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A numerical method for evaluating fire performance of prestressed concrete T bridge girders

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Abstract. This paper presents a numerical method for evaluating fire performance of prestressed concrete (PC) T shaped bridge girders under combined effect of structural loading and hydrocarbon fire exposure conditions. A numerical model, developed using the computer program ANSYS, is employed to investigate fire response of PC T shaped bridge girders by taking into consideration structural inherent parameters, namely; arrangement of prestressing strands with in the girder section, thickness of concrete cover over prestressing strands, effective degree of prestress and content of prestressing strands. Then, a sequential thermo-mechanical analysis is performed to predict cross sectional temperature followed by mechanical response of T shaped bridge girders. The validity of the numerical model is established by comparing temperatures, deflections and failure time generated from fire tests. Through numerical studies, it is shown that thickness of concrete cover and arrangement of prestressing strands in girder section have significant influence on the fire resistance of PC T shaped bridge girders. Increase in effective degree of prestress in strands with triangular shaped layout and content in prestressing strands can slow down the progression of deflections in PC T shaped bridge girder towards the final stages of fire exposure, to thereby preventing sudden collapse of the girder. Rate of deflection based failure criterion governs failure in PC T shaped bridge girders under most hydrocarbon fire exposure conditions. Structural inherent parameters incorporated into sectional configuration can significantly enhance fire resistance of PC bridge girders; thus mitigating fire induced collapse of these bridge girders.

Keywords: bridge fires; fire resistance; hydrocarbon fire; prestressed concrete bridge girder; numerical modeling

1. Introduction

Prestressed concrete (PC) T shaped bridge girders are widely used in medium- and long-span bridge construction (See Fig. 1) due to many advantages offer over other shaped girders (Peoplerail.com 2017). These advantages embrace light weight, cost effectiveness, ease of fabrication, batch production, rapid installation and good durability, etc. However, PC T shaped bridge girders used in bridge construction commonly exhibit slenderer than similar RC bridge girders due to presence of prestressing strands and thin web, which are susceptible to unstable (even collapse) under fire exposure conditions, specially in hydrocarbon fire exposure (Du *et al*. 2019a, Du *et al*. 2019b, Khalaf and Huang 2016, Kim and Kwak 2017, Song *et al*. 2020, Zhang *et al*. 2017a).

Fig. 1 Bridge construction using PC T shaped bridge girder (Peoplerail.com 2017)

In the past few years, great efforts have been made to model the response of structural members (as used in bridges) under extreme loading events, such as impact loading, blast and explosive loading and seismic loading (Bamonat *et al*. 2018, Nahid *et al*. 2017, Garlock *et al*. 2012, Zhang *et al*. 2017b, Zhang *et al*. 2019). Limited studies point to the fact that fire represents the most severe threat to bridge structure during their service life (Alos-moya *et al*. 2017, Garlock *et al.* 2012, Kodur and Naser 2019, Quiel *et al*. 2015, Zhang *et al*. 2017c). Bridge fires can lead to significant economic and public losses, and even cause loss of life in a number of severe fire incidents. Further, high intense fires, referred to as hydrocarbon fires (commonly occur in bridges), can lead to significant structural damage or even collapse of a bridge with PC thin-web girders.

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Fig. 2 Fire induced collapse of PC T shaped bridge girder in I-85 (Atlanta Chinese life network 2017, China.com - News Channel 2017, Huanqiu News 2017)

Fig. 3 Fire-damaged PC T shaped bridge girder (Maintenance online 2017)

There have been numerous bridge fire incidents, with serious consequences, and this is well documented in the literature (Alos-Moya *et al*. 2017, Aziz *et al*. 2015, Garlock *et al*. 2012, Kodur and Naser 2019, Nahid *et al*. 2017, New York State Department of Transportation 2008, Peris-Sayol *et al*. 2015, Shakya and Kodur 2015, Zhang *et al*. 2017a, Zhang *et al*. 2019). These bridge fire incidents were mostly caused by severe burning of oil, or gas or petrochemicals, spilled over during collision or overturn of tanker trucks. These fires burned rapidly and violently leading into extremely high temperature surpassing 1100°C within the first few minutes of fire broke out. In some cases, these fires lead to sudden collapse of bridge structural members.

One such example of fire incident is a PC bridge (comprised of eight pieces of PC T girders) on I-85 expressway near Piedmont road, Georgia, USA, which occurred on March 30, 2017. Sudden collapse of fire exposed bridge girder spans occurred after fire burning for 45 minutes (Atlanta Chinese life network 2017, China.com - News Channel 2017, Huanqiu News 2017), as shown in Fig. 2. Another fire incident on G-80 expressway in YunNan Province (China) on June 21, 2017, was caused by an overturned diesel-carried tanker truck. The petroleum fuel was sprinkled on the deck and then flowed through the drain holes to the underground of the bridge; thus causing flashover and then fire spread. As a result, fire exposed PC T shaped bridge girders were severely damaged and then had to be replaced with new girders (Maintenance online 2017), as shown in Fig. 3.

Currently, limited studies are concentrated on fire response of small-dimension PC slabs and RC beam used in building (Afaghi-Darabi and Abdollahzadeh 2019, Albero *et al*. 2018, Balaji *et al*. 2016, Kodur and Dwaikat 2008, Kodur and Shakya 2014, Sadaghian and Farzam 2014). However, very limited information in literature (Alos-Moya *et al*. 2017, Aziz *et al.* 2015, Kodur and Naser 2019, Zhang *et al*. 2017a, Zhang *et al*. 2019) are pointed to the fact that there is still on ways to predict fire resistance of structural members used in PC bridges, specially in thin-web bridge girders strengthened by high-strength prestressing strands. Taking into consideration severity of bridge hydrocarbon fire and substantial increase of vehicles transporting gas and petrol and chemicals, this paper presents a numerical analysis method that can be applied for investigating fire response of PC bridges with thin-web (T shaped) girders. Thereafter, a practical approach to guide structural inherent parameters into structural configuration is provided to mitigate fire risks of PC bridge girders.

2. Selection of PC T bridge girder for analysis

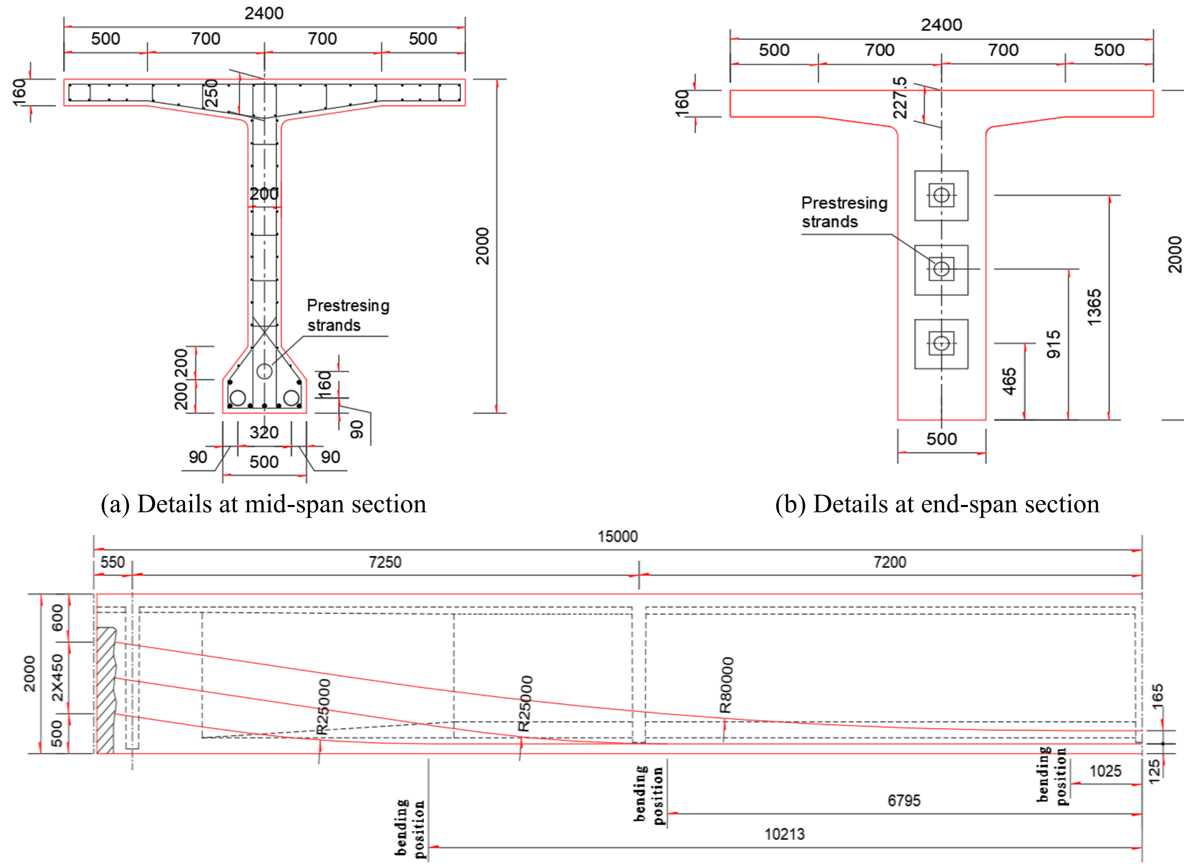
A typical simply supported PC bridge girder having a T shaped section, is selected for illustrating application of a built numerical method in the fire resistance analysis throughout entire fire exposure duration.

The selected T shaped bridge girder (post-tensioned PC bridge girder), with one-vehicle lane, is of 30 m span length, 2.0 m depth and 2.4 m width. Three prestressing strands designed as triangular pattern are located in the bottom of the web bottom and bottom flange. There are seven reinforcing bars of 20 mm diameter placed at bottom flange as reinforcement. Also, 10 mm diameter reinforcing bars are evenly distributed in web and top flange. In addition, 10 mm diameter stirrups are placed at 100 mm spacing along the span of the girder section. The concrete cover thickness to the strands and reinforcing steel is 40 mm and 30 mm, respectively.

The concrete cube strength is taken as 50 MPa (design strength) and reinforcing steel is of yield strength of 335 MPa. Prestressing strands pass through a steel corrugated pipe with diameter of 10 cm when the strength of concrete in casted T shaped bridge girder reaches 75% of the design strength. Subsequently, prestressing strands are anchored at both ends of the girder using anchor and then, the steel corrugated pipe is filled with the high-strength mortar to prevent the bond-slip between concrete and prestressing strands. The strand is of 1860 MPa limit tensile strength, and is placed in a parabolic profile, as shown in Fig. 4(c). Details of the selected PC T shaped bridge girder are shown in Fig. 4.

3. Numerical model

To investigate fire response of PC T shaped bridge girders with different structural inherent parameters, a numerical analysis method embracing detailed analysis procedure, discretization, boundary conditions and model validation is established.



(a) Details at mid-span section

(b) Details at end-span section

(c) Layout of prestressing strands

Fig. 4 Details of a selected PC T bridge girder (Units: mm)

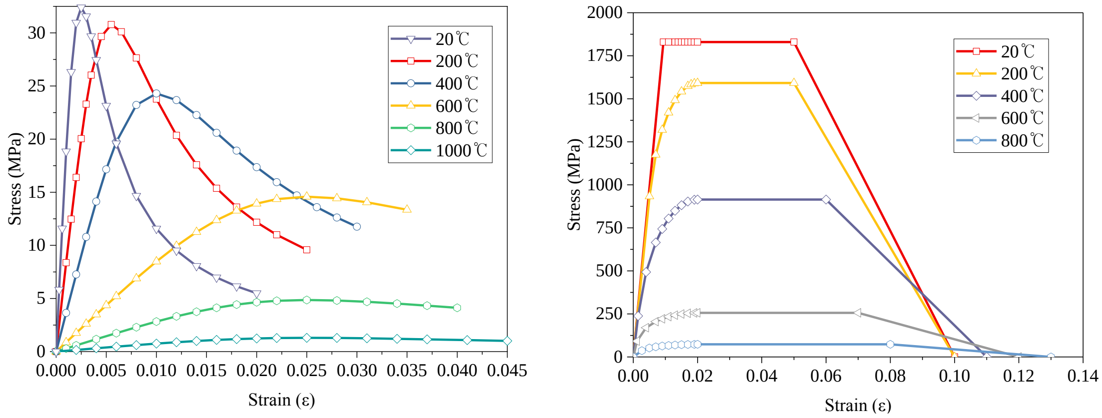
3.1 Analysis procedure

A numerical model, developed in ANSYS finite element program (ANSYS 2013), is utilized to trace the fire response of a PC T bridge girder under hydrocarbon fire exposure. This model can account for temperature-induced property degradation in concrete, prestressing strands and reinforcing steel, cracking and crushing in concrete, support conditions, and hydrocarbon fire exposure scenarios. Fire resistance analysis on PC T shaped bridge girder is carried out through incrementing time from the onset of fire exposure till failure of the girder. This analysis is performed using the following stages namely; fire modeling, heat transfer analysis only in mid-span, static load application, and mechanical analysis of bridge behavior in fire.

For thermal analysis, concrete within PC T shaped bridge girder was discretized using SOLID70 element with a 3-D transient thermal conduction capability. The prestressing strands and reinforcing steel is discretized with LINK33 element, which is a uniaxial element that have the ability to conduct heat between its neighboring nodes. The two thermal elements have linear shape functions and reduced integration. For structural analysis, the PC T bridge girder was modeled with two sets of elements, namely, SOLID65 element for the concrete, and LINK8 element for the prestressing strands and the reinforcing steel. SOLID65 element, with linear shape functions and reduced integration, is capable of simulating mechanical behavior in concrete. LINK8 element, that is a 3-D spar element having uniaxial tension-compression ability together with linear shape functions and reduced integration, is applicable to simulate mechanical behavior of prestressing and resinforcing steel embedded in concrete. Therefore, the two elements are particularly well suited for structural analysis of PC bridge girders in fire.

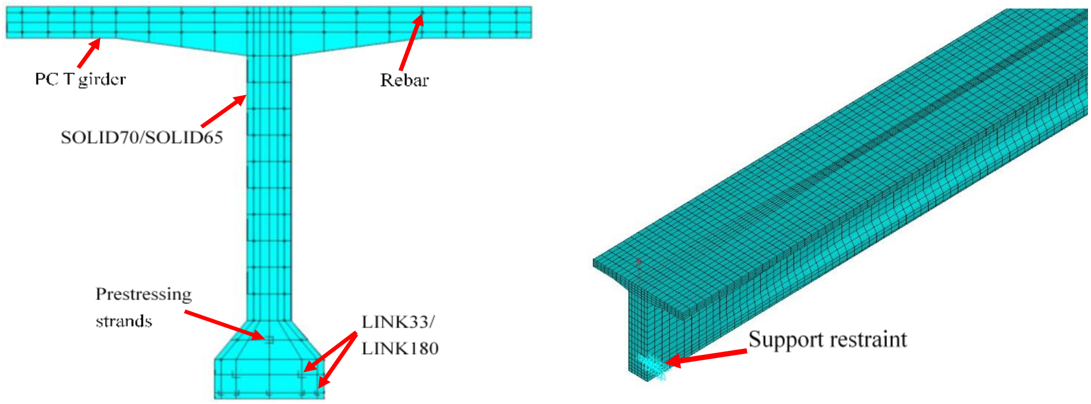
For thermo-mechanical coupled analysis, temperature-dependent thermal and mechanical properties are provided as input into ANSYS (ANSYS 2013). The progression of temperatures within girder section, under fire exposure, depends on temperature-dependent thermal properties, including thermal conductivity, specific heat and associated moisture and heat emissivity in concrete (CEN 2002, CEN 2004, CEN 2005). Mechanical properties involving density, elastic modulus, poison's ratio, stress-strain relations and thermal expansion of concrete, reinforcing steel and prestressing strands, are provided as input data for structural response analysis, and these properties vary with temperature (Lie and Denham 1993, CEN 2002, CEN 2004, CEN 2005, Li and Guo 1993).

The plastic damage in concrete is defined using Willam and Warnke (1975) model, which is capable of simulating nonlinear mechanical behaviour of compression and tension in concrete. The imperative input parameters include shear transfer coefficient of crack opening and crack closing, taken as 0.2 and 0.7 respectively. There is no consideration of concrete crushing in fire resistance analysis of PC T bridge girders due to the difficulty of convergence. The concrete



(a) Concrete (b) Prestressing strands

Fig. 5 Stress-strain relations of concrete and prestressing strands



(a) Cross-sectional discretization (b) 3-D mesh and boundary conditions

Fig. 6 Discretization and boundary conditions of PC T shaped bridge girder

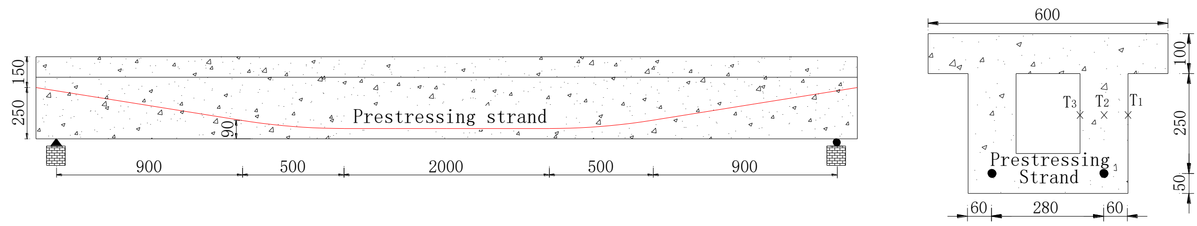
tensile cracking stress at room temperature, assumed to be 2.65 MPa, decreases with temperature rise as per provisions taken from Eurocode (CEN 2004). When concrete reaches tensile cracking stress at any of fire exposure, the tensile stress, suddenly dropped to 60% of the initial cracking stress, is utilized to perform an fire resistance analysis of cracked concrete (Song *et al.* 2020). The creep in concrete and the relaxation in prestressing strands at elevated temperatures are implicitly accounted in temperature dependent stress-strain relations, as shown in Fig. 5.

The structural analysis on fire exposed PC T shaped bridge girder is performed under an applied structural load, which is comprised of 100% dead load and 30% live load (ASTM 2014, Kodur and Dwaikat 2008). The live load (single-lane vehicle load) is assumed to consist of a concentrated load enforced on mid-span plus uniform load distributed over the span, and this can reflect actual load scenarios (Kodur and Dwaikat 2008, Song *et al.* 2020, Zhang *et al.* 2017a, Zhang *et al.* 2019). The applied structural loading is enforced on the PC bridge girder before fire, and then divided into a number of load steps together with sub-steps associated with time increment through fire exposure duration. These time-increment steps are herein adjusted to reach the satisfied convergence results at any time of fire exposure. This is due to the fact that nonlinear analysis for PC bridge girder at elevated temperatures is much difficult to converge. Divergence in structural analysis occurs when displacement convergence tolerance surpasses 10%, and then the numerical analysis procedure is stopped. To simulate the coupled interaction effect between concrete and prestressing strands, common-node method used for "SOLID" and "LINK" elements is applied to perform structural analysis. This can be attributed to the fact that there is high-strength mortar filled with the prestressing strand tube to ensure grip force between concrete and prestressing strands. Herein, prestress in strands can be defined using initial strains, which is equal to stress divided by elastic modulus in prestresing strands.

3.2 Discretization of PC T shaped bridge girder

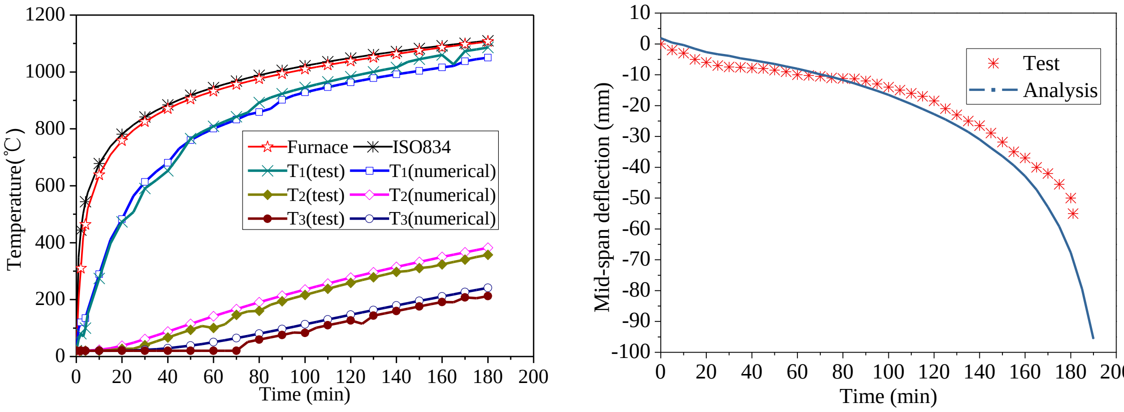
The PC T shaped bridge girder is assumed to be subjected to hydrocarbon fire exposure over length of 20 m along the mid-span, in which the bottom surface of bottom flange and top flange and outside of web is exposed to the heat flux resulted from the exposure to hydrocarbon fire.

The PC T shaped bridge girder is meshed with "SOLID" elements as shown in Fig. 6. Convective coefficient of 50 W/(m^2.°C) (CEN 2002) is applied in the heat transfer analysis for hydrocarbon fire exposure (ASTM 2014). An emissivity coefficient of 0.9, validated by model test, is used to model radiative heat transfer to the exposed girder. A Stefan-



(a) Elevation (b) Cross section

Fig. 7 Details of the test girder used for validation of the numerical procedure (Unit: mm)



(a) Temperature (b) Deflection

Fig. 8 Comparison of predicted and measured data

Boltzman radiation constant of 5.67×10^{-8} W/($m^2\cdot K^4$) is used in thermal analysis. For thermal and structural analysis, the following assumptions are made: (1) heat conduction along cross section of prestressing strands and reinforcing steel is neglected; (2) there is no bond-slip between the prestress strand and the concrete as discussed above; (3) no concrete spalling is considered due to the fact the spalling mainly occurs in high-strength concrete with high water content (Kodur and Dawait 2008).

3.3 Boundary conditions

To simulate simply supported conditions in structural finite element model, single-line nodes at lower face of the bottom flange located at one end of the girder are constrained at *x*, *y* and *z* directions (transverse, vertical and longitudinal directions). Similarly, single-line nodes, symmetric to mid-span, at the other end of the girder are constrained at x and y directions. This boundary condition can reflect a practical mechanical bearing scenario of simply supported conditions, and also the solution convergence can be highly improved throughout nonlinear analysis procedure as discussed earlier (Song *et al*. 2020).

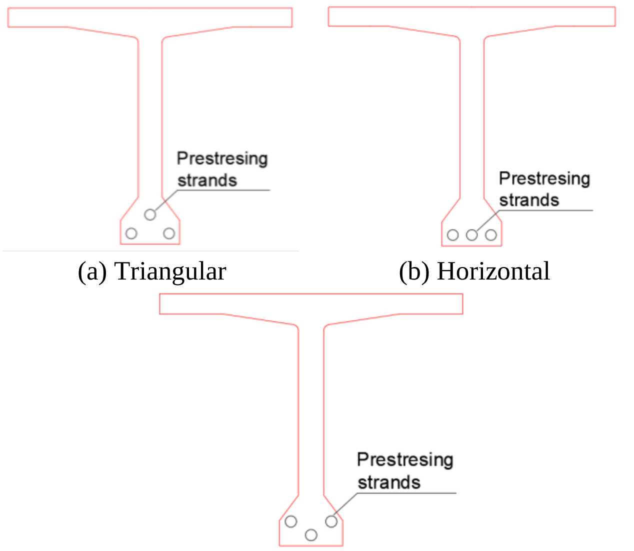
3.4 Failure criterion

The failure time of the girder is evaluated by applying deflection and strength (moment) failure limit state specified in BS 476 (BS476-20 1987). Failure of a PC T shaped girder occurs when the maximum deflection of the girder exceeds L/20 at any fire exposure time or the rate of deflection exceeds L^2/9000D, where, L is the span length and D is the effective sectional height. As per strength (moment) limit state, if moment capacity at mid-span of PC T shaped bridge girder descends below bending moment arising from applied bridge structural loading, then failure of the girder occurs. Herein, the moment capacity can be achieved using hand calculations through the reduced material strength in PC bridge girders count on temperature in section generated from heat transfer analysis.

3.5 Model validation

There is a lack of fire test data on the response of PC T shaped bridge girders in the case of fire exposure. Therefore, validation of the model is performed through selecting a PC box bridge girder tested under ISO 834 fire exposure condition (Zhang *et al*. 2017, Song *et al*. 2020, ISO 1999). The tested PC box bridge girder spans a length of 3.8 m, has width of 600 mm and height of 400 mm (See Fig. 7). The thickness in top and bottom flange is 100 mm, and that in web is 120 mm. The PC box bridge girder is fabricated using concrete with compressive strength of 50 MPa and strengthened using two prestressing strands with limit tensile strength of 1860 MPa. Herein, the materials in validation example are consistent with those being used in the selected PC T bridge girder.

The validation is carried out by comparing of both thermal and structural response from the numerical model with reported data in fire test. The analysis was performed with the mesh discretization, and also temperature-dependent properties and analysis skills as discussed earlier. The predicted response of fire shows a good quantitative and qualitative comparison with the reported data from the fire test



(a) Triangular (b) Horizontal

(c) Invert triangular

Fig. 9 Layout of prestressing strands in bridge girder section

(See Fig. 8). The slight differences in temperature, from measurement points T_1, T_2 and T_3, are mainly due to non-uniform temperature distribution in furnace and inhomogeneity of concrete materials used in the actual test girder. Also, the slight differences in mid-span deflection trends can be attributed to minor variation in the thermo-mechanical parameters, i.e., elastic modulus and strength and stress-strain relations, idealized for analysis.

4. Parametric studies

To investigate fire response of a typical PC T shaped bridge girder under localized hydrocarbon fire exposure conditions, a simply supported PC T shaped bridge girder is analyzed using ANSYS by subjecting it to simultaneous structural loading and fire exposure.

4.1 Analysis parameters

The validated numerical model is utilized to investigate the thermal response and structural response under varying parameters including effective degree of prestress, thickness of concrete cover to prestressing strands, layout of prestressing strands and content of prestressing strands. Effective degree of prestress is defined as the ratio of actual tension stress to limit tension stress (75% of 1860 MPa) in anchorage zone when prestressing strands is stretched. The effective degree of prestress in anchorage zone, changed from 80% to 60% before fire, are as input data in to structural analysis through taking into consideration prestress loss during tension and anchorage of strands. The gravity load herein remains unchanged.

Concrete cover thickness to prestressing strand is assumed to be 40 mm, 50 mm and 60 mm. Layout of prestressing strands across the span of the girder (from each end span to mid span) is assumed to vary in triangular shape, horizontal shape and inverted triangular shape, as shown in Fig. 9. Content (cross-sectional area) of prestressing strands is varied as per 0.9, 1.0 and 1.1 times design value before fire. These analysis parameters are tabulated in Table 1.

Table 1 Analysis parameters

Cases	Abbreviation of Analysis parameters	Illustration of analysis parameters	Value
Case 1	PSL	Prestressing strand layout	Triangular layout Horrizontal layout Inverted triangular layout
Case 2	CCT	Concrete cover thickness	40 mm 50 mm 60 mm
Case 3	PDP	Effective degree of prestressing in strands	60% 70% 80%
Case 4	CPS	Content of prestressing strands	0.9 1.0 1.1

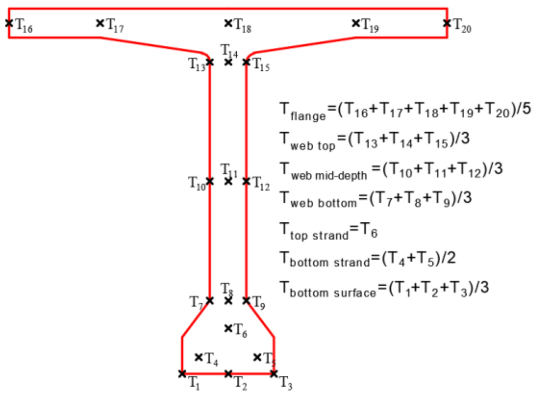


Fig. 10 Averaging temperature within PC T shaped bridge girder section

4.2 Thermal response

To illustrate temperature evolution in top flange, web, bottom flange and prestressing strands with fire exposure time, respectively, temperature in each portion of T shaped bridge girder is acquired through figuring out arithmetic mean of temperatures at several points generated in ANSYS, as shown in Fig. 10. Herein, the arithmetic mean value is calculated using temperatures resulted from several points located at the same level of height in cross section. This can be applicable to account for temperature gradient developed across the depth of the bridge girder together with temperature distribution of prestressing strands. Subsequently, it can be used to illustrate thermal bowing of PC T bridge girders under fire exposure conditions.

Sectional temperature generated from thermal analysis of PC T shaped bridge girder, under hydrocarbon fire exposure, is plotted as a function of time in Fig. 11. It can be seen that the temperature evolution in web bottom and mid-depth is almost similar, where there is a little difference in web top during the early stage of temperature rise (before 40 min) due

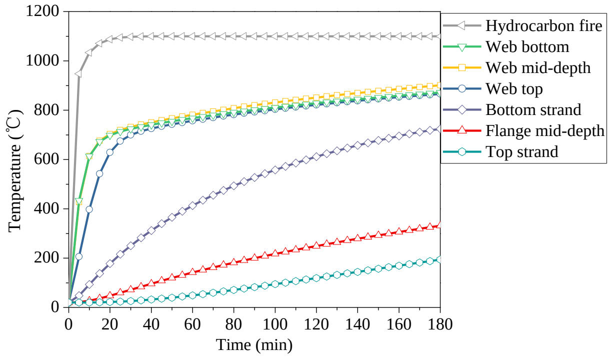
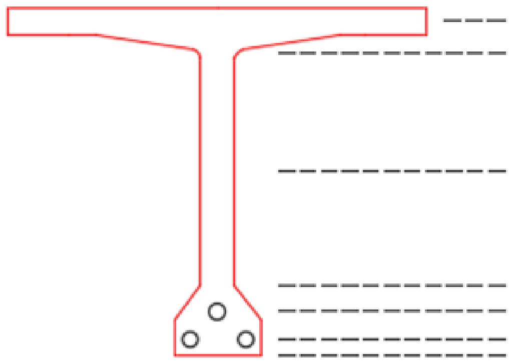
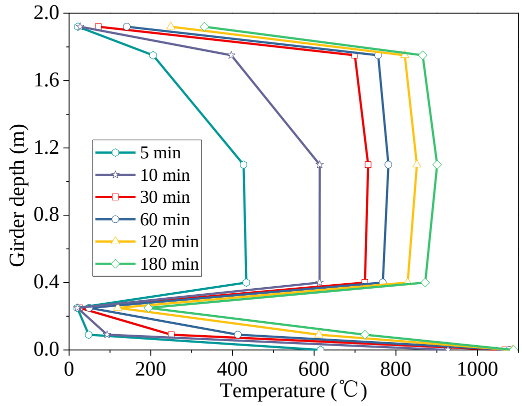


Fig. 11 Temperature progression within PC T girder section



(a) Cross section



(b) Thermal gradient

Fig. 12 Thermal gradient developed across the girder depth

to heat sink resulting from top flange. Temperature in top strand is much lower as compared to that in bottom strands due to thermal inertia generated by thickness of concrete cover. At about 60 minutes, temperature in bottom prestressing strands reach 400°C, which cause significant degradation of mechanical properties in prestressing strands at this level of temperature (See Fig. 5).

Thermal gradient generated from thermal analysis of PC T girder is plotted as a function of hydrocarbon fire exposure time, as shown in Fig. 12. It can be seen the thermal gradients between the surface of bottom flange and prestressing strands is significant due to thermal inertia of concrete. At the first few minutes (about 5 min) of fire exposure, the temperature difference between bottom flange and top flange reach 600°C. This level of temperature difference can lead to downwards thermal bowing of PC T shaped bridge girder. Thus, the stresses inside strands may increase due to changes of the girder's curvature related to non-uniform temperature distribution developed across the cross-section depth. At this fire exposure stage, the temperature distributed within the bottom flange is non-uniform and there is no rapid change in temperature of strands and neighbour concrete.

4.3 Structural response

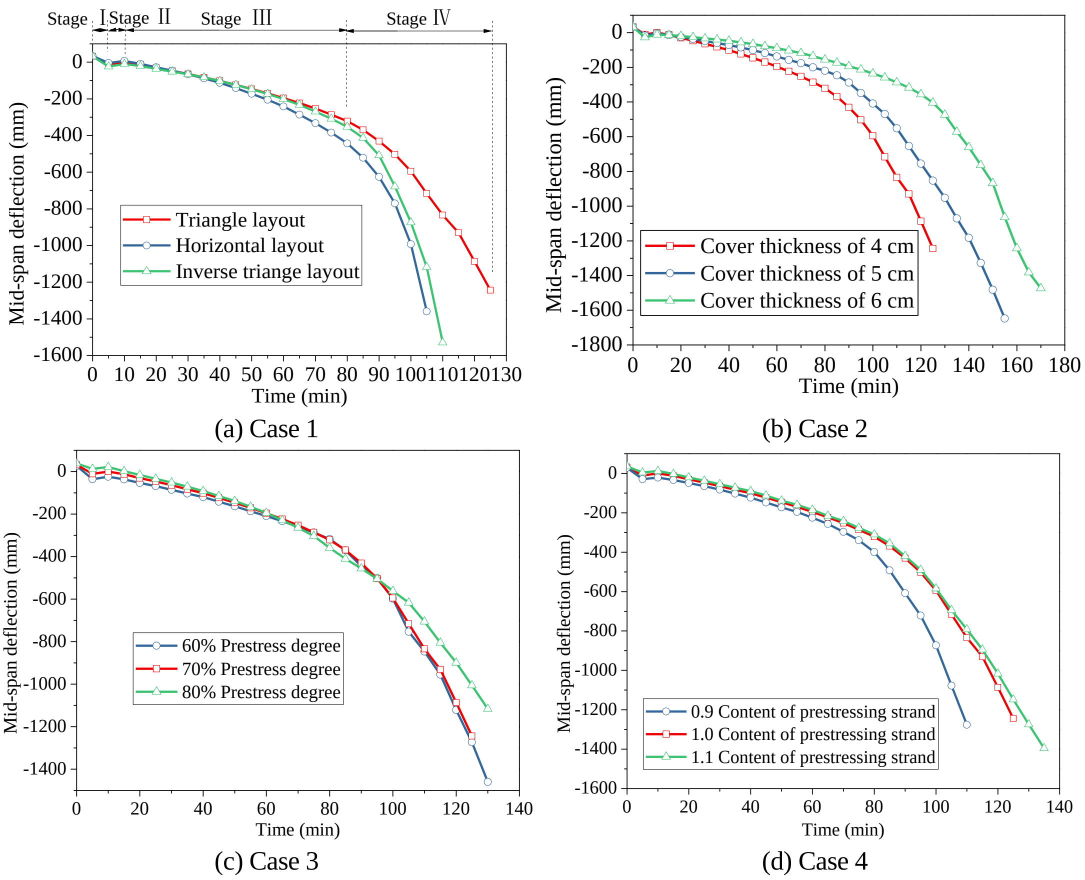
Mid-span deflection of a typical bridge girder is analyzed under four varying parameters, i.e., layout of prestressing strands in girder, concrete cover thickness to prestressing strands, effective degree of prestress and content of prestressing strands, as illustrated in Fig. 13. The general trend of the deflection progression can be grouped into four different stages, namely; stage I, stage II, stage III, and stage IV.

In stage I (the first 5 min of fire exposure), the slight increase in mid-span deflection is independent of structural loading. This deflection is mainly contributed to highly thermal expansion of concrete in bottom flange and resulting curvature within PC girder section originated from built-up large thermal gradients. In stage II (between 5 and 10 min of fire exposure), the mid-span deflection goes in to slightly hogging pattern, induced by temperature rise within top flange. Top flange resulted from elevated temperature generates a more significant thermal expansion deformation as compared to bottom flange, and thus causing upwards thermal arch. This can be attributed to the fact that heated area of top flange above the neutral axis is larger than heated area of bottom flange. Therefore, this stage is unique and remarkable in PC T shaped bridge girder as compared to other-shaped PC and RC beam provided in literature (Kodur and Dwaikat 2018, Song et al 2020).

In stage III (the time period of this stage varies with different structural inherent parameters), mid-span deflection increase gradually. This is mainly due to deterioration in mechanical properties of steel and concrete, and thus decreased sectional rigidity. At this stage of fire exposure, prestress strands begins to get hotter compared with the previous stage, thus causing thermal elongation. Towards the end at this stage of fire exposure, prestress is significantly lost due to deterioration in strength and stiffness in bottom strands (temperature surpasses 400°C, as shown in Fig. 11), concrete and reinforcing steel.

In the last stage of fire exposure (till failure of the girder), mid-span deflection increases at a rapid pace. This is mainly due to spread of plasticity in bottom strands, concrete and reinforcing steel, and also due to high temperature creep effect in prestressing strands and reinforcing steel at particularly elevated temperatures (temperature surpasses 400°C). At this stage, neutral axis shifts upwards towards the top flange.

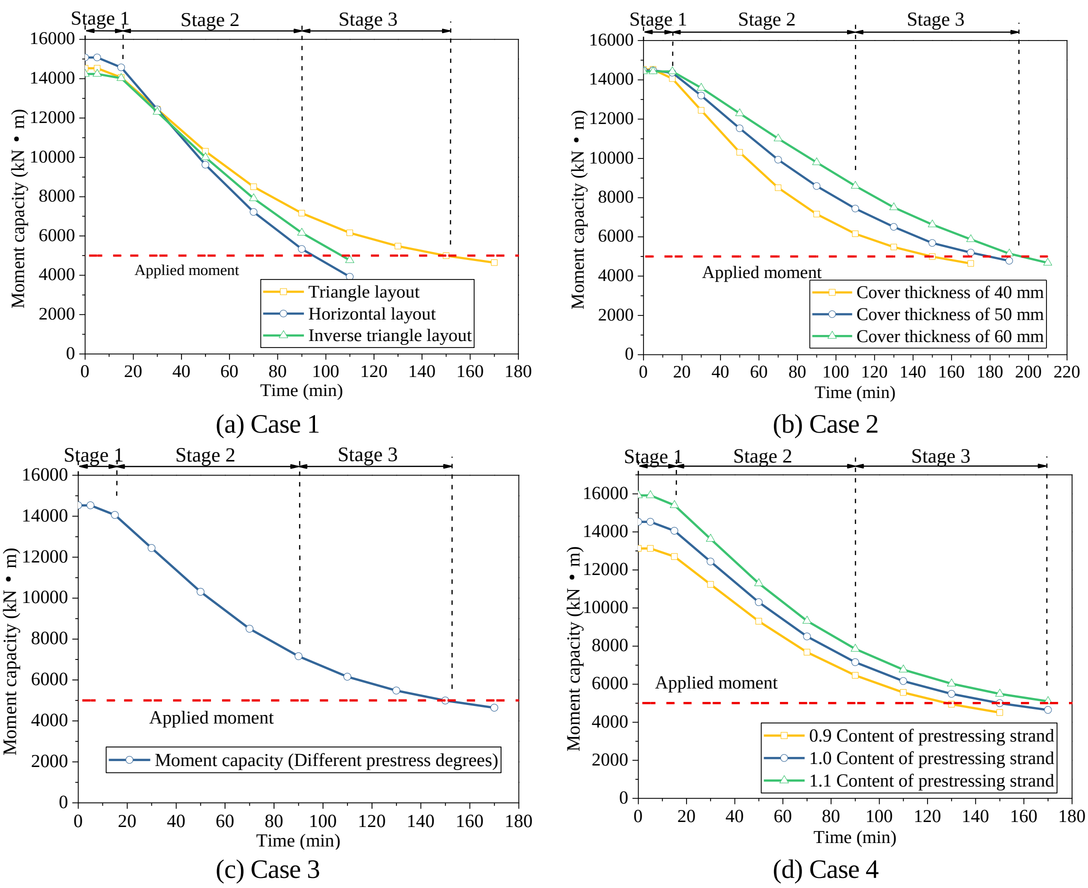
Progression of moment capacity, as a function of fire exposure time, is plotted in Fig. 13. The moment capacity is achieved using hand calculations through the reduced material strength in bridge girders dependent on temperature results from thermal analysis. The moment capacity reflects sectional resistance resisting bending moment generated from the applied structural loading. Herein, if the moment capacity is lower than bending moment, the girder is said to fail.



(a) Case 1 (b) Case 2

(c) Case 3 (d) Case 4

Fig. 13 Effect of the different parameters on the fire resistance of a simply supported PC T shaped bridge girder



(a) Case 1 (b) Case 2

(c) Case 3 (d) Case 4

Fig. 14 Degradation in moment capacity

Table 2 Summary of parameters studies

Case	Varying parameters	Value	Fire resistance (min)		
			Deflection based failure criterion	Rate of deflection based failure criterion	Moment capacity based failure criterion
Case 1	Prestressing strands layout	Triangular layout	No failure	119	149
		Horizontal layout	105	97	95
		Inverted triangular layout	109	99	106
Case 2	Concrete cover thickness	40 mm	No failure	119	149
		50 mm	149	134	177
		60 mm	170	154	195
Case 3	Effective degree of prestressing in strands	60%	130	114	149
		70%	No failure	119	149
		80%	No failure	127	149
Case 4	Content of prestressing strands	0.9	No failure	102	128
		1.0	No failure	119	149
		1.1	No failure	123	170

It can be seen from Fig. 14 that the progression of moment capacity present a degrading tendency with fire exposure time, in which the whole progression can be grouped into three stages namely, stage 1, stage 2 and stage 3.

In stage 1 (the first 15 min of fire exposure), there is no significant degradation of moment capacity. This can be contributed to the fact that strength of prestressing strands governing moment capacity has not reduced at this fire exposure stage when temperature in strands is in the range of 120°C (See Fig. 11).

In stage 2 (fire exposure between 15 min and 90 min), the moment capacity decreases rapidly due to significant deterioration in strength of prestressing strands, reinforcing steel and concrete with fire exposure time. Towards the end of this fire exposure stage, the neutral axis shifts upward towards the top flange.

The progression of moment capacity has a slowdown at the final stage of fire exposure (Stage 3). This variation can be attributed to lower temperature rise within top flange, which will govern the progression of moment capacity after the neutral axis shifts into top flange. The progression of moment capacity at this stage continues slowly till failure of the girder occurs. This failure is mainly dependent on temperature rise in the girder section and the associated loss of strength of prestressing strands, which in turn is a function of temperature in strands.

A summary of the results from parametric studies, including failure time based on deflection and rate of deflection and strength (moment capacity) failure criteria, for four different cases is presented in Table 2. In most cases, the time to failure based on rate of deflection failure criterion occurs earlier than that on deflection based failure criterion. For the girder analysed, the failure is said to occur when the mid-span deflection exceeds the limiting deflection of 1450 mm (L/20) or rate of deflection exceeds 46.7 mm/min (L^2/9000D) based failure criterion or the moment capacity drops below the bending moment (5003 kN.m) as per strength (moment capacity) based failure criterion.

The time to failure of PC T shaped bridge girder under most hydrocarbon fire exposure condition is governed by rate of deflection failure criterion. Prestressing strand arrangement, concrete cover thickness, effective degree of prestressing and content of prestressing strands have a significant influence (at least 13 min in each parameter) on fire resistance of PC bridge girder under hydrocarbon fire exposure scenarios.

5. Proposed approach to enhance fire resistance of PC bridge girders

This paper aims to present a rational and practical approach for evaluating fire performance of PC T shaped bridge girders to mitigate failure of PC bridge girders under fire exposure. The case study herein illustrated is for a PC T shaped bridge girder with thin web that is susceptible to hydrocarbon fire exposure. This approach can be extended to any PC bridge girders. Some structural inherent parameters, including layout of prestressing strands, thickness of concrete cover, effective degree of prestress and content of prestressing strands, incorporated into the bridge structural design, can effectively enhance inherent fire resistance of a PC bridge girder. When these strategies enhancing fire resistance are applied, fire resistance in bridges can be improved to mitigate risk of fire-induced collapse in a PC bridge.

The improved fire resistance of PC bridge girders through taking into account the structural inherent parameters can be approximately estimated using the following simplification formula.

$$\lambda = \frac{t_{total}}{n} \emptyset_i \tag{1}$$

Where, λ is the time increment of fire resistance of PC bridge girder with a certain structural inherent parameters namely; prestressing strands layout, concrete cover thickness, effective degree of prestressing and content of prestressing strands. t_{total} is the total fire resistance time of PC bridge girder with all structural inherent parameters. n represents total number of variable value. $\emptyset_i$ is the weight coefficient of PC bridge girder with different prestressing strands layout, concrete cover thickness, effective degree of prestressing and content of prestressing strands, respectively. This weight coefficient can be calculated as follows

$$\emptyset_i = \frac{\Delta t_{j(max)}}{\sum \Delta t_{j(max)}} \tag{2}$$

Where, $\Delta t_{j(max)}$ are the maximum time increment of fire resistance of PC bridge girder with different prestressing strands layout, concrete cover thickness, effective degree of prestressing and content of prestressing strands, respectively. $\Delta t_{j(max)}$ can be also expressed as $\Delta t_{\mathrm{PSL(max)}}$, $\Delta t_{\mathrm{CCT(max)}}$, $\Delta t_{\mathrm{PDP(max)}}$ and $\Delta t_{\mathrm{CPS(max)}}$. Herein, as per the time increment of fire resistance analysed above (See Table 2), $\emptyset_i$ in different parameters as presented above is taken as 0.22, 0.39, 0.15 and 0.24 in order. The prerequisite for the establishment of this simplification formula is that $\sum \Delta t_{j(max)}$ is approximated to $\frac{t_{total}}{n}$.

Through a case as analysed above, if thickness of concrete cover with 60 mm and effective degree of prestress 80% are applied in structural fire-resistant design of PC bridge girders, the maximum increment of fire resistance can achieve 64 min and calculated as follow. This increment of fire resistance can effectively ensure adequate time for firefighter' rescue and natural exhaustion of fuel; thus mitigating severe fire damage.

$$\lambda = 119 \times 0.39 + 119 \times 0.15 \approx 64 \tag{3}$$

6. Conclusions

Based on the results presented in this paper, following conclusions can be drawn on the fire response of PC T shaped bridge girders:

- Proposed finite element based numerical model, built in ANSYS, can be successfully applied to investigate the behavior of PC bridge girder under fire exposure, in the entire range of loading, from initial prestressing stage to structural collapse under fire.
- Rate of deflection based failure criterion governs failure in PC T shaped bridge girders, specially under hydrocarbon fire exposure conditions.
- Arrangement of prestressing strands in a girder span has influence on level of fire resistance attained in a PC T shaped bridge girder. Triangle layout can enhance fire resistance of PC T shaped bridge girder by 20 min in the case of high intensity fire exposure.
- Increase of concrete cover thickness to prestressing strand by 10 mm can enhance fire resistance of PC T shaped bridge girder by 10 min.
- Fire resistance can be enhanced by 17 min when content of prestressing strands increases from 0.9 to 1.0.
- Though a increase from 60% to 80% in effective degree of prestress can only enhance fire resistance by 13 min, increase in effective degree of prestress with triangular shaped strands can slow down progression of deflections in a PC T shaped girder towards the end of fire exposure.
- The proposed simplification formula can be used to approximately estimate the time increment of fire resistance in PC bridge girders.

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