Theoretical analysis and design of fire protection and thermal insulation of parallel wire or strand cables

Ping Ouyang\textsuperscript{1}, Boxuan Chen\textsuperscript{2,3,4}, Quanxi Shen\textsuperscript{2,3,4} and Wanxu Zhu\textsuperscript{2,3,4}

Abstract
In this study, a transient heat flow model has been established for parallel wire or strand cables at high temperature by employing the lumped thermal mass approach, and the numerical solution of the surface temperature as a function of time in each layer of the steel wire or strand inside the cable was calculated. Accuracy of the theoretical method is verified through uniform heating test of 73\textdegree{}F 15.7 mm steel strand cable. The results calculated show that temperature field inhomogeneity of cable section is overestimation on the condition that heat conduction inside the cable is not considered. Considering heat conduction or not, the maximum temperature difference of the core steel stand at the same time point is 373. Unprotected 73\textdegree{}F 15.7 mm cable is damaged in only 12 min in UL1709 fire, and arrangement of fire protection layer around cable can effectively retard the temperature rise of cable surface. The experimental results are in good agreement with the theoretical calculation values in early stage of fire, and the temperature difference between the two is within 10%. Besides, the numerical calculations were analyzed in accordance with the fire protection requirements limiting the surface temperature of cables. It was observed that the minimum thickness of the fire protection layer required to meet the PTI DC45.1-12 standard was linearly related to the numerical value of the section factor of the outermost layer of steel wires or steel strands in the equivalent model, and the slope of the function was approximately equal to the conduction coefficient of fire protection layer, as the cable was subjected to fire for 30 min. Further, based on this, a simple method was proposed to calculate the minimum thickness of the fire protection layer for parallel wire or strand cables.

Keywords
Parallel wire cable, fire protection design, temperature history, temperature field, section factor

Date received: 23 June 2022; accepted: 4 September 2022

Handling Editor: Chenhui Liang

Introduction
As an important component of the transportation infrastructure, bridges have enjoyed rapid development and boosted the transportation industry. Cable-stayed bridges and suspension bridges have been widely used owe to their excellent crossing ability. However, increased traffic volume and traffic complexity cause frequent bridge fires.\textsuperscript{1} As the major stress components...
of the cable bridges, cables have typically four main structural forms: the locked coil strand, spiral strand, parallel-strand bundle, and wire rope strand (all shown in Figure 1). Wire rope strand cables are usually applied to the stay-cable and main cable of suspension bridges, which generally manufactured from 15.2 or 15.7 mm steel strands. However, steel is not fire-resistant, and due to high thermal conductivity, its temperature rise promptly and its mechanical properties degrade relatively in fire environment. Previous studies have shown that the strength degradation of steel wire or strand begins at 200°C and intensifies over 300°C, and the steel components losing most of their strength at 600°C. The bridge cables are significantly damaged in case the cars passing on the bridges catch fire, especially the tankers. As a result, the study of the fire protection of the bridge cables is of vital significance.

Currently, a few experimental studies in the literature have focused on the fire protection performance of bridge cables. Fontanari et al. carried out the test research for locked coil and Warrington Seale (WS) rope under ISO834 temperature rise curve, and a good agreement between the experimental and the numerical results was found. In the test of WS rope, the polymer core was softened and ignited due to high temperature, which increased the release of energy. Lucarelli studied the heating law by uniformly heating the 19Φ10 mm hexagonal cable, with thermocouple was arranged at different positions to obtain the temperature field distribution of the whole section of cable. Chen et al. carried out simulated fire experiments on the stay cables. It was observed that the high-density polyethylene (HDPE) protective layers on the surface of the steel strands melted to produce the molten droplets, and the flow of the molten droplets accelerated the flame spread along the cable direction. Nicoletta et al. adopted novel imaging techniques to test the thermal strain and deformation of locked coil and steel stay-cables heated by a methanol pool fire. It showed that the reference values of cable thermal expansion provided by Eurocodes was underestimated in most cases.

Because there are some influencing factors that are difficult to control and realize in fire experimental studies, numerical method has become a common approach to analyze bridge fire problems. Bennetts and Moinuddin numerically studied the rise in the temperature of the cable surfaces. Based on the law of energy conservation, the authors developed a simplified two-dimensional heat transfer model by employing the lumped thermal mass approach, however, heat conduction between wires was not considered and no specific parameter selection method was provided for the fire protection and thermal insulation. In another study, Gong and Agrawal simulated the influence of the ship and truck fires on the cable bridges. The authors reported that the fire protection ability of bridges depends on the fire location, axial force of cables, and design bearing capacity of decks. Besides, Fontanari et al. developed a parameterized finite element model to simulate the thermo-mechanical response of locked coil and Warrington Seale (WS) rope, by taking into account the thermal gradient in cables, however, the study failed to specify the detailed modeling method and could not be directly applied to other conditions. Besides, Wang and Liu and Li et al. determined the thickness of fire protection layers and fire protection height for attaining the fire protection design of the cables pursuant to transient temperature field of bridge cables obtained via finite element analysis. In addition, Kotsovinos et al. analyzed the thermo-mechanical response of the steel strand cables by using the thermal resistance method. The authors regarded the total thermal resistance of the system as the parallel connection between the thermal resistances of the cavity, contact surface, and radiation. It was observed that internal force redistribution and load shedding occurred in cables on increasing the temperature during a fire, and the development of
force and moment are predicted. Based on the analysis methods of Kotsovinos and others, according to the study of Du et al.,\textsuperscript{17} radiation of cavities in the cable structure is considered. It is found that radiation of cavities will increase the temperature in the center of the cable section. However, all the outer steel wires and cavities are regarded as protective layer of the core steel wire, thus the method is only suitable for predicting heating curve of the core wire. Further, Chen and Shen\textsuperscript{18} improved Du’s calculation method to obtain the temperature history at any position of the cable section. The result showed that the temperature gradient of the cable section was affected by the number of wires, and the more the number of wires, the more inhomogeneous the temperature field distribution of the cable section.

The need for the fire resistance of the cables has gradually grown in bridge engineering field, and research on the temperature field of the cable section is the basis for evaluating fire safety of cables. At present, the equivalent solid steel round bar is generally used to analyze the temperature history of cable, whose nonuniformity of calculated temperature field distribution of cables is undervalued because without regard to the influence of cavities on heat transfer.\textsuperscript{17,18} Heat conduction between wires depends on the contact area of them. For a parallel wire cable, compared to solid section, the contact area of wires in cable is positively small due to cavities. The heating history of the cable section calculated through the improved equivalent multi-layer cylindrical wall model, which consider effect of cavity radiation, is still greatly inaccurate. Its calculated temperature of core of cable is too high, and the inhomogeneity of internal temperature field of the cable is underestimated.

In this paper, a theoretical calculation method of the heating history of unprotected cable and protected cable was established, and the temperature rise curve of each layer of steel wires or steel strands could be calculated to obtain the overall temperature field distribution of the cable section. The contact area of heat conduction between steel wires or strands was taken into account in the method, which was applicable to parallel steel wire or steel strand cables with various section arrangement forms and more accurate than previous numerical calculation approaches. Then, factors affecting the cable surface temperature were analyzed. Besides, with reference to the specifications of the Post-Tensioning Institute (PTI),\textsuperscript{19} a simple equation was proposed in this study to calculate the thickness of the fire protection and thermal insulation layer of the steel wire cables or steel strand cables, based on the principle of limiting the surface temperature of the outermost layer, thus, providing a theoretical reference for determining the thickness of the fire protection layer. The technical route of this paper is as shown in Figure 2.

**Heat transfer theory for cables**

*Theoretical basis of heat transfer*

Generally, the heat transfer is realized by three forms, including conduction, convection, and radiation, and these heat transfer modes occur simultaneously in the bridge cables during a fire.

Heat conduction refers to the exchange of the internal energy caused by a temperature gradient between two objects in complete contact or different parts of an object, which follows Fourier’s law, as shown in equation (1):\textsuperscript{20}

\[
q_x = -\lambda \frac{dT}{dx} \cdot A
\]

where, \( q_x \) is the heat flux from conduction per unit length (W), \( \lambda \) refers to the conduction coefficient of the
heat transfer medium \((W/(m \cdot K))\), \(\frac{dT}{dx}\) represents the temperature gradient along the \(X\) direction, the negative sign indicates that the heat flows from the high temperature to the low temperature direction, and \(A\) represents the contact area \((m^2)\).

Taking parallel wire and parallel strand as an example, heat conduction inside the cable occurs between the steel wires or between the steel strands, which regarded as cylinders. According to classical theory, a rectangular contact surface will be formed between two cylinders if there is a contact force:

\[
A = 2bl
\]  

(2)

where, \(l\) is the contact length of two cylinders (as the unit value of two-dimensional analysis), \(b\) is the half-width of the contact, as shown in the Figure 3. \(b\) is related to the diameter of two cylinders, contact force, its elastic modulus and Poisson ratio:

\[
b = \sqrt{\frac{8P}{\pi l} \times \frac{1 - \nu_1^2}{D_1} + \frac{1 - \nu_2^2}{D_2}}
\]  

(3)

where, \(P\) is the normal contact force between cylinders \((N)\), \(D_1\) and \(D_2\) are the diameter of two cylinders, respectively \((m)\), \(\nu_1\) and \(\nu_2\) are the Poisson ratio, respectively, \(E_1\) and \(E_2\) are the elastic modulus respectively \((Pa)\).

When the two cylinders have the same material and the same diameter, the equation (3) can be rewritten as:

\[
b = \sqrt{\frac{8PD(1 - \nu^2)}{El\pi}}
\]  

(4)

Therefore, as long as the normal contact force between two steel wires or steel strands is measured, the heat conduction contact area can be calculated exactly by equation (4).

Heat transfer via convection refers to the heat exchange between a fluid flowing through a solid surface and solid itself, and the heat transferred is based on the Newton’s law of cooling, as shown in equation (5):

\[
q_c = h_fA\left(T_g - T_b\right)
\]  

(5)

where, \(q_c\) stands for the heat flux from convection per unit length \((W)\), \(h_f\) denotes the convective heat transfer coefficient \((W/(m^2 \cdot K))\), \(T_g\) refers to ambient medium temperature, and \(T_b\) is the surface temperature of the object \((^\circ C)\).

Heat radiation refers to the phenomenon where an object radiates electromagnetic waves due to its temperature. An object will also absorb the heat from radiation generated by the external objects when it radiates the heat outwards. Therefore, the heat transfer via radiation is a comprehensive effect, that is, the superposition of the external radiation and internal heat absorption, as shown in equation (6):

\[
q_r = \sigma e_r F A \left[\left(T_g + 273\right)^4 - \left(T_b + 273\right)^4\right]
\]  

(6)

where, \(q_r\) stands for the heat flux from radiation per unit length \((W)\), \(\sigma\) is the Stefan-Boltzmann constant with a value of \(5.67 \times 10^{-8} W/(m^2 \cdot K^4)\), \(e_r\) indicates the emissivity of the system, and \(F\) refers to the view factor.

**Heat transfer calculation model for cables**

Based on the theory of Bennetts and Moinuddin, the lumped thermal mass approach was applied, and the influence of the cavities between the steel wires or steel strands inside the cable was taken into account. Assuming that the cable was subjected to the fire evenly, the heat transfer along the length was noted to be negligible. Meanwhile, as the heat conduction coefficient of steel is much higher than that of the fire protection layer, it can be considered that the temperature difference between the steel strands in the same layer is negligible, and the cavities inside a single steel strand can be ignored. The cavities between the steel wires or steel strands in the same and adjacent layers were regarded as the circular sets, and the temperature at any point in the wires or strands sets was only a function of time. Heat transfer occurs in the medium between two layers, as shown in Figure 4.
Thermal analysis of protected cable. In the case of a fire, the heat is transferred from the smoke to the fire protection layer by means of radiation and convection. For the sake of safety, it is believed that the fire protection layer itself does not absorb any heat, and the heat is fully conducted in the fire protection layer. Further, it was assumed that the conduction in the fire protection layer was linear, and an axial length of 1 m was selected for the calculation. Equation (7) was developed based on the energy conservation phenomenon, as shown below:

$$\sigma e_f \left[ (T_f + 273)^4 - (T_e + 273)^4 \right] + h_l(T_f - T_e) = \frac{\lambda_p}{d_p} (T_e - T_i)$$

where, $T_f$ indicates the flame temperature ($^\circ$C), $T_e$ refers to the external surface temperature of the fire protection layer ($^\circ$C), $T_i$ is the internal surface temperature of the fire protection layer ($^\circ$C), $\lambda_p$ refers to the conduction coefficient of the fire protection layer (W/(m·K)), and $d_p$ represents the thickness of the fire protection layer (m).

The fire protection layer in a cable is generally arranged outside the first layer (the outermost layer) of the steel wires or strands. It was assumed that the fire protection layer was in full contact with the first layer of the wire or strand set without any air gap, and the heat subsequently entered the first layer of the wire or strand set via conduction. The heat absorbed by the first layer was equal to the difference between the heat conducted from the fire protection layer to the first layer and heat taken away from the first layer by cavity radiation and conduction, as shown in equation (8):

$$A_{1o} \frac{\lambda_p}{d_p} (T_e - T_i) = A_{1o} \sigma a_{i,1} F_{i,1o}$$

$$\left[ (T_1 + 273)^4 - (T_2 + 273)^4 \right] + A_{1,2} \frac{\lambda_1}{d_{i,2}}$$

where, $A_{1o}$ indicates the outside surface area of the first layer of the steel wire or strand set, and $A_{1}$ represents the internal surface area of the first layer of the steel wire or strand set, both of which were calculated pursuant to the diameter of the equivalent ring model (m$^2$). $T_1$ is the temperature of the first layer of the steel wire or strand set, and the outermost layer of the steel wires or strands was in close contact with the internal surface of the fire protection layer, thus, $T_1 = T_i$. $T_2$ is the temperature of the second layer of the steel wire or strand set ($^\circ$C). $d_{1,2}$ is distance between the first layer and the second layer of steel wire or strand set. Further, $\varepsilon_{i,1,2}$ indicates the emissivity of the system comprising of the first and second layers of the steel strand sets, which was calculated as per equation (9):

$$\varepsilon_{k,k+1} = \frac{1}{1 + F_{ki,(k+1)o}(\frac{1}{\varepsilon_{1o}} - 1) + F_{(k+1)o,ki}(\frac{1}{\varepsilon_{k+1o}} - 1)}$$

Subscript $k$ refers to the $k$th steel wire or strand set, $k = 1, 2, 3 \ldots n$, $n$ is the total number of layers of cable steel wire, the same as below. Further, $F_{1o,ki}$ refers to the view factor between the internal surface of the $k$th layer and external surface of the $(k + 1)$th layer. Likewise, $F_{i,(k+1)o,ki}$ stands for the view factor between the external surface of the $(k + 1)$th layer and internal surface of the $k$th layer, with $F_{ki,(k+1)o} = F_{(k+1)o,ki} = 1$ for a concentric annulus. Moreover, $\varepsilon_{ki}$ refers to the emissivity of the internal surface of the $k$th layer of the steel wire or strand set, whereas $\varepsilon_{k+1o}$ represents the emissivity of the external surface of the $(k + 1)$th layer of the steel wire or strand set, with $\varepsilon_{ki} = \varepsilon_{i(k+1)o} = 0.822$ for steel wires.

$\lambda_1$ is the conduction coefficient of the first layer of the steel wire or strand set (W/(m·K)), which calculated according to equation (10)$^{23}$:

$$\lambda_k = 57.4 - 0.0329 T_k$$

![Figure 4. The heat transfer calculation model for the wire or strand cables.](image-url)
As the material of the steel wires or strands inside the cable was the same, and all layers of the steel wire or strand sets formed a concentric annulus, the relations $c_{k-1,k} = c_{k,k+1} = c_{1,2}$.

The total heat absorbed by the $n$th layer (the last layer) of the steel wire or strand set (located in the center) was equal to the heat transferred from the $(n-1)$th layer to the $n$th layer of the steel wire or strand set, as shown in equation (13):

$$A_{n,0}a_{n-1,n}F_{(n-1)n}(T_{n-1} + 273)^4 - (T_n + 273)^4 + A_{n-1,n} \frac{\lambda_n}{d_{n-1,n}} (T_n - T_{n-1}) = c_n \rho_n V_n \frac{\Delta T_n}{\Delta t}$$

Here, the flame temperature $T_f$ was known, and $T_1 = T_i$. There existed a total of $n+1$ unknowns including $T_e$, $T_1$, $T_2$,...,$T_n$. Once the time step $\Delta t$ was small enough, $\frac{\Delta T}{\Delta t}$ could be deemed as the derivative of the temperature $T_k$. On this basis, $n + 1$ equations were set up for all layers as per the law of energy conservation, including $n$ ordinary differential equation(s) and 1 algebraic equation. The boundary condition was the flame temperature $T_f$, and the initial condition was $T_e$, $T_1$, $T_2$...$T_n$ = the ambient temperature = 20°C. The MATLAB software was used, and the numerical solution of the temperature change in each layer of the steel wire or strand set with time was obtained by substituting the numerical value of $T_e$ obtained from the algebraic equation during the iterative process of solving the ordinary differential equation. It should be noted that the algebraic equation was quartic, thus, there was more than one solution for $T_e$, and a real number solution in line with the actual situation was required for the back substitution.

**Thermal analysis of unprotected cable.** For the unprotected cable, the outermost steel wires or steel strands are directly exposed to the fire environment, and the heat is transferred from the smoke to the first layer of steel wire and steel strand set by means of radiation and convection. Then the heat transferred to the inner layer of the cable through cavity radiation and heat conduction:

$$A_{1,0}a_{e}[T_f + 273]^4 - (T_i + 273)^4 + A_{1,0}h_i(T_f - T_i)$$

$$= A_{1,0}a_{e_1,2}F_{11,2e}[(T_1 + 273)^4 - (T_2 + 273)^4] + A_{1,2} \frac{\lambda_1}{d_{1,2}} (T_1 - T_2) + c_1 \rho_1 V_1 \frac{\Delta T_1}{\Delta t}$$

The heat transferred in the form of cavity radiation and heat conduction in the inner layer of the cable, which is consistent with the case of the protected cable.
The calculation of heat transfer in the inner layer is as shown in equations (12) and (13).

In equations were constructed for each layer according to law of energy conservation, and there existed a total of n unknowns including \( T_1, T_2, ..., T_n \). The boundary condition was flame temperature \( T_f \), and the initial condition was \( T_1, T_2, ..., T_n = \text{ambient temperature} = 20°C \).

**Verification of the theoretical calculation method**

In order to verify the reliability of the method given above, the temperature rise history of cable section obtained by the theoretical calculation method is compared with the numerical simulation results of Du et al.\(^{17}\) and the test results of Lugaresi\(^{9}\) respectively.

Du established refined finite element model of 7Φ5 mm and 61Φ7 mm steel wire cable, and the ISO834 standard temperature rise curve was adopted as heating curve. The given parameters in the literature are substituted into theoretical calculation method established in this paper, and temperature rise history of the outer steel wire is obtained. The comparison of two results is shown in Figure 5. It can be seen from Figure 5 that the theoretical calculation results are lower than the numerical simulation results in early stage of fire, whose the reason is that Du set the temperature of the cable surface to be consistent with the heat flow temperature. Thus, its value of the numerical simulation results is on the high side. As the heating duration lasts, the temperature of the outer steel wires gradually approaches ISO834 fire curve, and the difference between the theoretical calculation value and the numerical simulation value is also gradually narrowing.

Lugaresi carried out the test of heating law of 19Φ10 mm cable through uniform heating by Instron 600 lx temperature chamber. The temperature rise rate in Instron 600 lx temperature chamber was 10°C/min until it reached 600°C, and then it was maintained at this temperature. Lugaresi arranged thermocouples at different positions in the bar surface to obtain temperature distribution of cable section. The temperature rise curves of the outer steel bars and the core steel bar calculation by the numerical method established in this paper are compared with the test results, as shown in Figure 6. It can be seen that a good agreement between the test data and the theoretical calculation value is found when comparing the temperature rise of the outer steel wire, and the maximum temperature difference between them is within 10%. However, because the steel bars used in test were not regular cylinders, the results of temperature rise of core steel bar had some inconsistent between the theoretical value and the test data. The actual contact area between steel bar was larger than calculation value, so that the heat conduction inside the cable was underestimated. Although the heating curve of the core steel bar calculated in theory is different from the test results, the change laws of the two are basically the same.

In general, the theoretical calculation method proposed in this paper can accurately predict temperature history of each layer of steel wire or steel strand of cables, which provides a theoretical basis for the preliminary design of fire protection and thermal insulation system of cables.

**Analysis of theoretical calculation results**

The 73-hole steel strand cable of 15.7 mm was taken as an example, with the steel strand density of 7850 kg/m\(^3\). The layers of steel strands as well as the cavities between the adjacent layers of steel strands were equivalent to the circular sets as per the equal area principle, as shown in Figure 7.

After equivalence, the inner and outer perimeters of each circular set were calculated from the diameter of each circular set. Accordingly, the area of the internal and external surfaces of the steel strand set in each layer...
was obtained for an axial length of 1 m, as shown in Table 1.

The bridges are located in open spaces, and their fire conditions are quite different from those of the common buildings. Thus, using the ISO 834 temperature rise curve to simulate the bridge fires may result in large errors. The bridge fires are often caused by accidents of the moving vehicles, and fires resulting from the tankers cause a significant damage to bridges. As reported by the literature studies,6,7 the hydrocarbon temperature rise curve is capable of simulating the fires caused by tankers effectively, thus, ANSI/UL1709 standard temperature rise curve was applied in this study for simulation, as shown in Figure 8.

As shown in the temperature rise curve, the flame temperature rises rapidly to 1093°C within 5 min, which simulates the sharp temperature rise due to detonation during the early fire stage caused by tanker, and flame remains at this temperature during subsequent fire process.

Unprotected cable

Bennetts and Moinuddin12 did not consider the heat conduction between steel strands in cable for convenience when they established transient heat flow model. In this paper, theoretical calculation carried out in two situation that with and without consideration of heat conduction between steel strands, respectively. The comparison of temperature rise curves of the outer layer strand set, middle layer strand set, and core steel strand sets is shown in Figure 9.

where, $T_1$, $T_3$, and $T_5$ refers to the temperature of the first, the third, and the fifth layer of steel strand set without consideration of heat conduction inside the cable, respectively, while $T_{1,\text{cond}}$, $T_{3,\text{cond}}$, and $T_{5,\text{cond}}$ refers to the temperature of the first, the third, and the fifth layer of steel strand set under consideration of heat conduction inside the cable, respectively.

As can be seen from the Figure 9, the heating law of steel strand set of each layer is basically showing no difference, that is, the temperature rises rapidly in the early stage of the fire, and then the temperature rise curve becomes flat and has a tendency to approach fire heating curve as the fire continues.

The temperature difference of each layer in two cases is shown in the Figure 10. It can be seen from Figures 9 and 10 that whether heat conduction between the steel strands is considered or not has little influence

| Layers of steel strands | External surface area of steel strand sets $A_{k,o}/m^2$ | Internal surface area of steel strand sets $A_{k,i}/m^2$ | Volume per unit length $V_k/m^3$ |
|------------------------|---------------------------------|---------------------------------|-------------------------------|
| 1                      | 0.4445                          | 0.3317                          | 0.00697                       |
| 2                      | 0.3237                          | 0.2470                          | 0.00348                       |
| 3                      | 0.2219                          | 0.1415                          | 0.00232                       |
| 4                      | 0.1333                          | 0.0564                          | 0.00116                       |
| 5                      | 0.0493                          | /                               | 0.00019                       |

**Table 1.** The size parameters of the steel strand sets inside the cable.
on the temperature rise of the outermost steel strand set. The maximal temperature difference between the two is within 5% (3.48%) at 10 min of fire duration. However, it has a great impact on the temperature rise of the inner strand set, and the closer to the core, the greater the temperature difference between the two. The maximum temperature difference of the core steel wire in both cases reached 373°C at the same time point. Therefore, ignoring the heat conduction between steel strands will underestimate the temperature rise rate calculated of the inner layer of steel strands, resulting in the more over-valuation of the non-uniformity of the cable section.

When steel strands are exposed to fire, their mechanical properties will deteriorate with the increase of temperature. The strength degradation formula of 1860 MPa strand given by Zong et al. is:

\[
\eta_t = \frac{f_b (T)}{f_b} = 0.985 + 6.385 \times 10^{-4} T - 4.698 \times 10^{-6} T^2 - 2.691 \times 10^{-9} T^3 + 7.661 \times 10^{-12} T^4
\]

where, \( \eta_t \) indicates the strength degradation coefficient, \( f_b \) refers to the ultimate strength of strand at normal temperature (MPa), \( f_b (T) \) refers to the ultimate strength of strand at temperature \( T \) (MPa).

Under the UL1709 heating curve, the temperature field of cable section has been observed nonuniformity, and the temperature rise rate of the outer steel strand set is faster than that of the inner steel strand set. The strength degradation curve of each layer of steel strand set is shown in Figure 11. Thus, it is particularly important to accurately evaluate the overall mechanical performance of cable under high temperature. The strength degradation coefficient of the whole cable is calculated as shown in equation (16):

\[
\eta_t = \frac{\eta_{t1} V_1 + \eta_{t2} V_2 + \eta_{t3} V_3 + \eta_{t4} V_4 + \eta_{t5} V_5}{V_1 + V_2 + V_3 + V_4 + V_5}
\]

Figure 10. The temperature difference curve of each layer of the steel strand sets.

Figure 11. Strength degradation coefficient curve of each layer of steel strand.

Figure 12. Strength degradation curve of 73Ø15.7 mm cable.
fire occurs for about 12 min, indicating its strength is less than the stress of the cable, and the cable is destroyed.

The unprotected cable fails in a very short time due to the reduction of mechanical material properties of steel under fire circumstance, which seriously threatens the overall safety of the bridge. Therefore, it is necessary to install fire protection and thermal insulation system for bridge cables.

Protected cable

The external surface of the 73Ф15.7 mm cable was wrapped with the ceramic fiber fire-proof cloth, as shown in Figure 13. The fire-proof cloth had a conduction coefficient of 0.13, and a thickness of 2 mm.

On the basis of the theoretical calculation method in “Thermal analysis of unprotected cable,” the heating curve of the outer layer, middle layer and core steel strand set of the cable are calculated, as shown in the Figure 14.

According to the equation (15), at 300°C, the ultimate strength of steel strand is reduced to 74.3% of the normal temperature one. And the ultimate strength of steel strand will be only 8.8% of one at the normal temperature when it reaches 600°C, which can be considered that the steel strand does not have the capacity to continue to bear. The time required to reach 300°C and 600°C is 10 and 33 min respectively for the outermost steel strand of the cable, which covered with 2 mm ceramic fiber protective layer. While the time when the temperature of the outermost steel strand of unprotected cable reaches 300°C and 600°C is 4 and 9 min respectively. Through comparison, it can be concluded that even if only 2 mm fire protective layer is adopted, the temperature rise rate of each layer of steel strand of the cable can be greatly slowed down.

Experimental investigation

Composition of fire protection and thermal insulation system

This paper made an experimental investigation on the fire performance of fire protection and thermal insulation system, which taked the 73Ф15.7 mm OVM250 steel strand cable as the research object. The schematic diagram of the fire protection and thermal insulation system was shown in Figure 15. The fire protection layers were composed of the ceramic fiber fire-proof felt, with the conduction coefficient of 0.13 and the thickness of 40 mm. The thermocouple in this device was only used as the temperature acquisition instrument for the test, not as a component of the system.

The Ф15.7-1860 steel strands without HDPE sheath were bundled to form a cable by wires, and eight thermocouples were evenly arranged at different positions
on the cable surface. Then the fireproof felt was wrapped on the surface of the cable, which was installed in two layers with a thickness of 20 mm. When wrapping the fire-proof felt, temporarily fix it with adhesive tapes and bind it with cable ties. The length of the cable wrapping the fire-proof felt was 3000 mm, as shown in Figure 16. Put the above assembled cable into the steel pipe with a diameter of 386 mm closed at one end, that was to complete the fabrication of the test specimen of the fire protection and thermal insulation system of cable, as shown in Figure 17.

Test process

The fabricated test specimen was installed on the high-temperature gas furnace. Then the gap between the specimen and the installation hole of the furnace should be sealed with insulation. And eight thermocouples were arranged in the furnace evenly. The test scheme was shown in Figure 18.

The thermocouples were connected with the acquisition instrument and debugged them. During the test, the thermocouple temperature was collected and recorded every minute, and the temperature change was displayed in real time. The furnace should be heated according to the UL1709 temperature rise curve, which was the average temperature in the furnace was 2000°F ± 100°F (1093°C ± 56°C) within 5 min, and then the whole test process was maintained at this temperature for no less than 90 min. The specific operation was to ensure that the eight thermocouples on the furnace surface reached 1100°C within 5 min and remained above this temperature for 95 min in the subsequent test (95 min in this test). After reaching the holding time, the furnace and relevant valves should be closed, and power supply should be cut off. The test process was shown in Figure 19.

Analysis of test results

The temperature records collected by eight thermocouples on the surface of the outermost steel strand during test were compared with theoretical calculation results, as shown in Figure 20. CH01 to CH08 curves in Figure 20 were the temperature rise process of the outermost steel strand surface recorded by eight thermocouples. Further, comparison between the average temperature recorded by eight thermocouples and the numerical calculation results is shown in Figure 21.

The whole test was conducted for 100 min. The maximum temperature recorded by the thermocouples on the surface of the outermost steel strand of the cable was 206.5°C, and the maximum temperature of theoretical calculation was 196.1°C. It can be seen from...
Figure 21 that theoretical value is in good agreement with actual test data after 1 h of fire heating, and the maximum temperature difference between the two occurs at 48 min, with the value is 121.3°C for theoretical calculation and 132.8°C for average temperature of test, which is within 10%. It is indicated that the theoretical calculation method established in this paper could effectively predict the temperature rise of steel cable in the early stage of fire.

However, it is observed that there are obvious differences between the numerical calculation results and the average value of test data after 1 h of fire heating. It is speculated that the reason is that the thermocouple moves due to the thermal strain and deformation of the steel strand at the later stage of heating.9

Determination of thickness of fire protection layer

Factors affecting the temperature of the outermost layer of cable

To study the factors affecting the surface temperature of the outermost layer of the steel strands, all parameters of the steel strand cables were combined and numbered. Subsequently, the steel strands with the nominal diameters of 9.5, 11.1, 12.7, and 15.2 mm and with two, three, four, and five layers were selected, and the thickness of the fire protection layers of the cables were 10 and 20 mm. The fire protection layers were composed of the ceramic fiber fire-proof cloth, and the conduction coefficient of the fire-proof cloth was 0.13. The section factor $F_i/V$ (the ratio of the fire surface area of a steel component to its volume) of the outermost layer of the steel strands was calculated as per the cable equivalent model. For example, the section factor of 73Φ15.7 mm steel strand cables in Chapter 3 was $F_i/V = 0.4445/0.00697 = 63.77$. The specific parameters are listed in Table 2.

Figure 22 demonstrates the relationship between the surface temperature of the outermost layer of the steel strands of the bridge cables and section factor of the
The cables numbered A-2, B-2, C-2, and D-2 were not taken into account, and the relationship between the surface temperature of the outermost layers of the steel strands and section factor of the outermost layer of the steel strands of the equivalent model was redrawn, as shown in Figure 22(c) and (d), thus, indicating a more significant positive correlation in the modified curve.

Further, basalt fiber and glass fiber fire-proof cloths were chosen as the materials of the fire protection layer. Consequently, the simulation was carried out, and the relationship curves were drawn, as shown in Figure 22(e) and (f), where the conduction coefficients for the basalt fiber and glass fiber fire-proof cloths were 0.03 and 0.056. As observed from the curves, there existed a positive correlation between the surface temperature of the outermost layer of the steel strands of and section factor of the outermost layer of the steel strands of the equivalent model in spite of the different materials used for the fire protection layer. The reason for the increase of the middle section factor and the decrease of the temperature in Figure 22(e) and (f) was the same as the above analysis. That was the less layers of the cable steel strand led to the faster temperature rise of the outermost steel strand. It could be seen that the temperature rise speed of the outermost steel strand of the cable was related not only to its section factor, but also to the number of layers of the steel strand.

**Determination of the thickness of the fire protection layer for the cable**

The only standard that puts forward specific requirements for the fire performance of cables is PTI DC45.1-12**: Recommendations for Stay-Cable Design, Testing, and Installation** issued by the Post-Tensioning Institute in 2012. According to relevant requirements, under the UL1709 heating curve, the time when the surface temperature of the unloaded cable with external fire protection layer reaches 300°C shall exceed 30 min. The critical temperature of 300°C has been selected for two reasons: (1) to ensure that main tensile element (MTE) will not undergo plastic deformation under the working stress of 0.45f0 (400°C); (2) to ensure that HDPE around the cable is below its flash point (330°C).

It was proved that the surface temperature of the outermost layer of the steel wires or steel strands of cables was positively correlated with the section factor of the outermost layer of the cable equivalent model in Chapter 5.1. Thus, the thickness of the fire protection layer could be determined in accordance with the section factor of the outermost layer of the steel strands of the cable equivalent model. Using the ceramic fiber, basalt fiber and glass fiber fire-proof cloths as the fire protection layer, under the section factor of the

### Table 2. The section factor of the outermost layer of the steel strands as per the cable equivalent model.

| No. | Nominal diameter of steel strands (mm) | Layers of steel strands (layers) | Section factor of the outermost layer of steel strands (m⁻¹) |
|-----|--------------------------------------|---------------------------------|-----------------------------------------------------|
| A-2 | 9.5                                  | 2                               | 189.39                                              |
| A-3 | 3                                    | 3                               | 157.59                                              |
| A-4 | 4                                    | 4                               | 147.29                                              |
| A-5 | 5                                    | 5                               | 142.22                                              |
| B-2 | 11.1                                 | 2                               | 162.28                                              |
| B-3 | 3                                    | 3                               | 135.01                                              |
| B-4 | 4                                    | 4                               | 126.21                                              |
| B-5 | 5                                    | 5                               | 123.30                                              |
| C-2 | 12.7                                 | 2                               | 141.47                                              |
| C-3 | 3                                    | 3                               | 117.71                                              |
| C-4 | 4                                    | 4                               | 110.06                                              |
| C-5 | 5                                    | 5                               | 106.27                                              |
| D-2 | 15.2                                 | 2                               | 118.88                                              |
| D-3 | 3                                    | 3                               | 98.90                                               |
| D-4 | 4                                    | 4                               | 92.42                                               |
| D-5 | 5                                    | 5                               | 89.25                                               |

outermost layer of the steel strands of the equivalent model for a fire duration of 30-min. As observed from Figure 22, the changes in the thickness of the fire protection layer of the cable only varied the surface temperature of the outermost layer of the steel strands, instead of the overall shape of the curve. Moreover, the surface temperature of the outermost layer of the steel strands was positively correlated with the section factor of the outermost layer of the steel strands of the equivalent model. Thus, the bigger was the section factor of the outermost layer of the steel strands, the higher was the surface temperature of the outermost layer of the steel strands for the same duration.

In Figure 22, the surface temperature of the outermost layer of the steel strands numbered A-2, B-2, C-2, and D-2 was higher than normal conditions, which might be caused by the steel strand layers. As mentioned in Table 2, the cables were composed of two layers of the steel strands, where the first layer of the steel strands transferred the heat to the second layer while absorbing heat, whereas the second layer of the steel strands failed to transfer the heat to the internal layers, thus, making the temperature difference between the first and second layers of the steel strands smaller than that in the cables with multiple steel strand layers. As observed from equation (8), in case the difference between $T_1$ and $T_2$ was small, the first term on the right side of the equation was also small. That is, by contrast, less heat was transferred from the first layer of the steel strands to the second layer. Based on the heat conservation, for a cable with only two steel strand layers, the first layer of the steel strands retained more heat during the same duration, thus, the temperature rose faster.
Figure 22. The relationship between the surface temperature of the outermost layer of the steel strands and section factor of the equivalent model: (a) 10 mm-thick ceramic fiber fire protection layer, (b) 20 mm-thick ceramic fiber fire protection layer, (c) 10 mm-thick ceramic fiber fire protection layer (modified), (d) 20 mm-thick ceramic fiber fire protection layer (modified), (e) 10 mm-thick basalt fiber fire protection layer, and (f) 20 mm-thick glass fiber fire protection layer.
outermost steel strands of the different cable equivalent models, the minimum fireproof layer thickness of the steel strand cables meeting the PTI specifications was calculated, as shown in Figure 23.

As observed from Figure 23, the minimum thickness of the fire protection layer was linearly correlated with the section factor of the outermost layer of the steel strands of the equivalent model. The scattered points in Figure 23(a) were subjected to linear fitting, and the relation for calculating the minimum thickness of the fire protection layer using the ceramic fiber fire-proof cloth as the fire-proof material was obtained as follows:

\[ d = 0.1265 \frac{F_i}{V} - 0.4814 \]  \hspace{1cm} (17)

For this relation, the coefficient of determination (R-square) was 0.9613, the sum of squares due to error (SSE) was 7.237, and the root-mean-square error (RMSE) value was 0.719, thus, representing a good fitting of the scattered points.

The scattered points in Figure 23(b) were subsequently subjected to linear fitting, and the relation for calculating the minimum thickness of the fire protection layer using the basalt fiber fire-proof cloth as the fire-proof material could be determined as follows in equation (19):

\[ d = 0.02887 \frac{F_i}{V} - 0.0322 \]  \hspace{1cm} (18)

For this relation, the R-square was 0.9652, the SSE was 0.3379, and the RMSE value was 0.1554.

Similarly, the relation for calculating the minimum thickness of the fire protection layer using the glass fiber fire-proof cloth as the fire-proof material could be determined as follows:

\[ d = 0.05402 \frac{F_i}{V} - 0.1053 \]  \hspace{1cm} (19)

Here, the R-square was 0.9625, the SSE was 1.279, and the RMSE value was 0.3023.

As observed from equations (17) to (19), the intercepts were small, and the slopes were similar to the conduction coefficients of the corresponding fire-proof materials. As a result, the relation for calculating the minimum thickness of the fire protection layer could be summarized as a linear function passing through the origin with the conduction coefficient of the fire-proof material as the slope. Nevertheless, the heat transfer from the outer to the inner steel strands was limited in case of the few-layered cable steel strands, which accelerated the temperature rise in the outer steel strands. Consequently, the calculated result should be multiplied by the safety factor and rounded up for the sake of safety. The safety factor was related to the number of steel strand layers of the cable. After checking calculation and comparison, the value of safety factor was:

\[ \xi = \sqrt{1 + \frac{1}{n}} \]  \hspace{1cm} (20)

where \( n \) was the number of steel strand layers, and the relation for calculating the minimum thickness of the fire protection layer was as follows:

\[ d = \left[ \sqrt{1 + \frac{1}{n}} k \frac{F_i}{V} \right] \]  \hspace{1cm} (21)

The cable in Chapter 3 was used for verification, with numbers substituted into the equation (21). It was observed that the minimum thickness of the fire protection layer for the cable was 9.08 mm (rounded up to 10 mm). The calculated thickness of the fire protection layer was substituted in the transient heat flow model. Figure 24 displays the temperature rise curves of the outermost layer of the steel strand set obtained through...
simulation. For the fire lasting 30 min, the surface temperature of the outermost layer of the steel strands for cable was 243.8°C, which met the fire protection requirements. Thus, proving that the developed method was reliable in calculating the minimum thickness of the fire protection layer of the steel strand cables.

Conclusions

Based on the structural characteristics of the steel strand cables of bridges, a transient heat flow model of the steel strand cables at high temperatures was established in this study by using the lumped thermal mass approach, and the numerical solution of the change in the surface temperature of the steel strand layers inside the cables with time was obtained on the basis of this model. Subsequently, theoretical calculation method established in this paper is compared with the results of previous literature to verify its accuracy. Then the experimental investigation of protected cable was carried out. The conclusions are as follows:

1. The heating law of steel strand set of each layer of cables is basically similar and all tend to approach fire heating curve as the fire continues.

2. For unprotected cables, whether heat conduction between steel wires or steel strands is considered has little effect on the temperature history of cable surface. However it has a great influence on heating curve of the inner layer, especially in core area. The non-uniformity of the overall temperature field of the cable section will be overestimated if the heat conduction inside the cable is not considered.

3. The surface temperature of the 73Ф15.7mm unprotected cable reached 300°C in 4 min and 600°C in 9 min in UL1709 fire, and whole cable was damaged due to strength degradation in 12 min. While the time required to reach 300°C and 600°C is 10 and 33 min respectively for the outermost steel strand of the cable, which covered with 2mm ceramic fiber protective layer, indicating that arrangement of fire protection layer around cable can effectively retard the temperature rise of the cable in fire environment.

4. 73Ф15.7mm steel strand cables with 40mm ceramic fiber protective layer were tested according to the temperature rise curve of UL1709. The test results indicated that the maximum surface temperature of the outermost steel strand of the cable was 206.5°C in the environment above 1100°C for 95min, while theoretical calculation result was 196.1°C. The theoretical calculation results were in good agreement with the temperature rise history of the outermost steel strand obtained from the test in the early stage of fire. It is proved that the numerical calculation method can accurately calculate temperature rise of the cable surface and has potential practical values.

5. According to result from theoretical calculation, for the steel wire or steel strand cables with the fire protection layers of the same material and thickness, the surface temperature rose swiftly in case of the few-layered steel wires or steel strands inside the cable. Furthermore, the surface temperature was positively correlated with the section factor of the outermost layer of the steel wires or steel strands of the cable equivalent model. That is, the bigger was the section factor of the cable equivalent model, the higher was the surface temperature during the same duration.

6. The minimum thickness of the fire protection layer meeting PTI DC45.1-12 fire protection requirements was linearly correlated with the section factor of the outermost layer of the steel wires or steel strands of the cable equivalent model. Further, the slope of this function was close to the conduction coefficient of the corresponding materials of the fire protection layer.

Figure 24. The temperature rise curves of the outermost layer of the steel strand set.
On this basis, a simple method to calculate the minimum thickness of the fire protection layer could be developed.

The theoretical calculation method proposed in this paper not only considers the effect of internal cavity radiation of cables, but can quantitatively calculate heat conduction contact area between wires or strands, thus results are more accurate. However, the method discussed have the following limitations, which is also the direction of future research:

(1) In this paper, it was assumed that the cable boundary was uniformly heated, which was different from the real fire scenario. For example, the effects of fire location, fire source and wind velocity, etc. were not considered. Evolution behavior of complex fire environment is a difficulty of future research of fire analysis for bridge cable.

(2) Although the heat conduction contact area between steel wires and steel strands was quantitatively calculated in this paper, the contact force was calculated according to its deadweight, which was different from reality.

(3) In the calculation of protected cable, the possible contact gap between cable and fire protection layer was not considered. Besides, in this paper, it was presumed that the material properties of fire protection layer were invariant in fire, and it was believed that the fire protection layer itself does not absorb any heat for the sake of safety. In addition, the HDPE protective sheath wrapped on the surface of steel strand was ignored in calculation of cables, so the actual temperature field distribution of cables in fire needs further study.

Acknowledgements
The authors would like to express their gratitude to EditSprings (https://www.editsprings.cn/) for the expert linguistic services provided.

Declaration of conflicting interests
The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding
The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by the Natural Science Foundation of China (No. 52068014), Key R&D Projects in the Guangxi Autonomous Region (No. GUIKE AA2030 2006), and Major Construction Program of the Science and Technological Innovation Base in the Guangxi Autonomous Region (No. 2018-242-G02).

ORCID iD
Quanxi Shen https://orcid.org/0000-0002-6107-5570

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Appendix

Notations

\( A \) \quad flame contact area per unit length
\( A_{ko} \) \quad outside surface area of the kth layer
\( A_{ki} \) \quad internal surface area of the kth layer
\( A_{k,k+1} \) \quad contact area of the heat conduction between the kth layer and the (k+1)th layer
\( b \) \quad half-width of the contact
\( c_k \) \quad special heat capacity of the kth layer
\( D \) \quad diameter of cylinder
\( d_p \) \quad thickness of the fire protection layer
\( d_{k,k+1} \) \quad distance between the kth layer and the (k+1)th layer
\( \frac{dT}{dt} \) \quad temperature gradient along the \((x)\) direction
\( E \) \quad elastic modulus
\( F \) \quad view factor
\( F/V \) \quad section factor
\( F_{(k-1)ji,k0} \) \quad view factor between the internal surface of the \((k-1)\)th layer and outside surface of the kth layer
\( F_{(k-1)k0,ki} \) \quad view factor between the outside surface of the \((k-1)\)th layer and internal surface of the kth layer
\( f_b \) \quad ultimate strength of strand at normal temperature
\( f_b(T) \) \quad ultimate strength of strand at temperature \(T\)
\( h_t \) \quad convective heat transfer coefficient
\( l \) \quad contact length
\( P \) \quad normal contact force
\( q_c \) \quad heat flux from convection per unit length
\( q_r \) \quad heat flux from radiation per unit length
\( q_x \) \quad heat flux from conduction per unit length
\( T_b \) \quad surface temperature of the object
\( T_c \) \quad external surface temperature of the fire protection layer
\( T_f \) \quad flame temperature
\( T_g \) \quad ambient medium temperature
\( T_i \) \quad internal surface temperature of the fire protection layer
\( T_k \) \quad temperature of the kth layer
\( T_{k,cond} \) \quad temperature of the kth layer under consideration of heat conduction
\( t \) \quad time
\( V_k \) \quad volume of the kth layer
\( \Delta T_k \) \quad temperature rise of the kth layer
\( \Delta t \) \quad time steps
\( \varepsilon_{k,k+1} \) \quad emissivity of the system comprising of the kth and (k+1)th layers
\( \varepsilon_{ki} \) \quad emissivity of the internal surface of the kth layer
\( \varepsilon_{ko} \) \quad emissivity of the outside surface of the kth layer
\( \varepsilon_r \) \quad emissivity of the system
\( \eta \) \quad strength degradation coefficient
\( \eta_{ki} \) \quad strength degradation coefficient of kth layer
\( \lambda \) \quad conduction coefficient
\( \lambda_p \) \quad conduction coefficient of fire protection layer
\( \lambda_k \) \quad conduction coefficient of the kth layer
\( \nu \) \quad Poisson ratio
\( \rho_s \) \quad density of the steel
\( \sigma \) \quad Stefan-Boltzmann constant