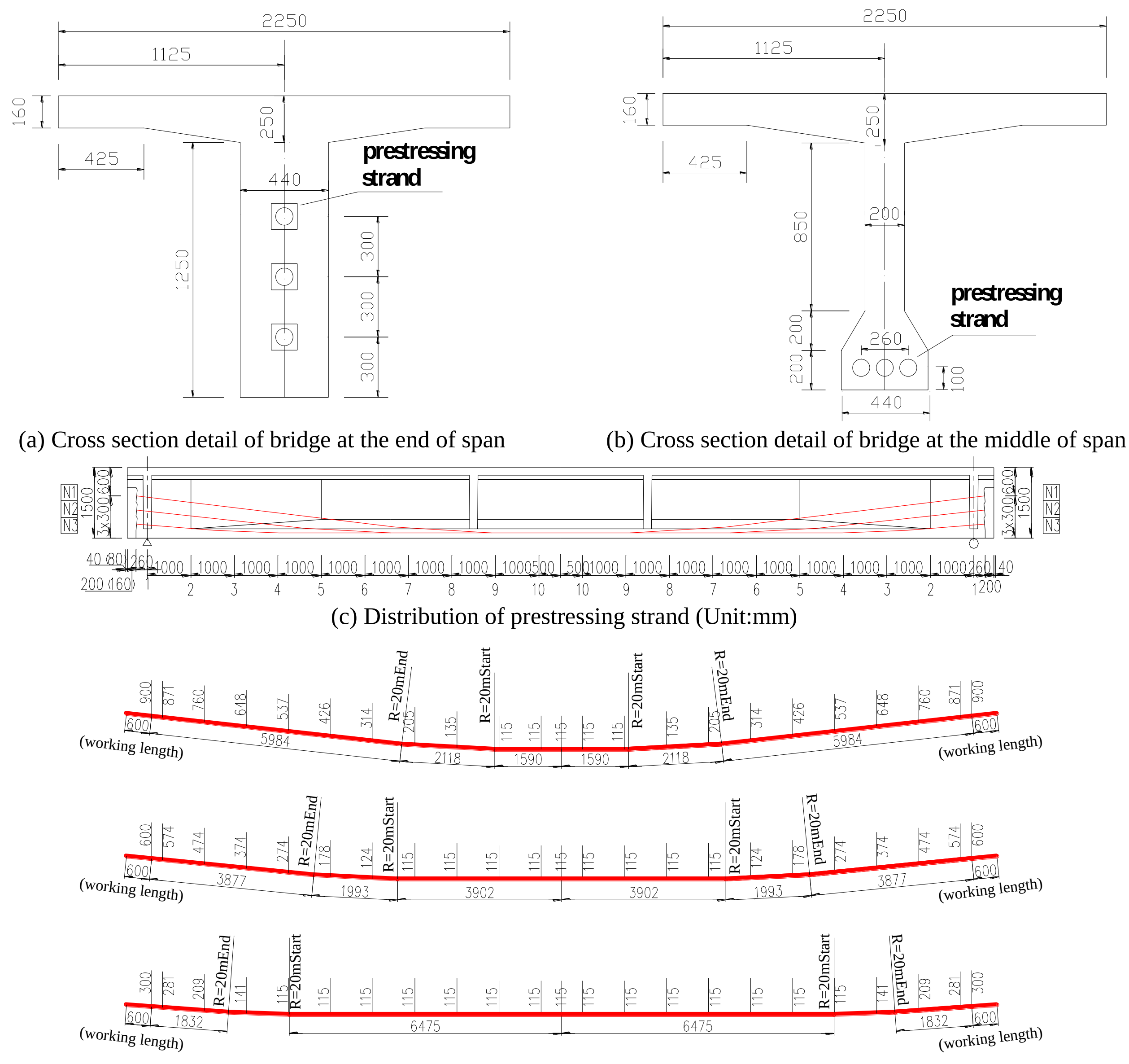
To illustrate the response of a typical PC bridge girder under fire conditions, a simply supported PC T girder was analyzed by subjecting it to structural loading and fire exposure. The analysis was carried out using ANSYS.

4.1 Selection of bridge girder

A PC bridge comprised of a T girder is selected for analysis. The T shaped girder has a span length of 20 m, width of 2.25 m, and a height of 1.5 m, and has simply supported ends. The girder is assumed to be made of concrete with a compressive strength (cube strength) of 50 MPa and prestressing strands with a tensile strength of 1860 MPa. Details of prestressing strands, including layout, are shown in Figure 2. To enhance shear capacity of PC T girder in the vicinity of the supports, the thickness of the web in girder is increased from 200 mm in mid-span section region to 440 mm in support regions.

4.2 Discretization

For heat transfer analysis, the selected PC T girder is discretized with two types of elements available in ANSYS, namely SOLID70 and LINK30. SOLID70 is a 3-D element with three-dimensional thermal conduction capability and has eight nodes with a single degree of freedom, namely temperature at each node. This element is well suited to three-dimensional, steady-state or transient thermal analysis problems. The external surface areas of the SOLID70 elements were used to simulate surface effects of convection and radiation that occur from the ambient air



(a) Cross section detail of bridge at the end of span (b) Cross section detail of bridge at the middle of span

(c) Distribution of prestressing strand (Unit:mm)

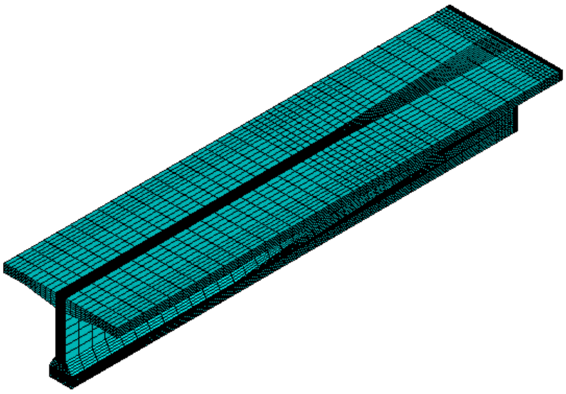
(d) Prestressing detail (Unit:mm)

Fig. 2 Details of prestressed concrete T girder selected analysis

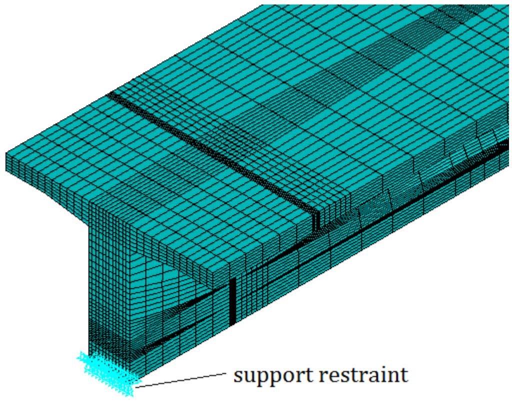
(fire) to exposed sides of the PC T girder. LINK30 is a uniaxial element with the ability to conduct heat between two nodes and used to simulate temperatures in prestressing strands along the span.

The PC T girder shown in Fig. 3(a) was meshed with SOLID70 elements. Both convection and radiation heating was applied at the exposed surface areas of the solid element. Convection coefficient of α_c=50 W/(m^2°C) was used in the thermal analysis for exposure under hydrocarbon fire and design fire, whereas, convection coefficient of α_c =25W/(m^2°C) and α_c =35W/(m^2°C) was used in the thermal analysis for exposure under ISO834 fire and external fire, respectively, and this is based on Eurocode 1 (CEN 2002) and ISO834 (1999) recommendations (ISO 1999). An effective emissivity factor of 0.9 was used for the fire exposure surfaces of the girder (Capua and Mari 2007). A Stefan-Botzmann radiation constant of 5.67×10^{-8} W/(m^2°C) was applied in the thermal analysis.

For structural analysis, the concrete portion of prestressed concrete T girders was discretized using SOLID65 elements, and prestressing strands were modeled with LINK8 elements. SOLID65 has eight nodes with three degrees of freedom, namely, three translations in *x*, *y*, and *z* directions. This element can be used for 3D modeling of solids with or without reinforcement and is capable of accounting for cracking of concrete in tension, crushing of concrete in compression, creep and large strains. The output from thermal analysis (temperature) was applied as a thermal-body load on the structural model to evaluate mechanical response of PC T girder. LINK8 element has two nodes with three degrees of freedom, namely three translations in *x*, *y*, and *z* directions. This element can be used for one-dimensional modeling of strands and is



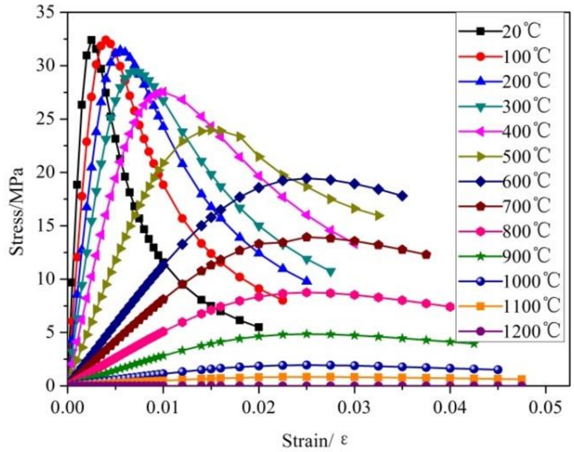
(a) 3-D mesh



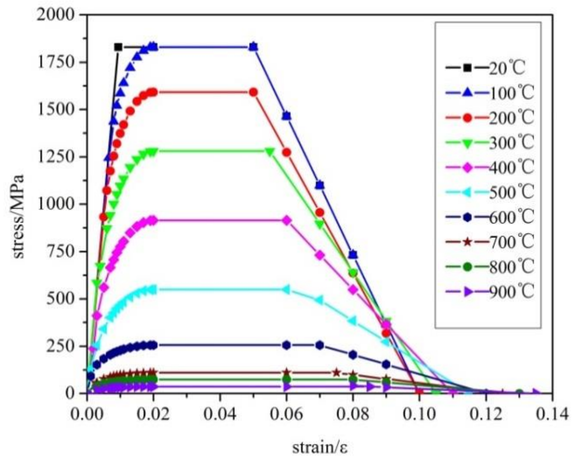
(b) Support and boundary condition

(c) Discretization of prestressing strands

Fig. 3 Discretization of bridge girder for analysis



(a) Stress-strain relationships for concrete



(b) Stress-strain relationships for prestressing strands

Fig. 4 Stress-strain relations of concrete and prestressing strand at different temperatures

capable of accounting for plasticity, large deflection and large strain effects. The 3-D meshing, incorporated into the variation in web, adopted in the analysis is shown in Fig. 3.

To account for coupled interaction between concrete and prestressing strands, node-to-node interaction was discretized in the structural model as shown in Fig. 3(a). The same nodes are shared between the solid elements of the concrete and the link elements of the prestressing strands. To discretize the boundary conditions in the structural finite element model, the support conditions of the bridge girder were applied on multiline nodes at the lower face of the bottom flange, as shown in Fig. 3(b). This boundary condition reflects a practical scenario, and improves the solution convergence during the finite element analysis.

4.3 Material properties

The progression of temperatures in concrete section under fire exposure depends on fire severity and thermal properties of constituent materials, namely, thermal conductivity, specific heat, density and thermal expansion, which vary as a function of temperature. Temperature-dependent thermal properties of concrete and prestressing strands were provided as input into ANSYS and these properties are assumed to follow Eurocode 2 and 3 provisions (CEN 2004, CEN 2005). Stress-strain relations of concrete and prestressing strands are critical for fire-resistance analysis, and these relations also vary with temperature. Temperature dependent stress-strain relations taken from literatures (CEN 2004) are used in the analysis and shown in Fig. 4. Mechanical properties of concrete and prestressing strands, are also applied as per Eurocode (CEN 2004, CEN 2005). The thermal and mechanical properties used in the analysis are given in Table 1.

4.4 Analysis details

For thermal analysis, prestressed concrete T girder is exposed to four different fire scenarios, namely hydrocarbon fire, ISO834 fire, design fire, and external fire

Table 1 Thermal and mechanical properties of concrete and prestressing strand

Material	Temp /℃	Thermal conductivity W/(m·℃)	Specific heat J/(kg·℃)	Density kg/m$_3$	Thermal expansion $\times 10^{-6}$	Strength reduction factor	Elastic modulus reduction factor
Concrete	20	1.33	900	2500	6.2	1.000	1.000
	200	1.11	1000	2450	7.6	1.000	0.700
	400	0.90	1100	2375	9.2	0.880	0.540
	600	0.75	1100	2355	10.8	0.640	0.370
	800	0.64	1100	2336	12.4	0.400	0.300
	1000	0.57	1100	2316	14.0	0.160	0.028
	1200	0.55	1100	2297	15.6	0.000	0.000
Prestressing strand	20	53.3	440	7850	7.6	1.000	1.000
	100	50.7	488	7850	9.3	0.983	0.968
	200	47.3	530	7850	11.4	0.878	0.946
	300	44.0	565	7850	13.5	0.696	0.849
	400	40.7	606	7850	15.6	0.471	0.633
	500	37.4	667	7850	17.7	0.247	0.378
	600	34.0	760	7850	19.8	0.080	0.198
	700	30.7	899	7850	21.9	0.036	0.101

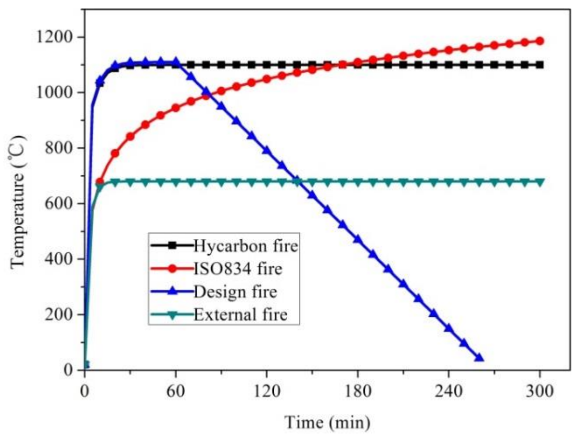


Fig. 5 Time-temperature curves for typical fire scenarios

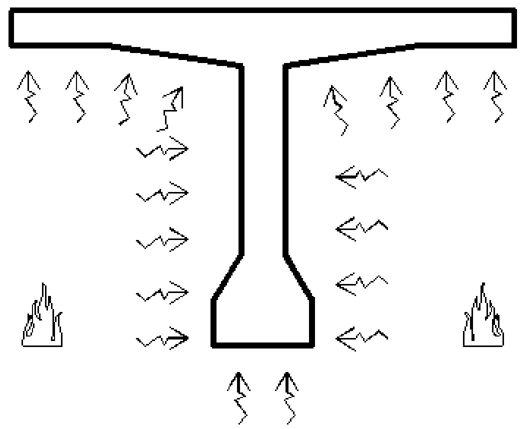


Fig. 6 Fire exposure on a T girder

(ASTM 2014, ISO 1999, SFPE 2004, and CEN 2002). The time-temperature curves representing four fire scenarios are shown in Fig. 5.

Fig. 6 shows exposure scenario in the PC T girder. The fire-resistance analysis of T girder carried out under an applied loading consisting of 100% dead load plus 30% live load. The self-weight of the T girder section (25 kN/m) and that contributed by the pavement (12 kN/m) were considered in the dead load. For the live load, a uniformly distributed load (12 kN/m), representing 0.3 times the live load was applied (Kodur and Naser 2013).

4.5 Failure criteria

To evaluate failure of PC T girder under different fire scenarios, four sets of failure criteria (temperature, strength, and two deflection limit states), were applied at each time step. The temperature and second strength failure criteria are applied as given in ASTM E119 (ASTM 2001), while the third (deflection) and the fourth (rate of deflection) failure criteria are taken from BS 476 (BS 1987). Accordingly, the failure in a PC girder is said to occur when one of the following limits is reached.

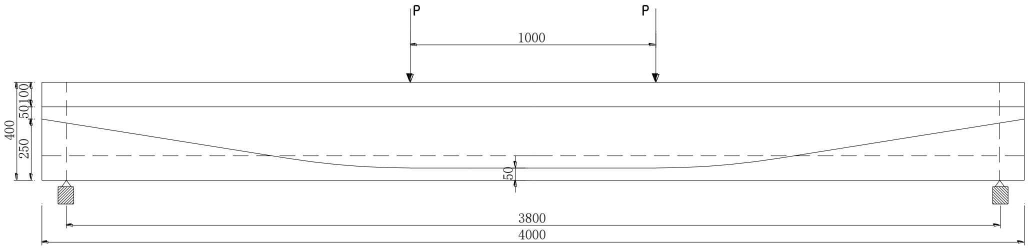
1. Temperature in prestressing strand exceeds the critical temperature, which is 426℃ for a prestressing strand.

2. Girder is unable to resist the bending moment resulting from specified applied service loading during fire conditions.

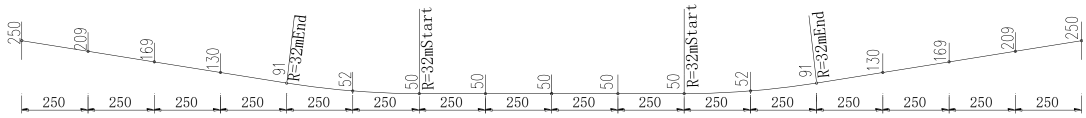
3. Maximum deflection in the girder exceeds L/20 (mm) at any fire exposure time, where L is the span length.

4. Rate of deflection in the girder exceeds the limit of $L^2/9000d$ (mm/min), where L is the span length of the girder (mm) and d is the effective depth of the girder (mm).

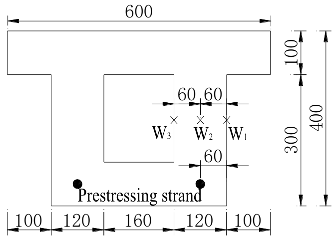
In the case of failure criteria 1, the failure of a PC girder under a fire exposure is based on the temperature attained in the prestressing strand (just prior to failure) without any consideration to structural behavior of the girder during fire.



(a) Longitudinal elevation (Unit:mm)



(b) Details of prestressing strand (Unit:mm)



(c) Transverse section (Unit:mm) (d) Test picture (e) Prestress measure

Fig. 7 Details of PC box scaled model girder

Thus, the fire resistance of a PC girder is only dependent on the location of prestressing strand within the cross section and the overall dimensions of the girder, without allowing for critical factors such as level of loading and restraint conditions.

Under failure criteria 2, specified service loading has major influence on evaluating bending moment. In building applications, the applied loading under fire conditions is taken as 1.2 times dead load plus 0.5 times live load (ASCE 2005). However, in bridges the applied loading under fire conditions can be taken as dead load plus 30% live load (Kodur and Naser 2013), due to the fact that a bridge structure is located in an open space and much of the live load may not be present due to the fact that vehicles can move away from the fire location.

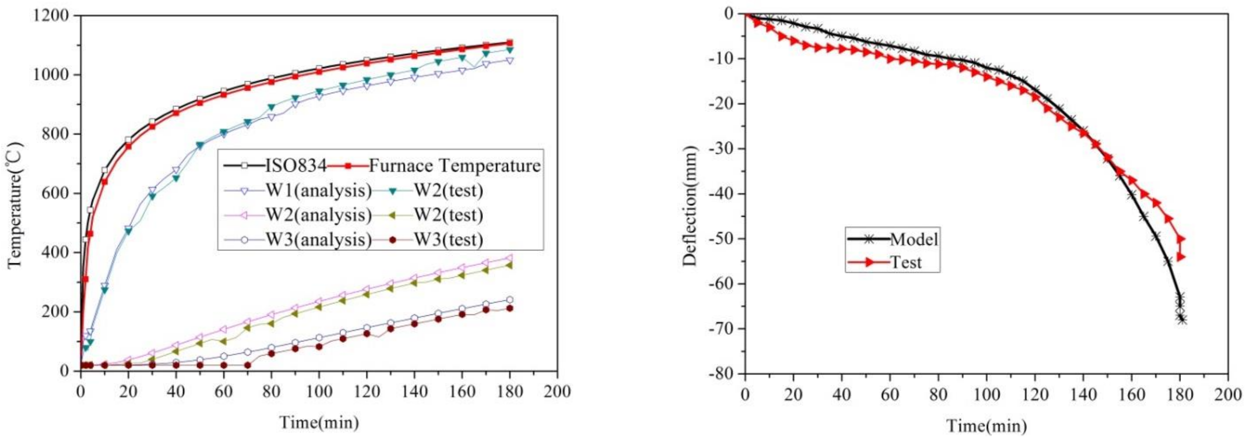
Limiting deflection and rate of deflection can be important under fire conditions, because the integrity of the structural member cannot be guaranteed under excessive deformations. However, the deflection limit under failure criteria 3 may not valid for some cases, due to the fact that PC bridge girders are usually designed as members with long span and small depth. In such situations rate of deflection limiting failure criteria may be more applicable.

4.6 Modal validation

Fire test data on the responses of PC T girders under fire conditions is lack. Considering that PC T girders and PC box girders are both thin-walled structures, and they have similar thermal and structural response under fire. Therefore, the developed ANSYS model is validated by test data of a scaled PC box girder under ISO 834 fire exposure (Hou 2014). The details of the PC box girder are shown in Fig. 7. The girder was exposed to three-side fire (outsides of two webs and one bottom plate, Fig. 7(d)), and a couple of 25 kN concentrated loads were applied on the location of 50 cm to the span center. The prestress was measured by the load sensor located in the anchorage zone (Fig. 7(e)).

The analysis is carried out with the same elements and mesh discretization and high temperature properties as discussed above. Fig. 8(a) shows a comparison of predicted concrete temperatures with those measured in the fire test. The predicted temperatures agree well with the measured data, in which the slight difference can be attributed to variation of the heat transfer parameters, such as emissivity and convection coefficients, used in the analysis as compared with the actual values in the test.

The comparison of the predicted mid-span deflections by ANSYS model and those measured in the test is shown in Fig. 8(b). It can be seen that the mid-span deflection gradually increases with time at the early stage (up to 120 min). These initial deflections are mainly due to high temperature gradients that develop across the web and bottom slab of the concrete section and the slight reduction in elastic modulus of concrete resulting from increased temperature in the girder. After 120 min, the rate of



(a) Cross-sectional temperature (b) Mid-span deflection

Fig. 8 Comparison of predicted and measured response parameters in fire exposed PC box girder

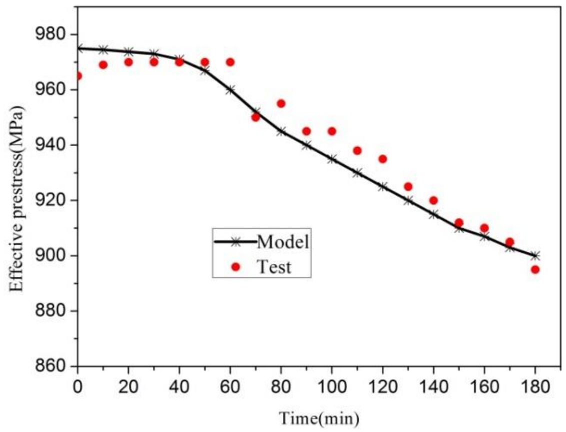


Fig. 9 Comparison of predicted and measured prestress in the anchorage zone

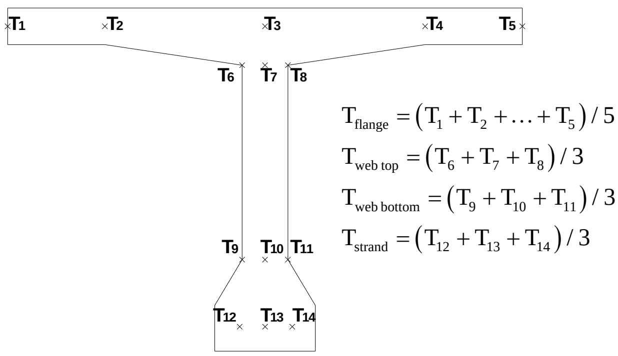


Fig. 10 Averaging temperature in the girder cross section

deflection increases slightly due to spread of plasticity resulting from faster strength and stiffness degradation of concrete and prestressing strands as a result of high temperatures. At about 180 min, bottom slab and web temperatures exceed 450℃ evenly and this leads to rapid rise in mid-span deflection due to the formation of plastic hinge at the mid-span section. Finally, the failure occurs at 180 min when mid-span deflection rate exceeds the deflection rate limit (L^2/9000d). Data presented in Fig.8b indicate a good comparison between predicted and measured mid-span deflections throughout fire exposure duration.

A comparison of stress in the anchorage zone predicted by the ANSYS model and those measured in the test are shown in Fig. 9. It can be seen that the stress gradually decreases with time in the early stage of the fire (up to 50 min). These initial stresses are mainly due to high temperature gradient that develops in the web and the bottom slab and slight reduction in material mechanical properties. After 50 min, the rate of stress decreases rapidly due to the deterioration in strength and stiffness properties of concrete and prestressing strands. Although measurement values of prestress presented in Fig. 9 fluctuates around the predicted curve, the general trend of the measured prestress is coincident with the predicted values.

Overall, predicted concrete temperatures, mid-span deflection, time to failure and prestress from ANSYS compare well with the reported data in fire.

4.7 Results and discussion

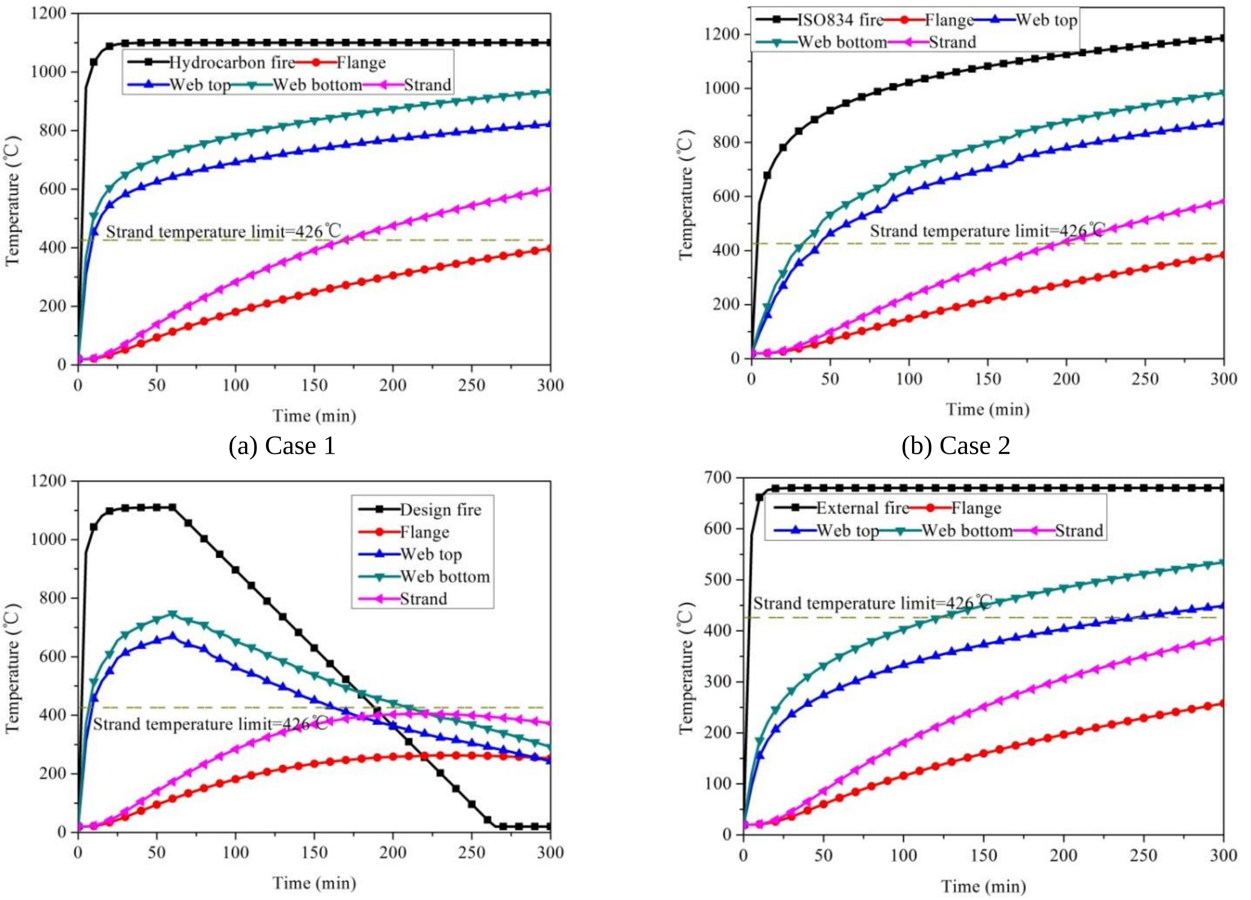
The validated ANSYS model is utilized to analysis the thermal and structural response of the T girder. Results from analysis are utilized to discuss the behavior of the T girder under different fire scenarios.

4.7.1 Thermal response

In order to illustrate temperature progression in flange, web, and prestressing strands as a function of fire exposure time, the temperature in each portion of the T girder is obtained by taking the arithmetic mean of the temperatures generated in ANSYS at several points (See Fig. 10).

Results from ANSYS thermal analysis for Case 1 to Case 4 are plotted in Fig. 11, which shows the temperature evolution in the girder with fire exposure time. It can be seen that the temperature-time response in girder cross section is influenced by fire severity.

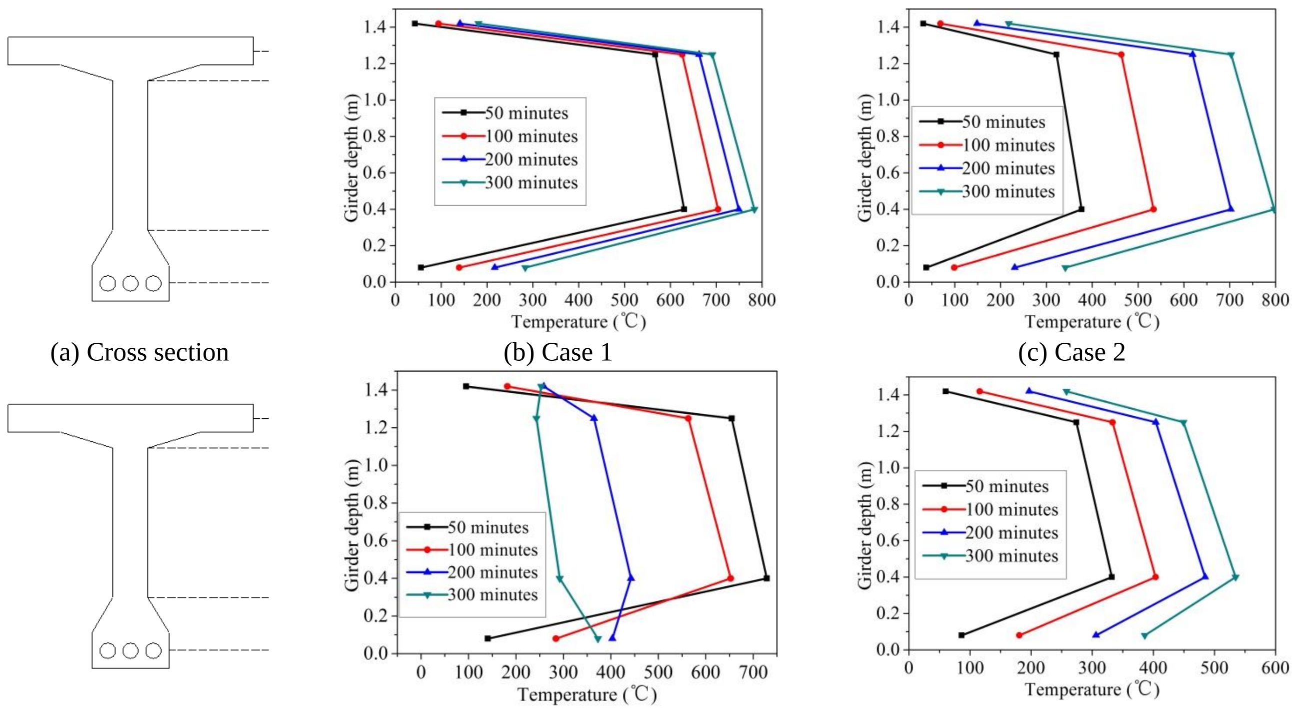
The temperatures in upper flange are much lower than that of the web and this can attributed to two reasons, one is that the web is exposed to fire from all the three faces, whereas the upper flange is only exposed to fire from bottom side only, and the other is that the thickness of the



(a) Case 1 (b) Case 2

(c) Case 3 (d) Case 4

Fig. 11 Temperature progression in a bridge girder subjected to different fire exposure scenarios



(a) Cross section (b) Case 1 (c) Case 2

(d) Cross section (e) Case 3 (f) Case 4

Fig. 12 Thermal gradient along the depth of a bridge girder section under different fire exposures web is smaller than that of the flanges, which leads to rapid rise in web temperatures. Also, temperature in the web bottom is slightly higher than that at the web top, and this is because of heat sink from top portion of web to the upper flange. Thus, web is prone to early buckling than the flange due to higher temperature development in web.

Temperatures in prestressing strand increase slowly with fire exposure time and are quite lower than those in the web (concrete) due to the large concrete cover thickness to the strands. As per failure criterion 1, the failure of girder occurs when the temperature in prestressing strands reaches 426℃. The fire exposure time corresponding to 426℃ in prestressing strands are 169 min and 196 min under hydrocarbon and ISO834 fire respectively. The temperatures in prestressing strands remain below 426℃ during the entire fire exposure time under Case 3 and Case 4. The temperature criterion may not be realistic in determining the failure of PC T girder.

The development of thermal gradient across the girder cross section is plotted in Fig. 12 for Case 1 to Case 4 of the analysis. The thermal gradients represent temperature difference between the mid-depth of the flange and the mid-depth of the web. It can be seen that thermal gradients are influenced by the type of fire scenario. At 100 min, the thermal gradient in Case 1 to Case 4 is 556℃, 512℃, 426℃ and 253℃ respectively. The significant thermal gradients that develop along the depth of the cross section in Case 1 to Case 3, result from higher temperatures in the web as compared to that in flange. However in Case 4 (under an external fire), the gradient is only 253℃. This is attributed to the fact that an external fire is much less severe (lower fire temperatures) as compared to other three fire scenarios (see Fig. 5). For Case 3 (under a design fire), with a cooling phase, though the gradient at 100 min is relatively large, the gradient drops to 145℃ at 200 min and only 14℃ at 300 min during the cooling phase of fire.

Generally, higher thermal gradients cause higher thermal strain in the web as compared to that in the flange. So slight curvature, namely thermal bowing, develops in the PC girder, resulting in high thermal stresses even in a statically determinate PC girder (unrestrained girder). The developed curvature at the initial stage of fire exposure is mostly resulting from thermal-gradient effect, instead of applied loading. Therefore, the curvature caused by the thermal gradients contributes to deflections at the early stage of fire exposure. Once concrete temperatures exceed 600℃, the deflection of bridge girder increases mainly due to degradation of the mechanical properties of concrete.

4.7.2 Structural response

Fig. 13 shows variation of moment capacity with time of fire exposure in prestressed concrete bridge girder under different fire scenarios. It can be seen that the temperature induced decrease in moment capacity is influenced by the type of fire scenario. For Case 1 (under hydrocarbon fire) and Case 2 (under ISO834 fire), the general trend of the moment capacity degradation can be grouped into two stages. At the early stage of fire exposure (about 40 min), the moment capacity in Case 1, decreases more rapidly than that in Case 2, due to the fact that rate of heating under hydrocarbon fire is much more rapid than under ISO834 fire. Thereafter, the moment capacity in both cases decrease gradually till failure of the girder.

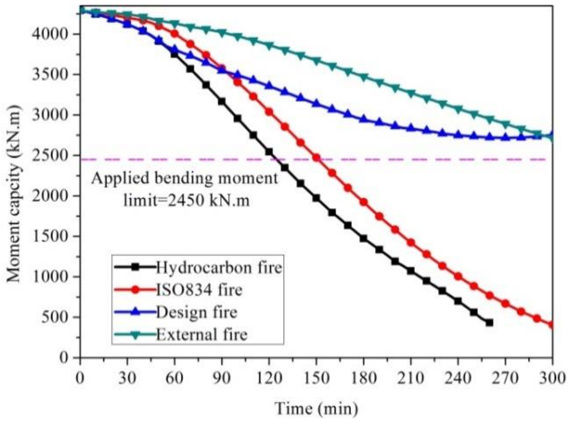


Fig. 13 Variation of moment capacity as a function of fire exposure time

The moment capacity degradation at early stages of fire exposure (up to 60 min) in Case 3 (under design fire) is similar to that in Case 1, and this can be attributed to nearly identical temperature-rise phase in design fire and hydrocarbon fire exposure. Thereafter, the moment capacity in Case 3 decreases slowly with fire exposure time, which is obviously different from that in Case 1 (hydrocarbon fire). This is because presence of a decay phase in a design fire results in slow deterioration or even recovery of strength in concrete and prestressing strand. Towards the final stages of fire exposure, the moment capacity-time plot enters a horizontal plateau due to recovery in the strength of prestressing strands as the temperatures within the girder cools down. The trend in the early stage of moment capacity in Case 4 (under external fire) is similar to that in Case 2 due to the fact that the temperature-rise (growth) phase in external fire is extremely close to that in ISO834 fire. Thereafter, reduction of moment capacity in Case 4 is much slower than that in Case 2 with fire exposure time. This is because the maximum fire temperature attained for under ISO834 fire exposure is high as compared to that under external fire exposure.

The maximum bending moment at mid-span resulting from reduced loading during a fire event is 2450 kN.m. When the degrading moment capacity falls below 2450 kN.m, the girder is said to fail under strength limit state. The failure time (fire resistance) corresponding to this strength limit state of 2450 kN.m is 124 min and 147 min respectively in Case 1 and Case 2, indicating that the girder under hydrocarbon fire is susceptible to failure earlier than that under ISO834 fire. The decreasing moment capacity does not reach 2450 kN.m throughout the fire exposure duration in Case 3 and Case 4, indicating that the girder does not experience failure under design or external fire scenario.

The variation mid-span deflection of the girder as a function of fire exposed time is illustrated in Fig. 14. The general trend of deflection progression follows that of the moment capacity and is also dependent on the type of fire scenario. According to failure criterion 3, when the maximum deflection in a girder surpasses L/20 (1000 mm) limit, the girder is said to fail. From the analysis results, no failure occurs in long-span PC girders during the entire fire exposure time based on this criterion. Therefore, Criterion 3 may not be suitable to evaluate fire resistance of long-span PC bridge girders.

Under failure criterion 4, when the rate of deflection exceeds the limit $L^2/9000d$ (29 mm/min), the failure is said to occur. According to this criterion, PC girder in Case 1 and Case 2 fail in 101 min and 153 min respectively, but no failure occurs in Case 3 and Case 4. These results are consistent with that of strength criterion. Hence rate of deflection criterion is better suited to evaluate fire resistance (failure) of long-span PC bridge girders.

A summary of results from the analysis on PC T girder exposed to four different fire scenarios, based on four sets of failure criteria, is presented in Table 2. Fire resistance is taken as the duration from the initial fire exposure time to failure of the girder or till "burn out" conditions are attained. Accordingly, the fire resistance (minimum failure time) of PC T girder under hydrocarbon and ISO834 fire exposures is determined to be 101 min and 147 min respectively by comparing values in Table 2. No failure occurs under design and external fire exposures.

The fire resistance of PC girder under strand temperature based criterion is higher than that under strength and rate of deflection failure criteria due to the fact the cover thickness to prestressing strands is large. Hence, assessing failure based on strand temperature may not be conservative. As per deflection failure criterion, no failure occurs in PC girder under four different fire exposures. Because the maximum deflection limit (L/20) may be extremely large in long-span PC girder, deflection failure criterion cannot be utilized to determine the fire resistance of PC girder. The strength and the rate of deflection failure limit states criterion should be applied to evaluate fire resistance of PC girder.

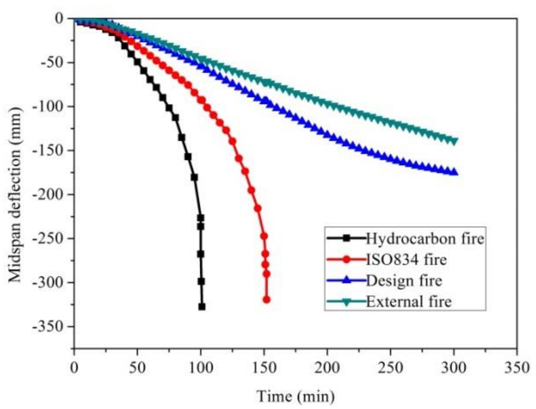


Fig. 14 Time-deflection of a simply supported PC T girder exposed to fire

Table 2 Summary of results from fire resistance analysis

Fire case	Fire scenario	Fire resistance (min)			
		Failure criterion 1 Strand temperature	Failure criterion 2 Moment capacity	Failure criterion 3 Deflection	Failure criterion 4 Rate of deflection
Case 1	Hydrocarbon fire	169	124	No failure	101
Case 2	ISO834 fire	196	147	No failure	153
Case 3	Design fire	No failure	No failure	No failure	No failure
Case 4	External fire	No failure	No failure	No failure	No failure

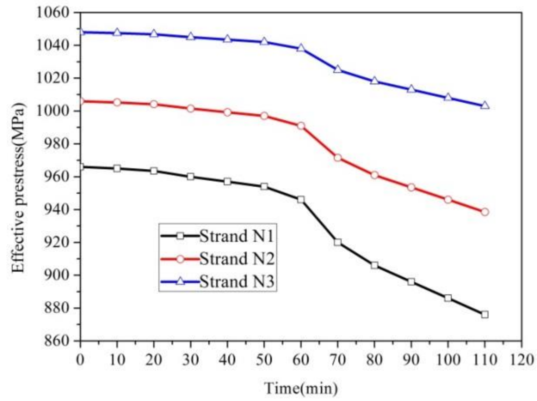


Fig. 15 Progression of effective prestress at midspan with fire exposure time

4.7.3 Effective prestress

From analysis in 4.7.2, it can be concluded that a PC bridge girder is highly susceptible to failure under hydrocarbon fire scenario. Therefore, the progression of effective prestress at midspan in PC T girder exposed to hydrocarbon fire is predicted by the ANSYS model. The effective prestress-time curves are given in Fig. 15, in which N1, N2 and N3 represent three prestress strands within PC T girder respectively (See Fig. 2(c)). It can be seen that the general trend of effective prestress can be grouped into two stages, similar to Fig. 9. The effective prestress of strand N3 is higher compared to that of strand N1 and N2 with fire exposure time due to its high initial value resulting from the location in line path. Overall, the prestress loss caused by elevated temperature is about 10% at the failure time of the PC girder, which may lead to the increase of deflection.

5. Conclusions

A nonlinear transient finite-element procedure is applied to evaluate fire resistance of PC bridge girders, and validated by test data of a scaled PC box girder under ISO834 fire condition. Based on the results of analysis, the following conclusions can be drawn:

- The type of fire exposure and associated fire severity has a significant influence on the resulting fire resistance of PC T girders. A prestressed concrete bridge girder is highly susceptible to failure under hydrocarbon fire scenario. However, A PC girder can survive lower intensity design fire or external fire scenario.
- The strand temperature failure criterion may not be conservative under some fire scenarios. Also, deflection based criterion may not be reliable in evaluating failure

of fire exposed PC bridge girders.

• The moment capacity and the rate of deflection failure criterion are more applicable to determine failure of PC bridge girder under fire scenarios.

• The prestress loss caused by elevated temperature is about 10% at the failure time of the PC T girder under hydrocarbon fire. The decrease of effective prestress within the strands can lead to the increase in deflection of the PC girder under fire.

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