Research Article

Interface Slip of the Steel Beam Strengthened with the CFRP Sheet under Temperature and Creep

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This paper studied the interface slip between the CFRP sheet and the steel beam under the action of temperature and creep. The formulas of the interface slip were established by using the elastic method and energy variational method, respectively, and the accuracy of the formulas was verified by finite element analysis Abaqus. The results showed that when the creep was not taken into account, the interface slip was the maximum at the end of the beam and the minimum at the middle of the span. When the temperature increased to 5°C, the slip increased about 0.005 mm. And when the thickness of the CFRP sheet increased to 0.05 mm, the slip increased about 0.003 mm. When the creep was taken into account, the interface slip increased with the increase of load and decreased with the increase of stiffness. When the stiffness reached about 10 ka, the variation of the stiffness on the slip was basically unchanged.

1. Introduction

Relative slip will occur between CFRP material and steel structure when the steel structure is reinforced with CFRP material. This slip may lead to peeling failure of the interface. Previous studies [1] showed that the interface peeling failure was an important reason why the CFRP materials cannot achieve the effect of strengthening and repairing steel structures. The interface slip between the interface of the steel beam and the CFRP sheet will occur under the action of temperature and creep when the steel beam is strengthened with the CFRP sheet. The interface slip will affect the interfacial interaction, reduce the bearing capacity and stiffness, and increase the deflection of the beam. Some experts have studied the interfacial mechanical properties of steel structures strengthened with CFRP materials.

Nguyen et al. [2] showed that the strength and stiffness of the adhesive between the interface of the CFRP plate and steel would degenerate lower than 10% in the environment with relative humidity of 90% and a temperature of 20–50°C when cycled for 1000 hours.

Yu et al. [3] conducted an experimental study on the interface properties of CFRP plates and steel plates. The type

of adhesive, the thickness of the adhesive layer, and the stiffness of CFRP plates were taken as parameters. The results showed that the bonding strength was closely related to the interfacial fracture energy. The bond strength was positively correlated with the stiffness of the CFRP plate. When the thickness of the adhesive layer was between 1 and 2 mm, the bonding strength would increase with the increase of the thickness. The effect of CFRP bonding length on the interface bonding performance was mainly reflected in that it was within the range of effective bonding length, and the effect beyond this range was very small.

Jiang [4] studied the interfacial properties of flexural steel beams strengthened by the CFRP plate and analyzed the influence of various factors on the reinforced members. When the prestressed CFRP plate was used to strengthen the beams, the bearing capacity could be improved by increasing the thickness of the CFRP, but the stiffness almost did not increase.

Fernando et al. [5] found that when the adhesive adopts elastic adhesive, the constitutive models of the interface between CFRP and steel and the interface between FRP and concrete were very similar and presented a triangle shape. On the basis of the simplified FRP-

concrete interface constitutive model proposed by Lu, Fernando et al. gave a constitutive model for the interface between CFRP and steel.

Al-Shawaf and Zhao [6] conducted an experimental study on the interfacial properties of CFRP-steel double-shear specimens under wet dressing and low temperature. It was found that the interface failure of the adhesive layer mainly occurred in the low-temperature environment. The effective bond length, axial strain distribution, and interfacial shear stress distribution of the CFRP-steel interface have little influence on the maintenance environment, and the increase of temperature could effectively improve the bond strength.

Zhao et al. [7] improved the bonding method. By increasing the bond length of the stressed side ($L1 > L2$), the load was guaranteed to occur on the side with short bond length. This improved method could significantly reduce the number of measuring points, but because the bonding was in two interfaces, the samples should be cured separately, increasing the test period, and the thickness of the bonding layer on both sides should be kept consistent as far as possible.

Xue [8] conducted an experimental study on the interface properties of CFRP-steel with the parameters length, width, number of layers of CFRP, and curing time. The results showed that the improvement of the ultimate bearing capacity of specimens was significantly affected by the bonding width. In order to improve the ultimate bearing capacity of the interface, the effective bond length could be effectively increased by increasing the number of CFRP layers. The peak strain of CFRP and the ultimate bearing capacity of the specimen would remain basically unchanged since the CFRP bonding length reached the effective bonding length. When the curing time of the specimen becomes longer, the effective transfer length of the interface would decrease, and the shear stress of the adhesive layer would increase.

Teng et al. [9] and Yuan [10] used the cohesion element in Abaqus to simulate the interface behavior of CFRP and steel based on fracture mechanics. There were two advantages of using the cohesion element. One was that the cohesion element sets the geometric thickness in the model. The difference between the cohesion element and the solid element was that there was no need to divide the mesh along the thickness direction, and the calculation accuracy was still high. Secondly, the stress distribution of the interface along the thickness direction can be obtained by setting the geometric thickness. The disadvantage was that this element was only suitable for the bilinear bond-slip model, but not for other bond-slip models.

Wang et al. [11] used 3D digital imaging technology (3D-DIC) to measure the shear stress and slip of the nonlinear adhesive interface and obtained the bond-slip relationship, which further proved the rationality of using the trilinear bond-slip model of the nonlinear adhesive interface. Since there were only 6 experimental data, the expression of the key parameters was not given. Therefore, more data were needed to obtain a bond-slip model for the nonlinear adhesive interface.

Heshmati et al. [12] used the double-sided shear test to study the mechanical behavior of the CFRP-steel interface and GFRP-steel interface in the distillation water/deicing salt solution. The results showed that the bond stiffness and strength of the interface between the two materials and steel were obviously reduced. The distribution of water on the FRP-steel interface was simulated by the finite element method, and the influence mechanism of water molecules on the interfacial bond property of CFRP-steel was analyzed.

Li et al. [13] carried out tensile shear tests on 17 CFRP plate and steel single-lap specimens. Studying the mechanical behavior and interfacial failure mode of CFRP-steel between different epoxy binders and CFRP materials, the effects of the type of binder and CFRP materials on the interfacial bond-slip constitutive and interfacial shear properties were analyzed. The results showed that the interface failure modes and shear capacity were different with different binder or CFRP materials.

Pang [14] studied interlaminar detachment failure and mixed failure modes of CFRP plates under the extreme service environment. The results showed that the interfacial bond property was only related to the binder properties when the mixing failure occurred. However, when the interlaminar detachment failure of CFRP plates occurred, the interfacial bonding property was related to both the binder and the properties of CFRP plates.

Wei et al. [15] conducted 12 double-shear joint tests of the CFRP plate and steel and analyzed the failure mode, ultimate load, CFRP plate strain, interfacial shear stress, and bond-slip relationship. The test results showed that freeze-thaw cycles had no effect on the interface failure mode. The freeze-thaw environment had no effect on the strain distribution of the CFRP plate, interfacial shear stress distribution, and shape of the curve of the bond-slip relationship, but the maximum strain of the CFRP plate, maximum interfacial shear stress, and maximum slip would decrease due to the freeze-thaw cycle.

Xu et al. [16] carried out long-term loading tests of CFRP-steel double-shear tests with 4 interfacial shear stress levels and 6 kinds of holding times in order to study the influence of loading history on the interfacial bond properties of steel structures reinforced by CFRP and carried out static tensile failure on the specimens that reached the specified loading time. The results showed that the creep deformation of adhesives could cause the redistribution of interfacial stress. With the increase of time, the CFRP strain increased, and the peak value of interfacial shear stress decreased. When the level of interfacial shear stress is high, the influence of interfacial creep damage on the bond-slip curve should be considered. When the bond length of CFRP was larger than the effective bond length, the interface creep damage had no obvious effect on the ultimate bearing capacity.

Xu et al. [17] carried out long-term loading tests on CFRP-steel double-shear tests under different tensile loads in order to study the creep characteristics of CFRP-steel interface adhesive. The results showed that the CFRP-steel interface adhesive exhibited creep deformation under long-term interfacial shear stress. The CFRP strain decreased

nonlinearly from the loading end to the fixed end and increased with the increase of loading time, and the rate of increase decreased gradually.

It can be found that the analysis of the interface slips under the influence of temperature and creep is relatively rare based on the research studies. This paper gave the calculation formula of the interface slip between the CFRP sheet and the steel beam under the effect on temperature and creep using the elastic method and energy variational method, and the accuracy of the formula was verified by Abaqus. Then, the influences of design parameters were discussed.

2. Elastic Method

Based on the elastic method [18] and the mechanical characteristics of the steel beam strengthened with the CFRP sheet, the following assumptions were made: (1) the reinforced steel beam was an elastomer in normal service condition; (2) the interface adhesive layer only bore shear force; (3) CFRP sheet only bore tensile force; (4) the section conformed to the plane cross-section assumption. The element of the CFRP sheet-strengthened steel beam is shown in Figure 1.

The equilibrium equation can be obtained from the element force:

$$M_s - (M_s + dM_s) + V_s dx + \tau dx \cdot y_s = 0. \quad (1)$$

According to the relationship between bending moment and curvature,

$$\frac{d\phi}{dx} = \frac{1}{E_s I_s} \frac{dM_s}{dx}. \quad (2)$$

Strain on the lower surface of the lower flange of the steel beam is

$$\begin{aligned} \varepsilon_s(x) &= \phi y_s - \frac{N_s}{E_s A_s} \\ &= \phi y_s - \frac{N_0 + P_{T_s}}{E_s A_s}. \end{aligned} \quad (3)$$

Strain on the surface of the CFRP sheet is

$$\varepsilon_p(x) = \frac{N_p}{E_p(T, t) A_p}, \quad (4)$$

where N_0 , V_s , and M_s are the axial force, shear force, and bending moment caused by external loading. τ is the interfacial shear stress. P_{T_s} is the axial force due to temperature changes [19].

So, the following can be available:

$$\begin{aligned} \frac{ds(x)}{dx} &= \varepsilon_s(x) - \varepsilon_p(x) \\ &= y_s \phi - \left(\frac{N_s}{E_s A_s} + \frac{N_p}{E_p(T, t) A_p} \right), \end{aligned} \quad (5)$$

$$\frac{d^2 s(x)}{dx^2} = y_s \frac{d\phi}{dx} - \left(\frac{1}{E_s A_s} \frac{dN_s}{dx} + \frac{1}{E_p(T, t) A_p} \frac{dN_p}{dx} \right).$$

FIGURE 1: The element force.

Because $N_s = N_p$, $(dN/dx) = -\tau$, and $\tau = k_a s(x)$, the differential equation of the interface slip can be obtained:

$$\frac{d^2 s(x)}{dx^2} - \alpha^2 s(x) - \beta V_s + \gamma \frac{dN_0}{dx} + \gamma \frac{dP_{T_s}}{dx} = 0, \quad (6)$$

where $\alpha^2 = k_a ((y_s^2/E_s I_s) + (1/E_p(T, t) A_p))$; $\beta = y_s/E_s I_s$; $\beta_\tau = k_a y_s/E_s I_s$; $\gamma = 1/E_s A_s$; $\gamma_\tau = k_a/E_s A_s$; $k_a = b_p G_a/t_a$; $E_p(T, t) = \phi(T, t) E_p$; $P_{T_s} = E_s \alpha_s \int_{-t/2}^{t/2} b(y) dy$; E_s , $E_p(T, t)$ are the elastic modulus of the steel beam and CFRP sheet; A_s , A_p are the cross-section area of the steel beam and CFRP sheet; I_s is the moment of inertia of the steel beam; y_s is the distance between the neutral shaft and the bottom of the steel beam; α_s is the expansion coefficient of the steel beam; $t(y)$ is the temperature function of the steel beam; $b(y)$ is the width; G_a is the stiffness of the adhesive layer; t_a is the thickness of the adhesive layer; E_p is the initial modulus of elasticity of the CFRP sheet; $\phi(T, t)$ is the influence coefficient of temperature and creep of the CFRP sheet [20], $\phi(T, t) = [1/1 + 0.1 \sinh((T/T_0) - 1)t^{0.05}] + (1/1 + (5/\beta_1) t^{0.2}) - 1$; β_1 is the ratio of creep modulus to elastic modulus, can be taken as 45; T is the temperature value; T_0 is the initial temperature; and t is the hour.

3. Energy Variational Method

Based on the energy variational method [21], it was assumed that, under the action of external loading, the displacement of the steel beam was U_s , the displacement of the CFRP sheet was U_p , the deformation of the beam was W , and the displacement of the adhesive layer was $\Delta_t = U_s - y_s W' - U_p$.

Strain energy of the steel beam is

$$\Pi_s = \frac{1}{2} E_s A_s \int U_s'^2 dx + \frac{1}{2} E_s I_s \int W''^2 dx. \quad (7)$$

Strain energy of the CFRP sheet is

$$\Pi_p = \frac{1}{2} E_p(T, t) A_p \int U_p'^2 dx + \frac{1}{2} E_p I_p \int W''^2 dx. \quad (8)$$

Strain energy of the adhesive layer is

$$\Pi_t = \frac{1}{2} \int k_a (U_s - U_p - y_s W')^2 dx. \quad (9)$$

The work of external loading is

$$\prod_0 = \int MW'' dx. \quad (10)$$

The total energy of the beam is

$$\begin{aligned} \prod = & \frac{1}{2}E_s A_s \int U_s'^2 dx + \frac{1}{2}E_s I_s \int W''^2 dx + \frac{1}{2}E_p(T, t) A_p \int U_p'^2 dx + \frac{1}{2}E_p(T, t) I_p \int W''^2 dx \\ & + \frac{1}{2}k_a(U_s - U_p - y_1 W')^2 dx + \int MW'' dx. \end{aligned} \quad (11)$$

According to the principle of minimum potential energy, the following can be obtained:

$$\begin{aligned} \delta \prod = & E_s A_s \int U_s' \delta U_s dx + E_s I_s \int W \delta W'' dx + E_p(T, t) A_p \int U_p' \delta U_p dx + E_p(T, t) I_p \int W'' \delta W'' dx \\ & + \int k_a(U_s - U_p - y_s W')(\delta U_s - \delta U_p - y_s \delta W') dx + \int M \delta W'' dx = 0. \end{aligned} \quad (12)$$

And δU_s and δU_p are independent, so

$$\begin{aligned} & \int [-E_p(T, t) A_p U_p'' - k_a(U_s - U_p - y_s W')] \delta U_p = 0, \\ & \int [-E_s A_s U_s'' + k_a(U_s - U_p - y_s W')] \delta U_s = 0, \\ & \int [E_s I_s W^{(4)} + E_p(T, t) I_p W^{(4)} + k_a y_s (U_s - U_p - y_s W') - M''] \delta W = 0. \end{aligned} \quad (13)$$

According to internal force equilibrium conditions,

$$\begin{aligned} N_s &= N_0 + P_{T_s} \\ &= E_s A_s U_s', \\ N_p &= E_p(T, t) A_p U_p'. \end{aligned} \quad (14)$$

The following can be obtained:

$$\frac{d^2 s(x)}{dx^2} - \alpha^2 s(x) - \beta V(x) + \gamma \frac{dN_0}{dx} + \gamma \frac{dP_{T_s}}{dx} = 0. \quad (15)$$

4. Interface Slip Formula

Under the action of uniform load, symmetrical load, and concentrated loading (the distance between the position of the load and the midspan was b), the length of the beam was L , and the paste length of the CFRP sheet was l_f ; taking the midspan as the origin of coordinates, down was the y -direction, and the right was the x -direction; taking half of the beam as the research object and combining boundary conditions, the interface slip formulas under different loads can be obtained.

(1) Under uniform load,

$$s(x) = \frac{e^{\alpha x} - e^{-\alpha x}}{\alpha^3 \left(e^{\alpha l_f/2} + e^{-\alpha l_f/2} \right)} \left\{ \beta q + \alpha^2 \left[\frac{P_{T_s}}{E_s A_s} - \frac{q y_s L (L - l_f)}{4 E_s I_s} \right] \right\} - \frac{\beta q}{\alpha^2} x. \quad (16)$$

(2) Under symmetrical loading,

Bending and shear section:

$$s_1(x) = \frac{\beta P (e^{\alpha l_0/2} + e^{-(\alpha l_0/2)})}{2\alpha^2 (e^{\alpha l_f/2} + e^{-(\alpha l_f/2)})} \left[e^{\alpha((l_f/2)-x)} + e^{-\alpha((l_f/2)-x)} \right] + \left[\frac{P_{T_s}}{E_s A_s} - \frac{P y_s (L - l_f)}{2 E_s I_s} \right] \frac{e^{\alpha x} - e^{-\alpha x}}{\alpha (e^{\alpha l_f/2} + e^{-(\alpha l_f/2)})} - \frac{\beta P}{\alpha^2}. \quad (17)$$

Bending section:

$$s_2(x) = \frac{e^{\alpha x} - e^{-\alpha x}}{e^{\alpha l_f/2} + e^{-(\alpha l_f/2)}} \left\{ \alpha \left[\frac{P_{T_s}}{E_s A_s} - \frac{P y_s (L - l_f)}{2 E_s I_s} \right] - \frac{\beta P}{2\alpha^2} \left[e^{\alpha((l_f/2)-(l_0/2))} - e^{-\alpha((l_f/2)-(l_0/2))} \right] \right\}. \quad (18)$$

(3) Under concentrated loading,

Left side of the loading point:

$$s_1(x) = \frac{\beta ((P/2) - (Pb/L)) \left[e^{\alpha((l_f/2)-x)} + e^{-\alpha((l_f/2)-x)} \right] + \alpha \left[(P_{T_s}/E_s A_s) - (y_s (L - l_f)/2 E_s I_s) ((P/2) - (Pb/L)) \right] (e^{\alpha x} - e^{-\alpha x})}{\alpha^2 (e^{\alpha l_f/2} + e^{-\alpha l_f/2})} - \frac{\beta}{\alpha^2} \left(\frac{P}{2} - \frac{Pb}{L} \right). \quad (19)$$

Right side of the loading point:

$$s_2(x) = \frac{\beta ((P/2) + (Pb/L)) \left[e^{\alpha((l_f/2)-x)} + e^{-\alpha((l_f/2)-x)} \right] + \alpha \left[(P_{T_s}/E_s A_s) - (y_s (L - l_f)/2 E_s I_s) ((P/2) + (Pb/L)) \right] (e^{\alpha x} - e^{-\alpha x})}{\alpha^2 (e^{\alpha l_f/2} + e^{-\alpha l_f/2})} - \frac{\beta}{\alpha^2} \left(\frac{P}{2} + \frac{Pb}{L} \right). \quad (20)$$

5. Numerical Analysis

5.1. Constitutive Relation. In order to verify the accuracy of the theoretical calculation, this paper used finite element calculation software Abaqus to check the calculation. The constitutive relation of the steel beam in the Abaqus model adopted the plastic analysis model. Figures 2 and 3 show the constitutive relationship of steel and CFRP sheet, and Poisson's ratio of steel is 0.3. CFRP sheet was an orthotropic material with no strength in the vertical fiber direction. The stress and strain relation curve of CFRP cloth was taken as ideal elasticity, and the elastic modulus of CFRP cloth was consistent with the value in the previous formula.

5.2. Calculation Results. Figures 4 and 5 show the strain distribution of the bottom flange of the steel beam and CFRP

sheet under the load of 10 N/mm and the temperature of 20°C and 25°C. Because the interface slip between the steel beam and the CFRP sheet cannot be obtained directly in Abaqus, the difference of strain between the steel beam and the CFRP sheet is used to calculate the interface slip.

Figure 6 shows the comparison between the finite element calculation and the formula calculation results. It showed that the two results were in good agreement and indicated that the formula was correct and can be used to calculate the interface slip between the steel beam and the CFRP sheet.

6. Parameter Analysis

6.1. Effect of Adhesive Stiffness. Figure 7 shows the interface slip distribution curve along the beam length of different adhesive stiffness. The curves were nonlinear, and the

FIGURE 2: Stress-strain curve of steel.

FIGURE 3: Stress-strain curve of the CFRP sheet.

FIGURE 4: Strain distribution under the temperature of 20°C. (a) Bottom flange of the steel beam. (b) CFRP sheet.

interface slip decreased with the increase of the stiffness. The change of the interface slip gradually decreased with the increase of the stiffness. When the stiffness reached 3 ka, the

change of the interface slip was very small, indicating that the increase of the stiffness had basically no effect on the interface slip after the stiffness exceeded 3 ka.

FIGURE 5: Strain distribution under the temperature of 25°C. (a) Bottom flange of the steel beam. (b) CFRP sheet.

FIGURE 6: The comparison between numerical results and calculation results. (a) Temperature of 20°C. (b) Temperature of 25°C.

6.2. Effect of Temperature. Figure 8 shows the interface slip distribution curve along the beam length of different temperatures. The curves were nonlinear. The higher the temperature was, the greater the interface slip was. The maximum slip was at the end of the beam. When the temperature increased to 5°C, the slip increased about 0.005 mm.

6.3. Effect of Thickness of the CFRP Sheet. Figure 9 shows the interface slip distribution curve along the beam length of different thicknesses of the CFRP sheet. The curves were nonlinear. The greater the thickness of the CFRP sheet was, the greater the interface slip was. The maximum slip was at the end of the beam. When the thickness of the CFRP sheet increased to 0.05 mm, the slip increased about 0.003 mm.

6.4. Effect of Loading under CFRP Creep. Figure 10 shows the interface slip distribution curve along with the time of different loads. The curves were nonlinear. At the beginning of loading, the slip was 0, and the slip increment increased with the increase of time. The slip increased with the increase of load. The larger the load was, the steeper the curve was. When the load increased to 5 N/mm or 5 kN, the slip increased about 4.4×10^{-7} mm, 1.2×10^{-6} mm, and 6.2×10^{-7} mm, respectively.

6.5. Effect of Adhesive Stiffness under Creep. Figure 11 shows the interface slip distribution curve along with the time of different adhesive stiffness. The curves were nonlinear. The slip decreased with the increase of stiffness. The greater the stiffness was, the gentler the curve was.

FIGURE 7: The effect of adhesive layer stiffness on the interface slip. (a) Uniform load. (b) Symmetrical concentrated load. (c) Midspan concentrated load.

FIGURE 8: Continued.

FIGURE 8: The effect of temperature on the interface slip. (a) Uniform load. (b) Symmetrical concentrated load. (c) Midspan concentrated load.

FIGURE 9: The effect of CFRP sheet's thickness on the interface slip. (a) Uniform load. (b) Symmetrical concentrated load. (c) Midspan concentrated load.

FIGURE 10: The effect of loading under creep on the interface slip. (a) Uniform load. (b) Symmetrical concentrated load. (c) Midspan concentrated load.

FIGURE 11: Continued.

FIGURE 11: The effect of adhesive stiffness under creep on the interface slip. (a) Uniform load. (b) Symmetrical concentrated load. (c) Midspan concentrated load.

However, the change of the interface slip decreased with the increase of stiffness. When the stiffness reached about 10 ka, the variation of the stiffness on the slip was basically unchanged.

7. Conclusion

- (1) The formulas of the interface slip of the steel beam reinforced with the CFRP sheet under the action of temperature and creep were given by using the elastic method and energy method, respectively. By comparing the results between the finite element calculation and the formula calculation, it showed that the two results were in good agreement and indicated that the formula was correct and can be used to calculate the interface slip between the steel beam and the CFRP sheet.
- (2) The results of formulas showed that when the creep was not taken into account, the interface slip was the maximum at the end of the beam and the minimum at the middle of the span. When the stiffness reached about 3 ka, the slip was basically unchanged. When the temperature increased to 5°C, the slip increased about 0.005 mm. And when the thickness of the CFRP sheet increased to 0.05 mm, the slip increased about 0.003 mm.
- (3) The results of formulas also showed that when the creep was taken into account, the interface slip increased with the increase of load and decreased with the increase of stiffness. When the load increased to 5 N/mm or 5 kN, the slip increased about 4.4×10^{-7} mm, 1.2×10^{-6} mm, and 6.2×10^{-7} mm, respectively. The change of the interface slip decreased with the increase of stiffness. When the stiffness reached about 10 ka, the variation of the stiffness on the slip was basically unchanged.

Data Availability

Some or all data, models, or codes generated during this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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