Parametric Analysis of Tensile Behavior for Adhesive Anchor in Steel-to-Concrete Connection Exposed to Fire

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Abstract: Adhesive anchor is an effective tool for structural retrofit and strengthen which is typically used in a steel-to-concrete connection, however the bond strength of adhesive would have significant reduction at elevated temperature which could cause safety problem. Therefore this paper proposed a numerical analysis of 3D FE model to investigate the performance of steel-to-concrete connection exposed to fire. Variables that affect the thermal response of adhesive anchor including fire resisting coating's thickness, edge distance, fire-protection area as well as embedment depth of anchor have been studied. The results show that tensile strength of adhesive anchor presents a great reduction at elevated temperature compared to the strength in normal temperature. Parametric analysis indicates that thicker fire resisting coating can provide better protection for anchor and the anchor temperature is controlled in a relatively lower level. The maximum temperature of anchor in the case of edge distance 40mm would reach above 600℃ after a fire exposure of 90 minutes. Compared to the total coating protection on concrete surface, partial protection measurement tends to lead to nonuniformity of temperature distribution on concrete surface in the early stage of heating. The increase of embedment depth has slight effect on temperature gradient of anchor at elevated temperature.
Keywords: adhesive anchor; fire; bond stress; steel-to-concrete connection

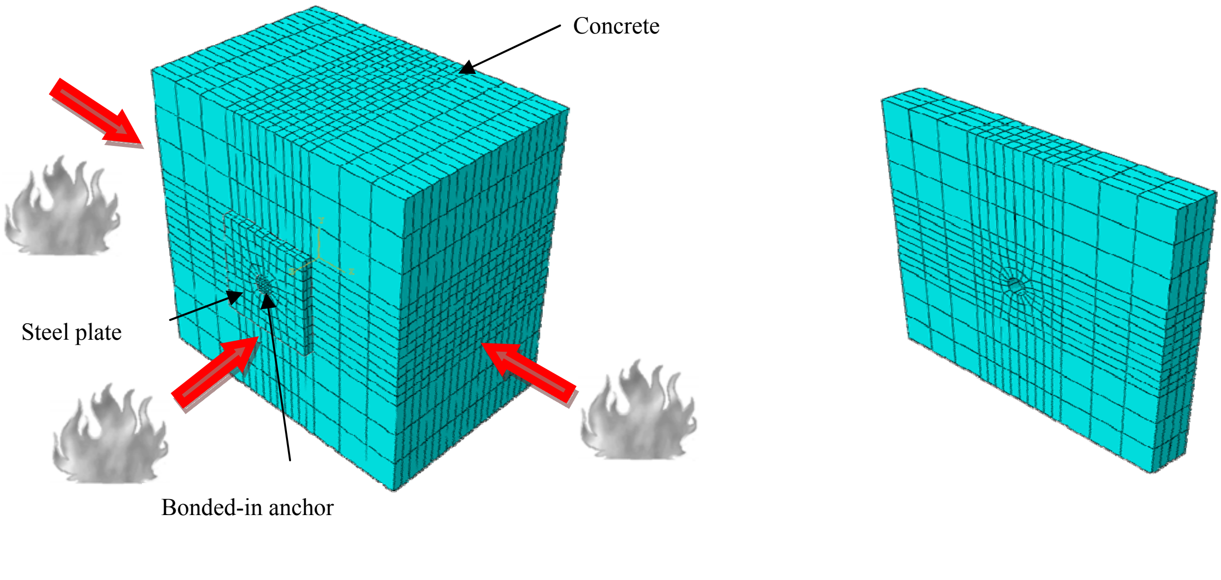
1. INTRODUCTION

Adhesive anchor is widely used in civil engineering where a steel component is intended to connect with an existing concrete element. In a typical steel-to-concrete connection the steel plate is an essential component to transfer applied load from steel component to concrete base, therefore a combined steel system consisting of anchor, steel plate and steel element exists in connection. As a material with good conductivity and temperature-dependent strength, steel generally is required to be covered by fire resisting material to avoid temperature arising too fast. Furthermore there is a obvious disadvantage for adhesive which plays an important role in anchorage system that the bond strength would have significant reduction at elevated temperature, thus the purpose of fire design for connection is to control the temperature of adhesive under allowable value. For a steel-to-concrete connection the existing analysis shows that the strength of connection would be governed by steel strength of anchor for a ductile design[1-3] (Ronald A.Cook, 1992;Ehab A.Ahmed etc,2008;S.E.Robinson A.M.Said,2011). Because the experiment of fire research is high-cost and demanding, numerical analysis has been approved to be an effective and alterative method, the simulation results for anchors in room temperature agree well with experimental data[4-7](J.Ozbolt, 2007;Chang Xu,2011;Aaron J.Wang,2012;Yong-Gang Zhang, 2001). Currently limited knowledge about adhesive anchor in a steel-to-concrete connection exposed to fire is available. Existing research in anchorage field focuses on the structural performance of bonded-in reinforcement in concrete at elevated temperature, little knowledge about the thermal and structural response of adhesive anchor in steel-to-concrete connection subjected to fire is available.

In this study a parametric analysis for a 3D FE model of steel-to-concrete connection with adhesive anchor subjected to fire has been carried out to study the influence of factors such as fire resisting coating, edge distance, fire protection area and embedment depth on anchor's temperature development and structural performance.

2. MODEL INFORMATION

The simulation model includes reinforced concrete base, adhesive anchor, steel plate and fire resisting coating. Anchor and steel plate both locate in the middle of concrete base surface which is totally protected by fire resisting coating. The whole model is supposed to expose to fire at three surfaces as shown in Fig. 1 and the other three surfaces have no fire action. The dimensions of steel plate and anchor diameter in all models keep as a constant.



(a) Steel-to-concrete connection (b) Fire resisting coating

Fig. 1 Model details

In order to obtain accurate temperature distribution, the anchor cross-section has more refined mesh. The ISO834 standard time-temperature curve is used in this research. According to related requirements, the structural elements should support reliably the designed load without loading capacity reduction even in a fire rating of at least 90 minutes, so in heat analysis the model is supposed to subject a fire action for 90 minutes. A room temperature 20℃ is specified as an initial condition and it is assumed that the initial temperature is uniformly distributed throughout the whole model[8].

The analytical approach consists of two sequential analysis steps; (1) heat transfer analysis, and (2) structural analysis. The nonlinear heat transfer analysis is conducted first to determine the distribution and magnitude of temperature field of all components at different heating phases. The analysis is transient because temperature varies with time in fire and an overall temperature history needs to be solved for the following structural analysis step[9]. Then the structural analysis is conducted to investigate the tensile behavior of adhesive anchor in elevated temperature, which is obtained from the previous results of heat analysis. A sequential heat transfer and structural analysis is possible because the structural analysis is uncoupled with the heat transfer which means the structural analysis results are independent on the heat transfer analysis.

In structural analysis the tension load is axially applied to anchor top end by longitudinal displacement. For properly assigning the temperatures field obtained from the heat analysis to the same location of the structural model, the FEM geometry and mesh in structural analysis is identical to the model used in corresponding heat transfer analysis[10].

2.1 Material properties

For concrete, steel and fire resisting coating the material properties are greatly influenced by elevated temperature and quite different from the properties in room temperature. The thermal properties for all material in model are listed in Table 1.For the reason of simplified analysis, the thermal coefficients, conductivity and specific heat, are all assumed to be constants. The strength and deformation properties of uniaxially compressive concrete and tensile anchor at elevated temperatures could be obtained from Eurocode2 respectively.

Table 1. Material properties at elevated temperature

Material	Concrete	Steel	Fire-resistance coating
Emissivity	0.9	0.8	0.95
Poisson's ratio	0.17	0.3	-
Thermal conductivity	1.92	30	0.12
Specific heat(J/kg•℃)	1000	500	600
Density (kg/m^3)	2400	7850	450
Thermal expansion	0.000008	0.000012	-

2.2 Bond behavior

The anchorage mechanism for chemical anchor is that the force applied to anchor could be transferred to concrete base through the bond behavior of adhesive between anchor and concrete. The bond stress is not distributed uniformly along anchor length, so position function must be considered in order to obtain accurate bond stress for any given position. What's more, the bond performance of adhesive will decrease with the increase of temperature. Existing research on the fire resistance of bonded-in rebar in reinforced concrete beam under tensile load shows that the bond-slip relationship of adhesive at elevated temperatures could be presented by a serial of τ-s curves. According to analysis results[11], the bond stress for a certain position of anchor at a given temperature could be predicted as Equation(1), where *P(x)* is the position function shown in Equation(2), *f(s,T)* is the nominal time-dependent bond-slip relationship predicted as Equation(3) which describes the ratio of slip s at a given temperature to the peak slip $s_{max,T}$ at the corresponding temperature. At any temperatures the ascending part for all curves has the identical formula, while the relative slips for descending part could be predicted by different formulas due to the elevation of temperatures. The relationship of *f(s,T)-slip* for temperature scope 20℃ ~160℃ is graphically described in Fig.3.

$$\tau(x,T,s) = P(x)\cdot f(s,T)\cdot \tau_{ave} \tag{1}$$

$$P(x) = 1.35\sqrt{1-(\frac{10x}{3L}-1)^2} \qquad 0 \le x < 0.3L$$
$$P(x) = 1.625 - 0.917\times\frac{x}{L} \qquad 0.3L \le x < 0.9L \tag{2}$$
$$P(x) = 0.8\sqrt{1-(\frac{10x}{L}-9)^2} \qquad 0.9L \le x < L$$

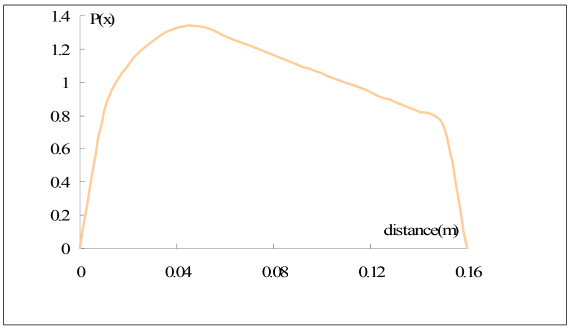


Fig.2 Position function

$$f(s,T) = 0.07(\frac{s}{s_{\max,T}}-1) + 0.93(\frac{s}{s_{\max,T}}-1)^5 + 1 \qquad 0 \le \frac{s}{s_{\max,T}} \le 1$$

$$f(s,T) = \frac{2.08\times\frac{s}{s_{\max,T}}}{2.45\times(\frac{s}{s_{\max,T}}-1)^{2.12} + 2.08\times\frac{s}{s_{\max,T}}} \qquad 1 \le \frac{s}{s_{\max,T}} \le 8, 25^\circ C \le T \le 40^\circ C \tag{3}$$

$$f(s,T)=\frac{2.57\times\frac{s}{s_{\max,T}}}{1.39\times(\frac{s}{s_{\max,T}}-1)^{1.94}+2.57\times\frac{s}{s_{\max,T}}}\qquad 1\le\frac{s}{s_{\max,T}}\le 8, 40^{\circ}C\le T\le 140^{\circ}C$$

$$f(s,T)=\frac{2.84\times\frac{s}{s_{\max,T}}}{0.68\times(\frac{s}{s_{\max,T}}-1)^{2.02}+2.84\times\frac{s}{s_{\max,T}}}\qquad 1\le\frac{s}{s_{\max,T}}\le 8, 140^{\circ}C\le T\le 250^{\circ}C$$

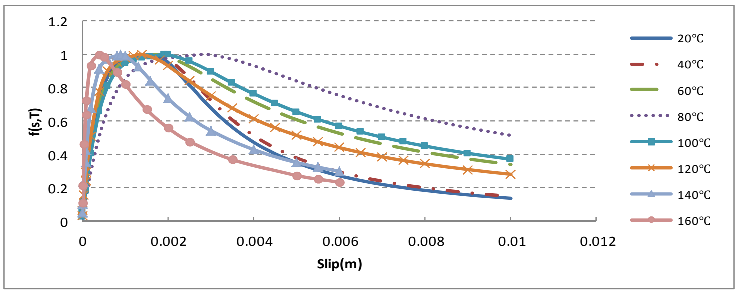


Fig.3 Nominal time-dependent bond-slip relationship

The average bond stress τ_{ave} is also a temperature-dependent parameter which could be derived from Equation(4) on the assumption that the bond stress is distributed uniformly along the anchor length. Fig.4 shows that there is an obvious strength decline for bond stress if the anchor temperature is above 40℃, and the stress drops to about 3MPa with a rather small peak slip at temperature 160℃, which means the anchor has lost 80% tensile capacity and could hardly sustain tension any longer.

$$\tau_{ave,T}=\begin{cases}15.88 & (25℃\le T\le 40℃)\\ 22.10\text{-}0.155T & (40℃< T\le 60℃)\\ 30.49\times e^{-0.0145T} & (60℃< T\le 250℃)\end{cases} \qquad (4)$$

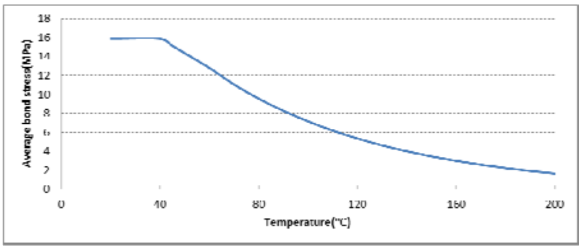


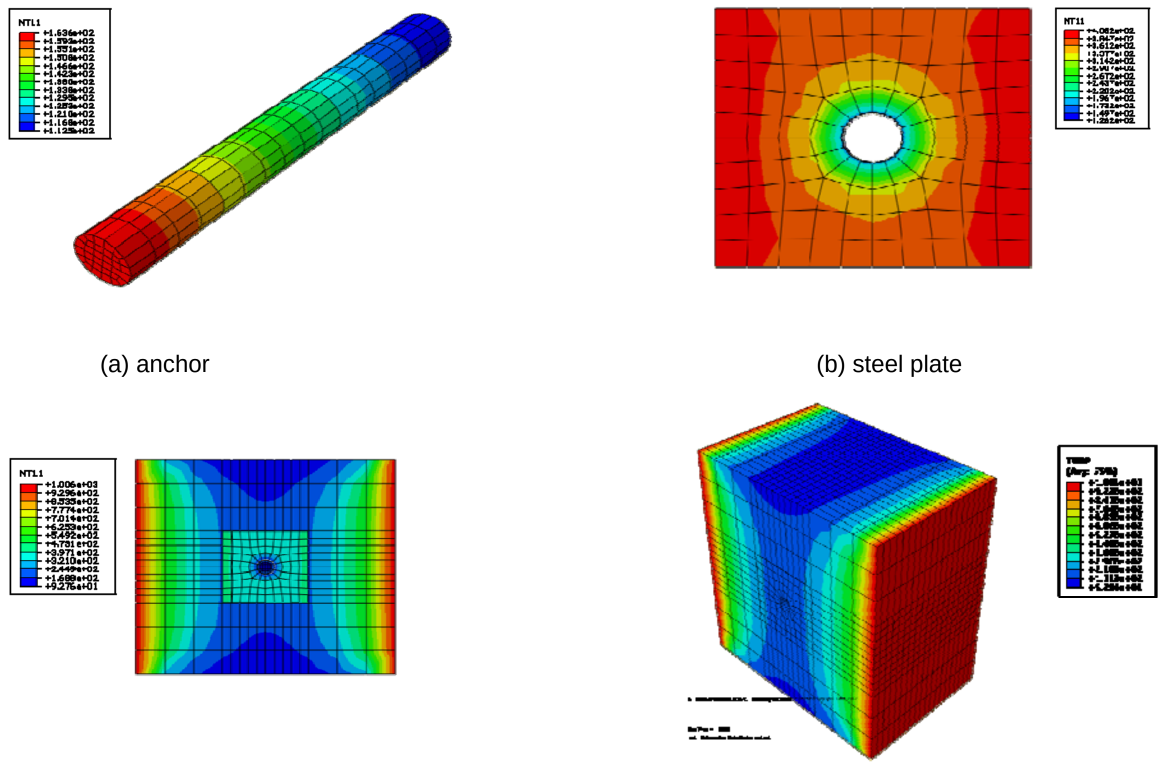
Fig.4 Average bond stress-temperature curve

As a crucial issue, the bond behavior of adhesive between anchor shank and concrete is simulated by using a serial of nonlinear springs which are defined by node pairs in 3D model. The relationship of force-displacement for spring is calculated by the force difference of adjacent cross-section in anchor. In the model there are three springs for each node pair which is consisted of one anchor node and one concrete node which shares the same coordinates with anchor node. The spring in the longitudinal direction of anchor is defined with nonlinear property, while the spring' stiffness in other two directions are infinite because they have no effect on the tension performance of anchor.

2.3 Heat analysis

As mentioned above, heat analysis has been carried out in the first step and the thermal response of each component after fire rating of 90 minutes is presented in Fig.5. As to anchor the maximum temperature occurs in the top end of anchor shank and at the early phase of heating temperature has a relatively identical distribution along anchor length. With the increase of time, the temperature near anchor top has faster growth and eventually reaches 163℃ after 90-minutes heating, meanwhile the minimum temperature 110℃ occurs at bottom end of anchor, so the final temperature gradient isn't uniform.

In the sequentially structural analysis, the temperature field used in structural model is obtained from the previous thermal analysis as an initial condition. Based on the results of bond stress presented above, the temperature range for all structural analysis is from 20℃ to 160℃ because the adhesive would totally lose its bond strength if the temperature is above 160℃. Tensile behavior for anchor in cases of different fire rating has been studied and the key variables are listed in Table 2. The peak force has an obvious drop after the duration time of fire is over 40 minutes. The fail mode is controlled by the steel strength at lower temperature because the bond stress hasn't reached the maximum value before the steel yield, but with the temperature increasing, the negative effect of heat on the bond behavior leads to the bond failure occurs prior to the steel failure after the temperature is above 100℃.



(a) anchor (b) steel plate

© fire resisting coating (d) concrete base

Fig.5 Temperature contour for each component

Table. 2 Analysis results of tensile anchor at different temperatures

Load Case	Fire rating(minute)	Slip (mm)	Peak force (kN)	Anchor maximum temperature (℃)	τ_{ave} (Mpa)	Failure mode
1	0	1.6	127	20	15.88	Steel yield
2	40	1.73	125	60	12.8	Steel yield
3	50	2.8	119	80	9.56	Steel yield
4	60	1.91	96	100	7.15	Bond failure

5	70	1.4	71	120	5.35	Bond failure
6	90	0.4	39	160	3.00	Bond failure

The tension force-slip curves at different temperatures have been compared in Fig.6, the shape of curves in temperature 20℃ and 60℃ agree with each other well because temperature has little effect on bond behavior and the force has no significant reduction even after the peak value. However, for the cases of temperature above 80℃, the tensile strength of anchor has begun to decrease with the elevated temperatures and the peak strength has dropped down to 40kN in the case of 160℃.

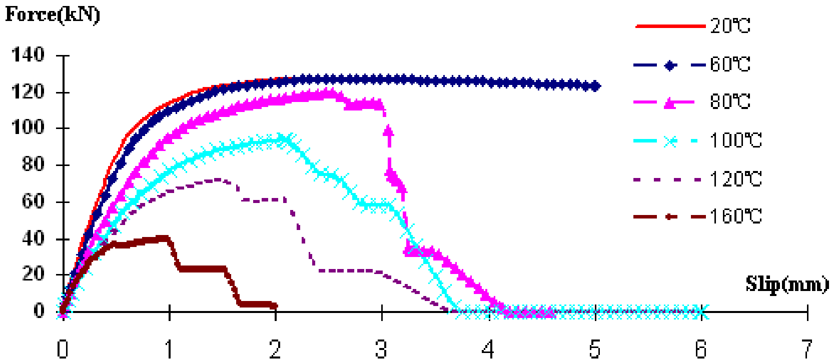
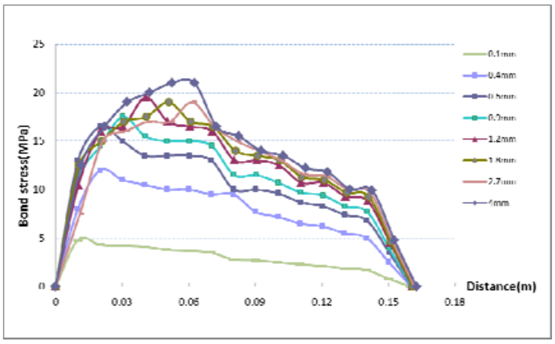
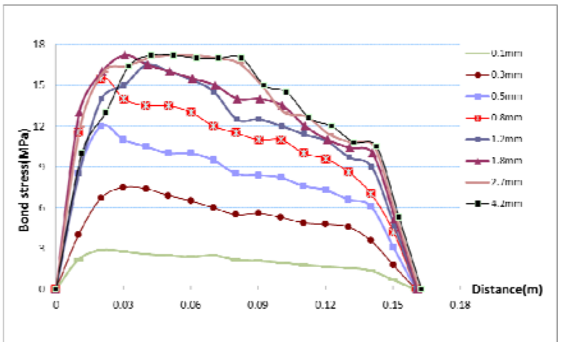


Fig.6 Force-slip curves for anchor at different temperature

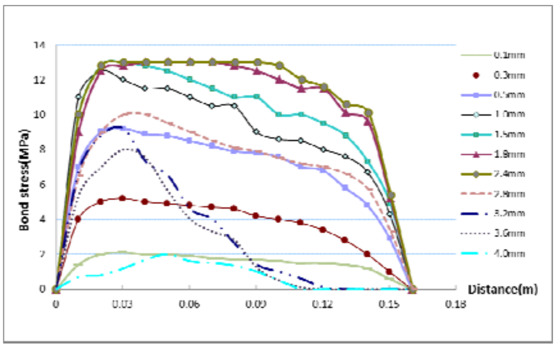
Fig.7 describes the bond stress distribution along anchor length under different maximum anchor temperature as room temperature, 60℃, 80℃, 100℃, 120℃, and 160℃ respectively. For room temperature, the maximum bond stress appears at the position of distance 0.03m in the early loading, and the peak value of bond stress tends to move inward inside with the increment of slip. The bond stress could reach peak value 20 Mpa in the middle portion of anchor after steel failure. The peak value of bond stress decrease with the increment of temperature and there is typical yield plat in some curves at the peak slip. In cases that anchorage strength is controlled by the bond failure, the bond stress usually has a sharp drop after peak value which is shown by dashed lines in curves.



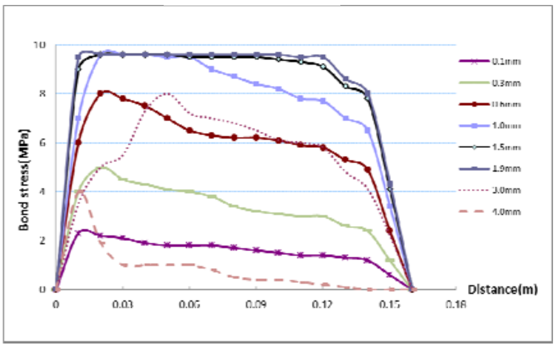
(a) room temperature



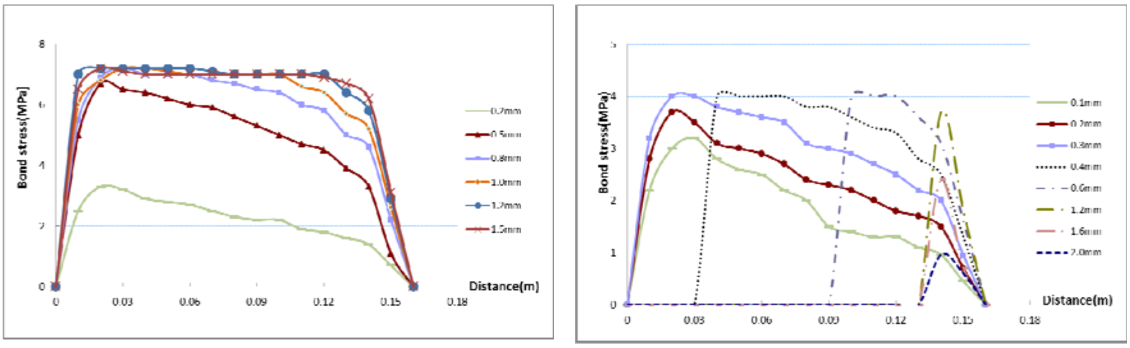
(b) 60℃



(c) 80℃



(d) 100℃



(e) 120℃ (f) 160℃

Fig.7 Bond stress distribution at different temperatures

3. PARAMETRIC ANALYSIS

In this section some typical variables have been investigated to presents sensitivity analysis of the thermal response of adhesive anchor in post-installed steel-to-concrete connection in fire. Parameters include thickness of fire-protection coating, edge distance, fire-protection area, and embedment depth of anchor. The results are presented as following:

3.1 Fire resisting coating

As a fire-resistance material, the coating is directly exposed to fire, and should have good thermal resistance in order to protect steel elements. Different thickness of coating will lead to significantly variation of thermal gradient in anchor, and therefore in this section heat analysis of post-installed steel-to-concrete connection with different values of coating thickness have been simulated. The only difference for these three models is the value of coating thickness. In this section all anchors have the same value 160mm of embedment depth. Model information in detail is listed in Table.3.

Table. 3 Model details for coating thickness analysis

Fire rating (minutes)	Coating thickness(mm)	Maximum anchor temperature (℃)	Displacement (mm)	Peak force(kN)
30	20	85	6	121
	30	60	6	124
	40	41	6	126
60	20	159	5	53
	30	120	5	82
	40	98	5	89
80	30	164	3	47
	40	140	6	58

Fig.8 describes the final temperature distribution along the anchor length after fire duration of 90 minutes for different coating thickness respectively. Based on the comparison of curves, conclusions can be drawn that coating thickness has significant impact on anchor's temperature development. 30mm should be the critical value for fire resisting coating if anchor temperature is expected to below 200 ℃ in a typical steel-to-concrete connection after fire duration of 90 minutes.

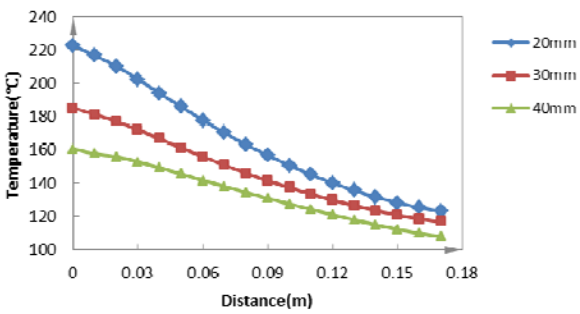


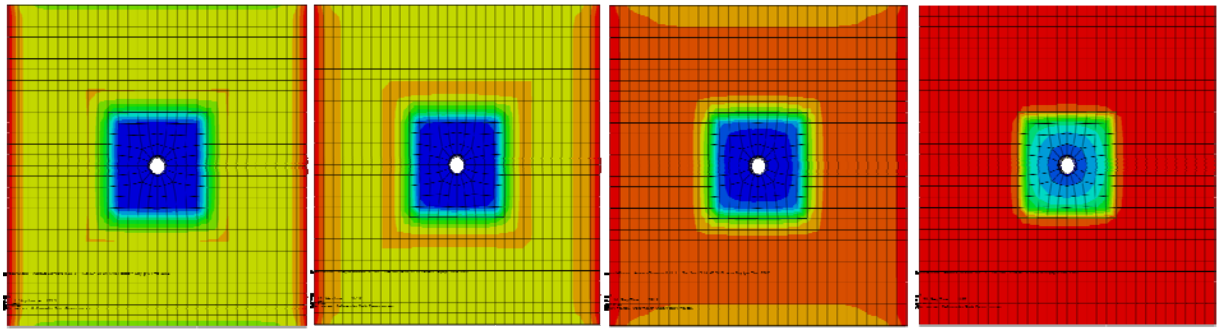
Fig. 8 Analysis results for three thickness values of fire resisting coating

3.2 Fire protection area

In some applications the fire resisting coating isn't designed to cover the whole surface of concrete base, e.g. only give a local protection for the steel surface. What's more, fire resisting coating may probably partially debond from the structural element's surface at high temperature. For the case that fire-resistance coating is partially removed, the temperature field of adhesive anchor is expected to change. In this section the thickness of fire resisting coating keeps a constant of 30mm and the thermal response of anchor in post-installed steel-to-concrete connection with different protection area have been investigated. Table 4 lists the main results for structural analysis and the column "percentage of protection area" are the ratio of protection area to the area of whole concrete surface. For further understanding the heat transfer in case of partial fire-protection, a series of temperature contour of concrete surface with protection ratio 36% are presented in Fig.9.

Table. 4 Model details for protection area analysis

Fire rating (minute)	percentage of protection area	Maximum anchor temperature (℃)	Displacement (mm)	Peak force(kN)
30	16%	168	3	47
	36%	120	3	74
	100%	42	3	126



(a) 2 min (b) 5 min (c) 10 min (d) 30 min

Fig. 9 Temperature contour of concrete surface at different time

The temperature in region without any protection will overall reach to a high level in a very short time, while the temperature in central region covered by fire-resistance coating has a relatively slow increase. There is obvious temperature boundary between protecting area and unprotected area in the early stage of heating, and then the temperature for surrounding region of fire resisting coating gradually develops to the value same as that of unprotected concrete surface. After 30 minutes the surface temperatures almost rise to the identical level except the area that steel plate covers. In order to find out the effect of protection area on the thermal response of anchor, a serial of time- maximum temperature curves have been presented as shown in Fig.10. According to the comparison, the anchor for model with less protection area is expected to show relatively higher temperature.

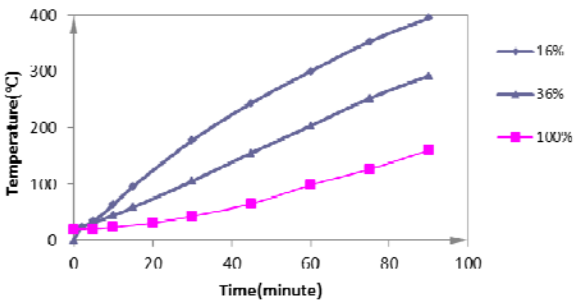


Fig. 10 Time-maximum temperature curves of anchor for three ratio of protection areas

3.3 Edge distance

When the anchor is installed close to the edge of concrete base, the close-edge surface would become a shortcut for heat transfer and the temperatures for inner concrete would have a rapid growth no matter how well protected in other surfaces. In this section the effect of edge distance on the thermal response of adhesive anchor in steel-to-concrete connection at elevated temperature will be discussed and the thickness of fire resisting coating keeps a constant of 40mm. According to the requirement of related codes, minimum distance from the center of anchor shaft to the edge of concrete in one direction is 50mm, thus three kinds of edge distance have been determined to investigate the thermal behavior of adhesive anchor. The detailed results for three cases have been listed in Table.5.

Fig.11 shows the time-temperature relationship for anchor in different edge distances and the temperatures are obtained from the maximum value of anchor. Based the current findings, the normal working temperature for adhesive is 60℃ and the required fire rating is no less than 60 minutes for structural elements. So it is necessary to take fire protection measurement on concrete surface to keep the anchor in a relatively low temperature if the edge distance is less than 100mm.

Table.5 Structurally parametric analysis details for concrete cover

Fire rating (minutes)	Concrete cover(mm)	Maximum anchor temperature (℃)	Displacement (mm)	Peak force(kN)
17	40	160	3	32
	90	52	4	119
	140	25	4	126
50	90	163	3	38
	140	160	5	120

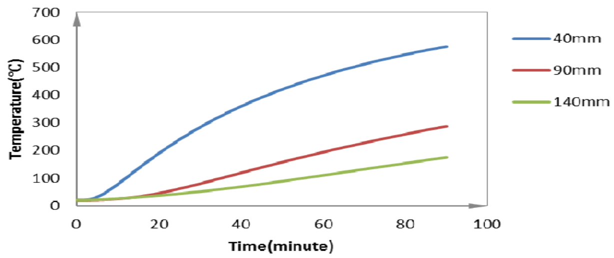


Fig. 11 Time-maximum temperature curves of anchor for different edge distances

3.4 Embedment depth of anchor

Embedment depth is an important factor and different failure modes would occur in cases of different anchor length. The commonly used embedment depth ranges from 8d to 15d(d means anchor diameter). In this section three kinds of embedment depth have been studied and the thickness of fire resisting coating keeps a constant of 40mm.Further information for model is described in Table.6.

Table.6 Structurally parametric analysis details for embedment depth

Fire rating (minutes)	Embedment depth(mm)	Maximum anchor temperature (℃)	Displacement (mm)	Peak force(kN)
90	160 (8d)	160	2	39
90	240 (12d)	157	6	80
90	320 (15d)	152	6	89

The temperature distribution along anchor length in different embedment depth is plotted in Fig.12. The shape of curves for the three cases almost agree well in the front part and the maximum temperatures are between 150℃ and 160℃.The results of temperature comparison indicate that embedment depth has slight impact on temperature gradient of anchor.

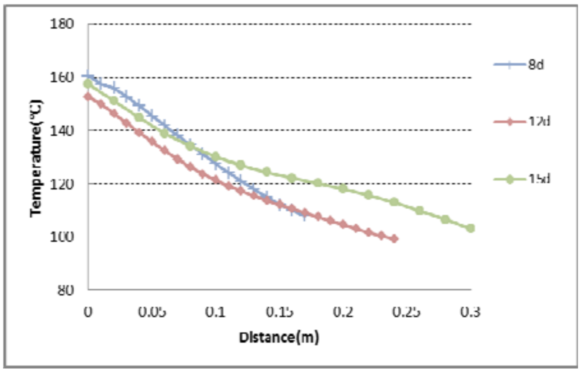


Fig.12 Temperature distribution along anch length for different embedment depth

4.CONCLUSION

In this research factors influencing the thermal behavior of adhesive anchor in steel-to-concrete connection at elevated temperature have been studied. Variables including thickness of fire resisting coating, fire protection area, edge distance and embedment depth of anchor are numerically analyzed in 3D model respectively and some conclusions are presented as following:

(1) Thickness of fire resisting coating has significant impact on anchor's temperature development. A thickness of 30mm should be the critical value if anchor temperature is expected to below 200 ℃ in a typical steel-to-concrete connection after fire duration of 90 minutes.

(2) For the parametric analysis of different fire protection area, there is obvious temperature boundary between protecting area and unprotected area in the early stage of heating .The anchor for model with less protection area is expected to show relatively higher temperature.

(3) It is necessary to take fire protection measurement on concrete surface to keep the anchor in a relatively low temperature if the anchor is installed to concrete base with minimum edge distance less than 100mm.

(4) The comparison results of temperature distribution along anchor length indicate that embedment depth has slight impact on temperature gradient of anchor.

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