RESEARCH ON SHEAR STRESS ANALYSIS METHOD OF CARBON FIBER REINFORCED COMPOSITE CFRP-STEEL INTERFACE

by

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This article designs and develops a small double shear CFRP-steel composite structure specimen, and establishes a new expression for the relationship between specimen measurement strain, interface shear strain, and shear stress. Compared with traditional methods, the calculation method considers the small deformation of the steel plate during the stress process, which makes the designed specimen size smaller and more suitable for engineering testing applications.

Key words: *CFRP-steel interface, anti-shear deformation characteristics, minor deformation of steel plate*

Introduction

In order to study the shear characteristics of CFRP-steel interface, scholars usually design and fabricate double shear or single shear specimens for testing [1-3] and have systematically studied the bonding performance [4, 5] and failure mechanism of CFRP-steel interfaces through different types of shear tests [6]. The double shear CFRP-steel composite structure specimen based on traditional electrical measurement technology can be used to test the shear deformation resistance of the CFRP-steel interface [7, 8]. However, traditional calculation methods assume that the steel plate is a rigid body when establishing the expression of the relationship between the measured strain of the specimen and the interfacial shear strain and shear stress, without considering the small deformation of the steel plate. Therefore, in traditional methods, there are certain limitations on the thickness of the steel plate and requirements for the ratio of the cross-sectional area of the steel plate to the CFRP plate (the larger the ratio, the better), resulting in double shear specimens that are more similar to a structure. In order to facilitate the testing of the mechanical properties of CFRP-steel interfaces in engineering, it is necessary to design a smaller specimen size and derive a calculation formula that takes into account the deformation of the steel plate for use with double shear specimens made of smaller and thinner steel plates. By using the derived indirect measurement principle expression for the shear strain at the CFRP-steel interface, as long as the axial strain of the CFRP plate and steel plate is measured, the shear strain at the CFRP-steel interface can be easily analyzed, while solving the problem of traditional specimen size being too large.

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Design and preparation

The specimen components are designed as: upper and lower steel plates, CFRP plates pasted on both sides of the steel plate surface using structural adhesive (leaving a small gap between the upper and lower steel plates), as shown in fig. 1(a).

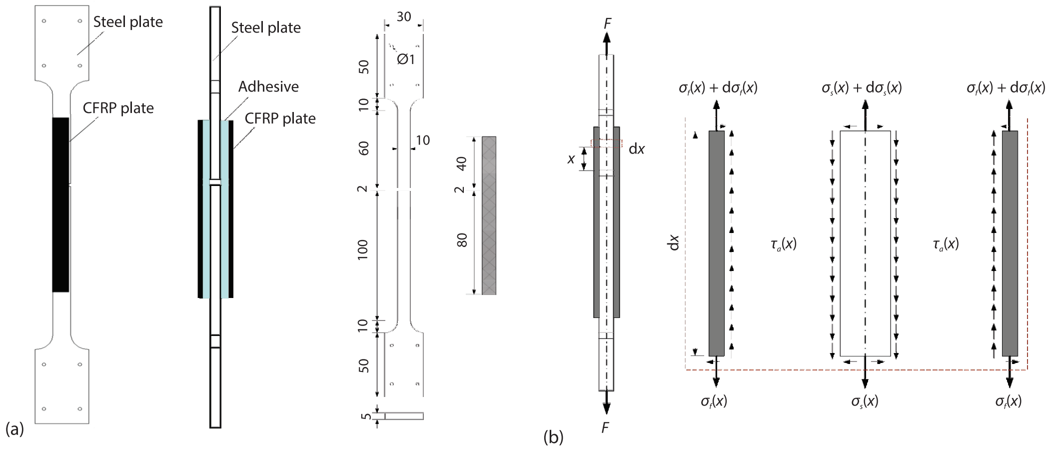

Figure 1. Structural composition of the sample and stress state of specimen micro element

Characteristics of sample stress

It can be easily seen from fig. 1(b) that, when a load, F, is applied to the clamping parts of the upper and lower steel plates of the specimen, the adhesive layer between the CFRP plate and the upper and lower steel plates undergoes axial displacement deformation (shear deformation). It is transmitted to the CFRP plates on both sides in the form of shear stress, τ. The resultant force of the τ on the sides of the upper steel plate balanced with the upper end load F. The resultant force of shear stress on the sides of the lower steel plate balanced with the lower end load F. The τ direction of the upper and lower parts of the CFRP plate is opposite, and the resultant τ of the upper part balanced with the resultant τ of the lower part. As the applied load F increases, the shear deformation of the interface continues to intensify, ultimately leading to fracture failure.

There is the fact that the bonding length between the CFRP plate and the upper steel plate is only half of the bonding length between the CFRP plate and the lower steel plate. According to the equilibrium condition of the CFRP plate, it is obvious that the τ at the upper part of the CFRP plate is greater than that at the lower part of the CFRP plate. Therefore, the fracture failure of the interface first occurs in the bonding area between the CFRP plate and the upper steel plate, which is the characteristic area that determines the bearing capacity of the specimen, restricts the shear deformation evolution and fracture of the interface of the specimen. It is the measurement point, which is the lay-out area of concern in this paper.

Analysis method

Figure 1(b) shows the stress state of the specimen element, dx, under tensile force, F. In fig. 1(b), $\sigma_t(x)$ represents the normal stress on the cross-section of the steel plate. The $\sigma_t(x)$ is the normal stress on the cross-section of the CFRP plate. The $\tau_a(x)$ is the shear stress between the steel plate and the CFRP plate. Based on the equilibrium conditions of the specimen element dx, it is easy to determine the relationship between $\tau_a(x)$ and $\sigma_t(x)$ and that between $\tau_a(x)$ and $\sigma_t(x)$.

Method I

Taking the CFRP plate element dx, the equilibrium of the CFRP plate element in the x direction is obtained:

$$\left[\sigma_f(x)+\mathrm{d}\sigma_f(x)\right]h_f t_f - \sigma_f(x)ht_f + \tau_a(x)h_f\mathrm{d}x = 0 \tag{1}$$

which is simplified

$$\tau_a(x)\mathrm{d}x = -t_f\mathrm{d}\sigma_f(x) \tag{2}$$

where t_f is the thickness of the CFRP plate and h_f – the width of the CFRP plate. Considering that the CFRP plate is in an elastic deformation state, the line strain at position $\varepsilon_f(x)$:

$$\sigma_f(x) = E_f\varepsilon_f(x) \tag{3}$$

where E_f is the elastic modulus of the CFRP plate. Substituting eq. (3) into eq. (2) yields:

$$\tau_a(x)\mathrm{d}x = -t_f E_f\mathrm{d}\varepsilon_f(x) \tag{4}$$

We now rewrite eq. (4):

$$\tau_a(x) = -\tau_f E_f\frac{\mathrm{d}\varepsilon_f(x)}{\mathrm{d}x} \tag{5}$$

The negative sign in eq. (5) indicates $\varepsilon_f(x)$ decrease as the co-ordinate x increases. The N strain gauges are arranged in the x-direction of the CFRP plate in the testing area, and the line strain values of the i^{th} and $i+1^{\text{th}}$ strain gauges are measured as $\varepsilon_{fi}(x)$ and $\varepsilon_{ci+1}(x)$. There fore, the shear stress at the midpoint of the two strains is $\tau[(x_{i+1}-x_i)/2]$ approximately:

$$\tau_a\left(\frac{x_{i+1}-x_i}{2}\right) = E_f t_f\frac{\varepsilon_{fi}-\varepsilon_{fi+1}}{x_{i+1}-x_i} \tag{6}$$

where x_i and x_{i+1} are the x-co-ordinates of the i^{th} and $i+1^{\text{th}}$ strain gauges, respectively. Indicating that if the values of $\varepsilon_{ci}(x)$ (i = 1, 2,..., n) at each point are measured, the distribution pattern of shear stress $\tau_a(x)$ on the CFPR-steel interface can be obtained from eq. (6).

Method II

The shear stress at the interface can be obtained not only by strain measurement on the CFRP plate, but also by measuring the line strain in the x-direction on the intermediate steel plate. As shown in fig. 3, taking the steel plate element dx for analysis, the equilibrium of the steel plate element in the x direction is obtained:

$$\left[\sigma_s(x)+\mathrm{d}\sigma_s(x)\right]ht_s - \sigma_s(x)ht_s - \tau_a(x)h\mathrm{d}x = 0 \tag{7}$$

which is simplified:

$$\tau_a(x)\mathrm{d}x = \frac{1}{2}t_s\mathrm{d}\sigma_s(x) \tag{8}$$

where t_s is the thickness of the steel plate and h – the width of the steel plate. Considering that the steel plate is in an elastic deformation state, the linear strain $\varepsilon_s(x)$ at position x is given:

$$\sigma_s(x) = E_s\varepsilon_s(x) \tag{9}$$

where E_s is the elastic modulus of the steel plate. Substituting eq. (8) into eq. (7) yields:

$$\tau_a(x)\mathrm{d}x = \frac{1}{2}t_s E_s\mathrm{d}\varepsilon_s(x) \tag{10}$$

We now rewrite eq. (10):

$$\tau_a(x) = \frac{1}{2} t_s E_s \frac{\mathrm{d}\varepsilon_s(x)}{\mathrm{d}x} \tag{11}$$

The linear strain values of the i^{th} and i+1$^{\text{th}}$ strain gauges are measured to be $\varepsilon_{si}(x)$ and $\varepsilon_{si+1}(x)$, respectively. Therefore, the shear stress $\tau_a[(x_{i+1} - x_i)/2]$ at the midpoint of the two strains is approximately:

$$\tau_a\left(\frac{x_{i+1} - x_i}{2}\right) = E_s t_s \frac{\varepsilon_{si+1} - \varepsilon_{si}}{x_{i+1} - x_i} \tag{12}$$

where x_i and x_{i+1} are the x-co-ordinates of the i^{th} and $i + 1^{\text{th}}$ strain gauges, respectively. Indicating that if the values of $\varepsilon_{si}(x)$ (i = 1, 2,..., n) at each point are measured, the distribution law of shear stress $\tau_a(x)$ on the CFRP-steel interface can also be obtained from eq. (12).

Equations (6) and (12) provide indirect measurement formulas for the interfacial shear stress of CFRP-steel reinforcement based on axial line strain of CFRP plate and axial line strain of steel plate, respectively. It is pointed that taking the geometric mean of the analytical results of eqs. (6) and (12) can help improve testing errors and enhance testing accuracy.

In order to facilitate the analysis of the deformation mechanism of the CFRP-steel interface, a small area is taken at x from the lower end of the upper steel plate. Select two points on the cross-section at position x: A_s and A_f. Among them, point A_s is located at the junction of the interface and the steel plate. The A_f point is located at the junction of the interface and the CFRP plate. When the sample is subjected to a tensile force F, A_s point generates displacement $u_s(x)$ along the x direction point A'_s, while A_f point generates displacement $u_f(x)$ along the x direction point A'_f.

Let the relative displacement of point A_f with respect to point A_s in the x direction:

$$\Delta u(x) = u_f(x) - u_s(x) \tag{13}$$

Considering that the CFRP-steel interface (adhesive layer) is very thin, it can be assumed that the shear strain of the interface is uniformly distributed along the transverse direction (along the direction for the thickness t_a of the adhesive layer). Therefore, the shear strain $\gamma_a(x)$ of the adhesive layer at position x:

$$\gamma_a(x) = \frac{\Delta u(x)}{t_a} = \frac{u_f(x) - u_s(x)}{t_a} \tag{14}$$

where t_{a} is the thickness of the interface (adhesive layer). The shear strain of the interface is given by eq. (14).

The linear strains along the x-direction on the steel plate side and CFRP plate side of the interface at any position x are $\varepsilon_s(x)$ and $\varepsilon_c(x)$, respectively. Based on the relationship between the deformation displacement and the linear strain at position x, the displacements $u_s(x)$ and $u_f(x)$ on both sides can be determined:

$$u_s(x) = \int_0^x \varepsilon_s(x)\mathrm{d}x \quad \text{and} \quad u_f(x) = \int_0^x \varepsilon_f(x)\mathrm{d}x \tag{15a,b}$$

In order to establish the relationship between the shear strain of CFRP-steel interface and the axial (x-direction) linear strain $\varepsilon_s(x)$ and $\varepsilon_f(x)$ of the tested sample, the integral eqs. (15a) and (15b) are approximated:

$$u_s\left(\frac{x_i+x_{i+1}}{2}\right)=\frac{\varepsilon_s(x_2)+\varepsilon_s(x_1)}{2}\left(x_2-x_1\right)+\frac{\varepsilon_s(x_3)+\varepsilon_s(x_2)}{2}\left(x_3-x_2\right)+\ldots$$
$$+\frac{\varepsilon_s(x_{i+1})+\varepsilon_s(x_i)}{2}\left(x_{i+1}-x_i\right)=\frac{1}{2}\sum_{k=1}^{i}\left[\varepsilon_s(x_{k+1})+\varepsilon_s(x_k)\right]\left(x_{k+1}-x_k\right) \tag{16}$$

$$u_f\left(\frac{x_i+x_{i+1}}{2}\right)=\frac{\varepsilon_f(x_2)+\varepsilon_f(x_1)}{2}\left(x_2-x_1\right)+\frac{\varepsilon_f(x_3)+\varepsilon_f(x_2)}{2}\left(x_3-x_2\right)+\ldots$$
$$+\frac{\varepsilon_f(x_{i+1})+\varepsilon_f(x_i)}{2}\left(x_{i+1}-x_i\right)=\frac{1}{2}\sum_{k=1}^{i}\left[\varepsilon_f(x_{k+1})+\varepsilon_f(x_k)\right]\left(x_{k+1}-x_k\right) \tag{17}$$

Substituting eqs. (16) and (17) into eq. (14), the shear strain at the midpoint of points x_i and x_{i+1} is obtained:

$$\gamma\left(\frac{x_i+x_{i+1}}{2}\right)=\frac{1}{2t_a}\sum_{k+1}^{i}\left\{\left[\varepsilon_f(x_{k+1})-\varepsilon_s(x_{k+1})\right]-\left[\varepsilon_f(x_k)-\varepsilon_s(x_k)\right]\right\}\left(x_{k+1}-x_k\right) \tag{18}$$

Here, (i = 1, 2,..., n) are the measured strain values on the CFRP plate and steel plate at point x_i, respectively. Equation (18) indicates that as long as the axial strain of the CFRP plate and steel plate is measured, and that the shear strain of the CFRP-steel interface may be easily given. Equation (18) is the indirect measurement principle expression for the interfacial shear strain of CFRP-steel interface.

Conclusion

In this work, we considered the small deformation of steel plates during the stress process using traditional calculation methods. We established the expression for the relationship between the measured strain of the specimen and the interfacial shear strain and shear stress. Using the indirect measurement principle expression of the shear strain at the CFRP-steel interface, as long as the axial strain of the CFRP plate and steel plate was measured, the shear strain at the CFRP-steel interface can be easily analyzed. The newly designed specimen is smaller for the size, making it more convenient for testing on general material testing machines in engineering inspections, and improving the problem of traditional specimen sizes being too large.

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Nomenclature

t_f – thickness of the CFRP plate, [m]
t – thickness of the steel plate, [m]
E_f – elastic modulus of CFRP plate, [Nm^{-2}]
h_f – width of the CFRP plate, [m]
h – width of the steel plate, [m]
E_s – elastic modulus of steel plate, [Nm^{-2}]

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