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ARTICLE

Interfacial Interaction of CFRP Reinforced Steel Beam Structures

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ABSTRACT

Due to the increase of service life, the phenomenon of performance degradation of bridge structures becomes more and more common. It is important to strengthen the bridge structures so as to restore the resistance level and extend the normal service life. Carbon fiber reinforced polymer (CFRP) materials are thus used for the assembly reinforcement of bridges for the advantages of high strength, light weight, corrosion resistance and long-term stability of physical and chemical properties, etc. In view of this, based on the previous theoretical study and the established formula of the interfacial shear stress of CFRP reinforced steel beam and the normal stress of CFRP plate, this paper discusses the sensitive parameters that affect the interfacial interaction of CFRP strengthened beam structures. Through the analysis, the priority design indicators and suggestions are accordingly given for the design of reinforced beam structures. Young's modulus of CFRP composite and shear modulus of the adhesive have the greatest influence on the interfacial interaction, which should be carefully considered. It is suggested that CFRP material with Ec close to 300 GPa and thickness no less than 3 mm, and adhesive material with Ga less than 5 GPa and 3-mm thickness can be adopted in CFRP reinforced steel beam. The conclusions of this paper can provide guidance for the interfacial damage control of CFRP reinforced steel beam structures.

1. Introduction

Bridges are an important part of the modern transportation system, and the safe operation, long-term performance maintenance, real-time state assessment and sudden damage warning are particularly significant to guarantee the normal and orderly operation of the entire system. With the rapid development of infrastructure construction, there has been a substantial increase in demand for traffic volume. The traffic density and vehicle load are also increasing, and the overloading induced structural damage of the bridges exacerbates the natural aging. All these factors lead to the degradation of the bearing capacity and durability of the bridges. To ensure the safe operation of the bridge structures, the hot research of bridge engineering has gradually changed from large-scale construction to the stage of detection, repair, reinforcement, renovation and maintenance [1-3].

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Fiber reinforced polymer (FRP), for the advantages of non-enhanced structural section and deadweight, easy construction, high tensile strength, excellent corrosion resistance, good fatigue strength, non-magnetic and non-conductive properties, wear resistance, easy cutting, low density, etc, has been applied to the reinforcement of local parts of bridge structures [4-5]. The reinforced structure is a new composite structure composed of the existing bridge structure, FRP material, and epoxy resin colloid. The new material and construction process of the FRP reinforced structures bring about much uncertainty. The uncertainty should be reasonably considered in the reinforcement design and performance analysis of the reinforced structure to ensure the safe and reliable of reinforced structure within a certain confidence interval. As a kind of FRP material, carbon fiber reinforced polymer (CFRP) has attracted much attention in the field of reinforcement. Compared with the traditional reinforcement method, CFRP with the characteristics of light weight, high strength, corrosion-resistant, convenient in construction, and non-disturbance to the appearance and function of the structure, has a wide application prospect. Therefore, to understand the service performance of CFRP-reinforced bridge structures, it is necessary to analyze the action mechanism under mechanical load. The interfacial bonding performance is the key to coordinated deformation and load transfer of CFRP reinforced structures. Some domestic and foreign scholars have analyzed the interfacial damage in the whole process by introducing different bond-slip models [6-12]. However, most of these studies focus on describing the interfacial degradation process.

Given the analysis above, the interfacial shear stress and normal stress expressions of CFRP strengthened beam structures obtained by theoretical analysis based on the previous research basis are adopted to discuss the sensitive parameters that affect the interfacial interaction in this paper. The study provides a foundation for the subsequent research of smart CFRP-fiber Bragg grating (FBG) composites capable of simultaneously strengthening the structure and monitoring the structural performance [13]. The priority design parameters of the CFRP reinforced structures are suggested through the sensitive analysis.

2. Interfacial Action of the CFRP Reinforced Steel Beam

2.1 Model Description

To monitor the interfacial debonding of a CFRP reinforced structure, it is essential to understand the mutual interaction and the damage mechanism. Therefore, a theoretical model is first formulated to describe the stress relationships. A steel beam model with a H-shaped cross section is considered, where a CFRP composite is attached on the beam bottom. As shown in Figure 1, the simply supported constraint and four-point bending loading are considered. The span and the height of the beam are $2(l+a)$ and $2z_0$, respectively. The length, width and thickness of the CFRP composite are separately denoted as $2l$, b_c and t_c. The origin of the coordinate system is located at the neutral axis of the beam, as shown in Figure 1. P is the load, and b is the horizontal distance of the load point to the origin of the coordin1ate.

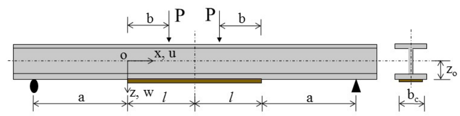

Figure 1. Steel beam strengthened with CFRP composite

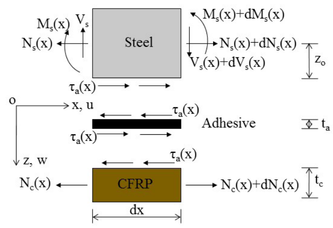

Figure 2. Infinitesimal element of a three-layered strengthened beam

An arbitrary cross section is considered in the theoretical derivation. An infinitesimal element, dx, is selected from the CFRP reinforced beam. The stress state of a three-layered model is shown in Figure 2. $M_s(x)$, $N_s(x)$ and $V_s(x)$ are the bending moment, axial force and shear force of the steel beam, respectively. $N_c(x)$ is the axial force of the CFRP plate. $\tau_a(x)$ is the interfacial shear stress. The thickness of the adhesive layer is t_a. Two assumptions are made: (1) the bending stiffness of the beam to be strengthened is much greater than the stiffness of the strengthening plate; and (2) the stresses in the adhesive layer don't change along the thickness direction (i.e., the adhesive layer is thin). Therefore, the bending moment in the CFRP composite is negligible, which implies that the normal stress in the bonding zone can be ignored, as displayed in Figure 2.

The interfacial shear stress can be derived from the reference [14]

$$\tau_a(x) = \frac{G_a P}{t_a E_s W_s}\left[\frac{a}{\lambda}\tanh(\lambda b)\cosh(\lambda x) - \frac{\cosh(\lambda x)}{\lambda^2 \cosh(\lambda b)} - \frac{a}{\lambda}\sinh(\lambda x) + \frac{1}{\lambda^2}\right] \tag{1}$$

where $\lambda^2 = \frac{G_a b_c}{t_a}\left(\frac{1}{E_c A_c} + \frac{z_o}{E_s W_s} + \frac{1}{E_s A_s}\right)$

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According to the assumption given in [15], if $\lambda b > 5$, Eq. (1) can be simplified as

$$\tau_a(x) = \frac{G_a P}{t_a E_s W_s} \frac{a\lambda e^{-\lambda x} + 1}{\lambda^2} \tag{2}$$

and the normal stress of the CFRP composite can accordingly be expressed as

$$\sigma_c(x) = \frac{G_a P}{t_c t_a E_s W_s} \frac{a(1 - e^{-\lambda x}) + x}{\lambda^2},\ 0 \le x \le b \tag{3}$$

2.2 Sensitive Parametric Analysis

The geometrical and material parameters of the steel beam and the CFRP composite are described in Table 1. The parameters a, b and l are 0.55 m, 0.2 m and 0.35 m. respectively. Substituting correlated parameters in Table 1 into the formula of λ, the value λ$b$can be figured out, with value 6. 76 larger than 5. Therefore, the proposed Eq. (2) and Eq. (3) can be adopted to describe the interfacial action of the model. According to the expressions of interfacial shear stress and normal stress of CFRP plate, the main sensitive parameters affecting the interfacial interaction include: external load, Young's modulus and thickness of CFRP plate, and shear modulus and thickness of adhesive layer. Therefore, these ssensitive parameters have been discussed separately to consider the influence on the stress state of the CFRP reinforced steel beam.

Table 1. Physical parameters of the CFRP reinforced steel beam in test

Content	Label	Value	Unit
Flange thickness of steel beam		9×10^{-3}	m
Web width of steel beam		6×10^{-3}	m
Width of steel beam		1.25×10^{-1}	m
Half of the height of steel beam	z_0	6.25×10^{-2}	m
Area of cross section of steel beam	A_s	2.892×10^{-3}	m^2
Area of cross section of CFRP plate	A_c	3×10^{-4}	m^2
Width of CFRP plate	b_c	1×10^{-1}	m
Thickness of CFRP plate	t_c	3×10^{-3}	m
Thickness of adhesive layer	t_a	1.5×10^{-3}	m
Young's modulus of steel	E_s	2.06×10^{11}	N/m^2
Young's modulus of CFRP	E_c	3.07×10^{11}	N/m^2
Shear modulus of adhesive layer	G_a	1.154×10^{9}	N/m^2
Applied load	P	1×10^{4}	N

(1) The applied load P

The profiles of the interfacial shear stress and the normal stress of the CFRP composite under the different loads (P = 10 kN, 20 kN, 30 kN) can be obtained by substituting the given parameters into Eq. (2) and Eq. (3). The abscissa axis in Figure 3 is x, with its value ranging from 0 to b (where b=0.2m). It can be noted that the interfacial shear stress decreases nonlinearly from the end to the central, with the maximum value in the end (x=0) in Figure 3(a). The normal stress of the CFRP composite presents an increasing tendency from the end to the central, and the maximum value occurs in the central in Figure 3(b). The normal stresses of the CFRP plate are generally far larger than the interfacial shear stress. With the increase of the applied load, the interfacial stress and the normal stress of the CFRP plate have obvious increase. The larger load can lead to larger interfacial action, which may finally make the CFRP reinforced beam suffer from interfacial debonding damage.

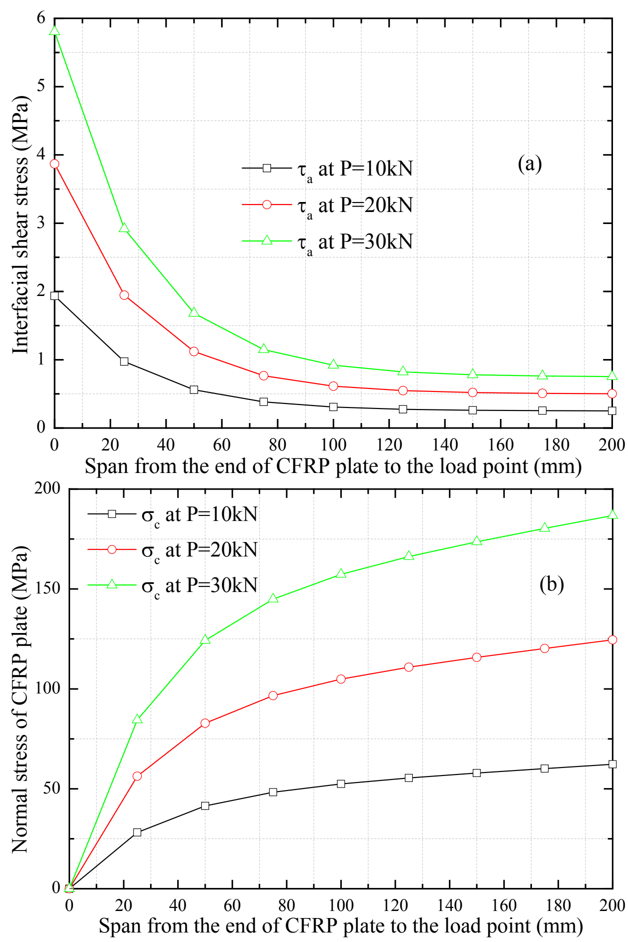

Figure 3. Profiles of (a) the interfacial shear stress and (b) the normal stress of CFRP plate varied with the applied load

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(2) The Young's modulus of CFRP plate E_c

The variations of the interfacial shear stress and the normal stress of the CFRP plate along with the Young's modulus of CFRP composite are displayed in Figure 4. It can be seen that both the interfacial shear stress and normal stress increase with the growth of Young's modulus of CFRP material. In other words, the high strength of the CFRP material may bring about strong interfacial interaction, which can induce the occurrence of interfacial debonding damage. The optimal design of CFRP material should be carefully considered to obtain a reasonable balance between the reinforcement of the steel structure and the interfacial interaction, so as to achieve a long-term stable and durable reinforcement effect.

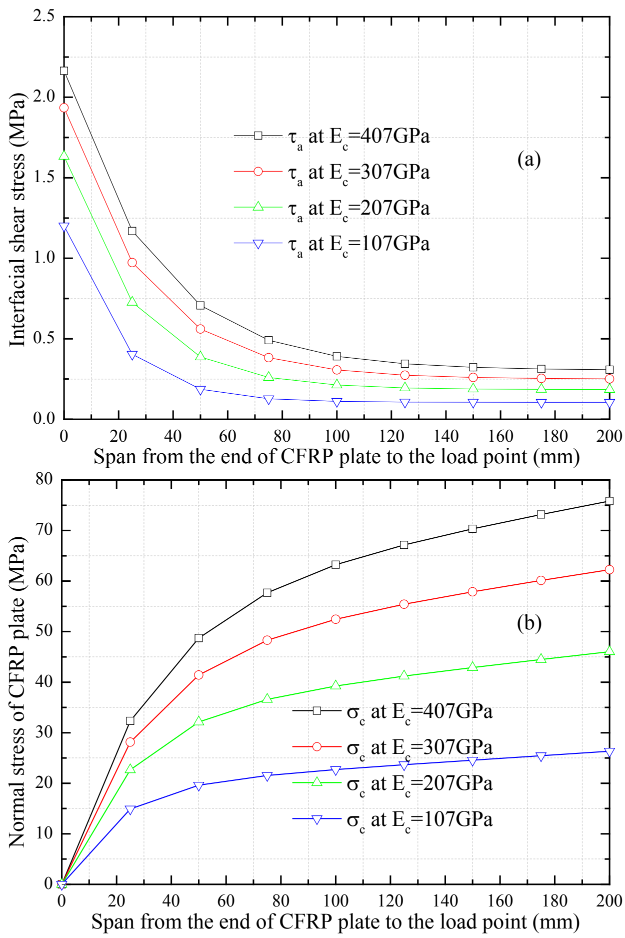

Figure 4. Profiles of (a) the interfacial shear stress and (b) the normal stress of CFRP plate varied with the Young's modulus of CFRP plate

(3) The shear modulus of adhesive G_a

The variations of the interfacial shear stress and the normal stress of the CFRP plate along with the shear modulus of adhesive layer are displayed in Figure 5. It can be seen that as the shear modulus of the adhesive layer increases, the normal stress of the CFRP plate also increases, but eventually tends to be the same. The interfacial shear stress increases with the growth of shear modulus of the adhesive material before the first inflection point, but decreases with the increase of the shear modulus after the first inflection point. At the same time, it can also be found that reducing shear modulus of the adhesive layer at x=0~20 mm (that is, near the end of the CFRP plate) can effectively reduce the interfacial shear stress, and reducing the shear modulus at x=30 mm ~ 80 mm can effectively reduce the normal stress. Therefore, when the CFRP plate is adopted to reinforce the steel beam, priority should be given to the design of the adhesive material. Appropriate adhesive material can effectively reduce the interfacial shear stress of the reinforced structures

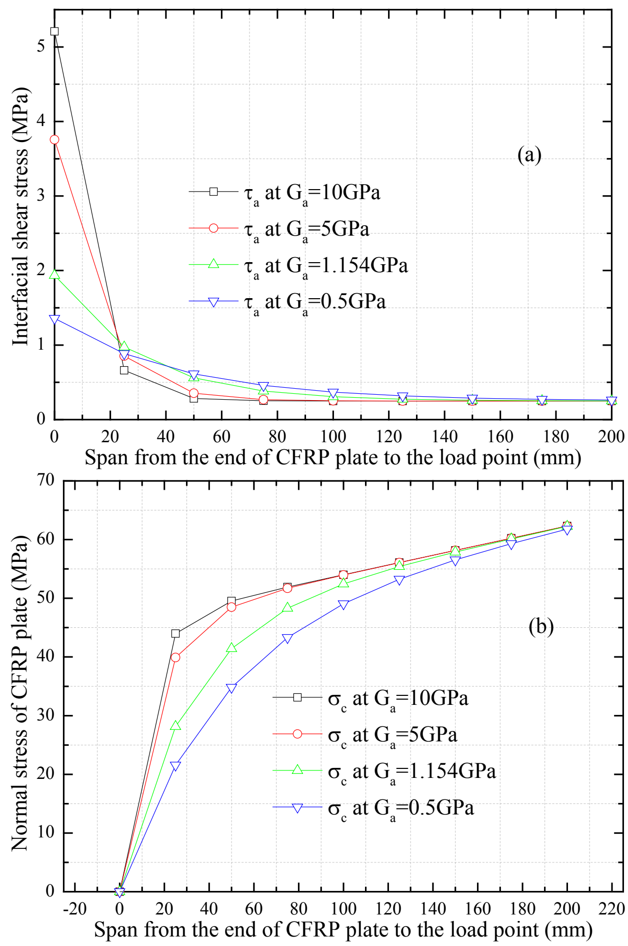

Figure 5. Profiles of (a) the interfacial shear stress and (b) the normal stress of CFRP plate varied with the shear modulus of adhesive

(4) The thickness of CFRP plate t_c

The variations of the interfacial shear stress and the normal stress of the CFRP plate along with the thickness of CFRP plate are displayed in Figure 6. It can be seen that interfacial shear stress does not change with the increase of the thickness of CFRP plate, which shows that the influence of the thickness of CFRP plate on interfacial shear stress is negligible. However, the normal stress of CFRP plate decreases obviously with the increase of the thickness of CFRP plate. Especially when the thickness of CFRP plate increases from 1 mm to 3 mm, the normal stress is almost reduced by 2 times. It means that the extreme thin CFRP plate may suffer from tensile fracture. Therefore, a thicker CFRP plate is beneficial to improve the tensile strength of the CFRP reinforcement.

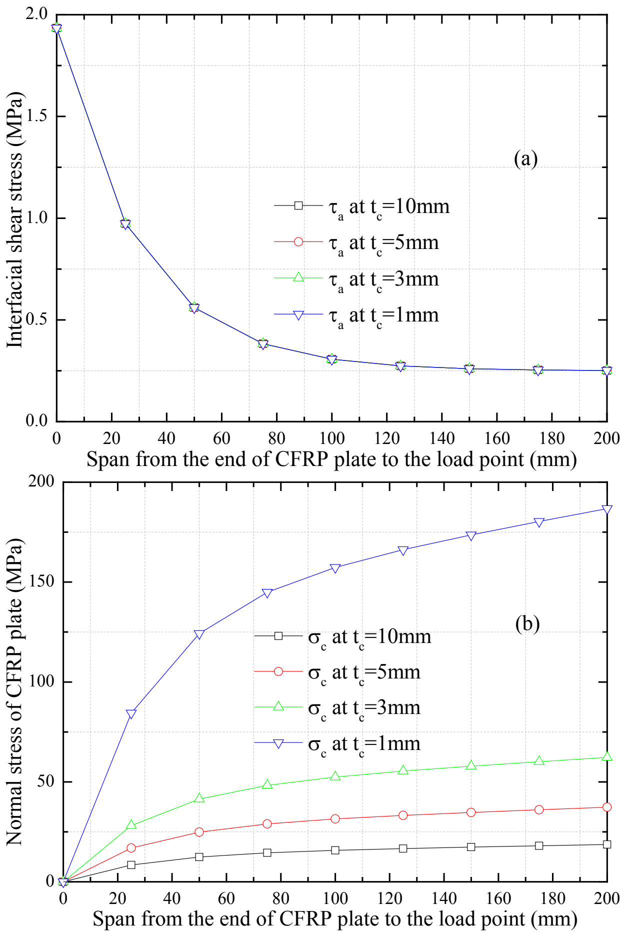

Figure 6. Profiles of (a) the interfacial shear stress and (b) the normal stress of CFRP plate varied with the thickness of CFRP plate

(5) The thickness of adhesive t_a

The variations of the interfacial shear stress and the normal stress of the CFRP plate along with the thickness of adhesive are displayed in Figure 7. It can be seen that both the interfacial shear stress and the normal stress of CFRP plate decrease with the increase of the thickness of adhesive layer. At *x*=0~20 mm, the interfacial shear stress decreases significantly with the increase of the thickness of adhesive, after which the thickness of the adhesive layer has little effect on interfacial shear stress. At *x*=0~100 mm, the normal stress of the CFRP plate obviously decreases with the increase of the thickness of adhesive layer, after which the effect gradually becomes weak. Therefore, the thicker adhesive layer will efficiently reduce the interfacial shear stress and normal stress of the CFRP plate, thereby improving its durability.

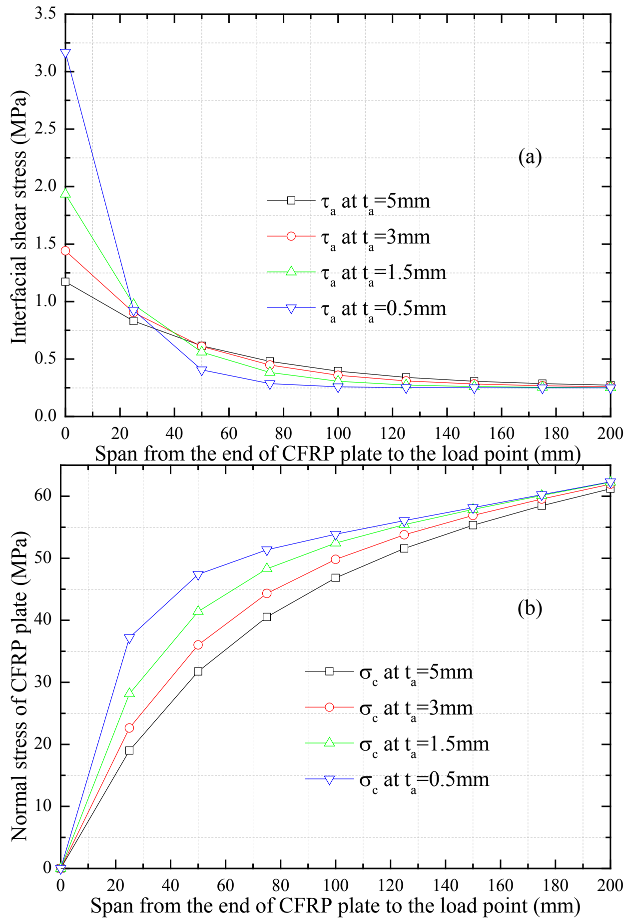

Figure 7. Profiles of (a) the interfacial shear stress and (b) the normal stress of CFRP plate varied with the thickness of adhesive

Based on the analysis, it can be seen that the change of Young's modulus of CFRP composite and shear modulus of the adhesive have the greatest influence on the interfacial interaction. Therefore, in the design of the CFRP reinforced composite beam, priority should be given to the design of the CFRP composite material and the adhesive material to achieve the optimal control of the interfacial strength of the composite beam.

2.3 Discussions

The sensitive parametric analysis indicates that the interfacial stress is significantly influenced by the applied

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load P, Young's modulus of CFRP composite E_c, shear modulus of the adhesive G_a, and thickness of the adhesive t_a. Generally, a relatively lighter load, smaller Young's modulus of CFRP composite and shear modulus of the adhesive, and thicker adhesive layer can bring about the smaller interfacial shear stress in the overall contacted interface. These design instructions can be used to avoid or postpone the occurrence of the interfacial debonding damage of the CFRP reinforced beam structures.

Similarly, the normal stress of the CFRP plate is highly impacted by the applied load P, Young's modulus E_c and thickness t_c of CFRP composite, shear modulus G_a and thickness t_a of the adhesive. It should be noted that the smaller shear modulus and thicker adhesive layer can lead to relatively smaller stress in the CFRP plate. That means the failure of the CFRP plate can be buffered by the proper design of the adhesive layer. These findings can be used to instruct the design of smart CFRP-FBG plate for strengthening the beam structures.

3. Conclusions

To understand the structural performance of CFRP reinforced beam structures, a parametric study has been conducted to discuss the influence of the material and geometrical parameters of the CFRP composite and the adhesive on the interfacial action of the reinforced steel beams. The study intends to provide design guidance for the optimal design of smart CFRP-FBG reinforced beams and control the interfacial debonding damage and fracture of the smart CFRP composites during the operation. The following conclusions can be drawn from the study:

(1) The proper selection of CFRP composite and the adhesive material should be carefully considered. It is suggested to use CFRP material with E_c close to 300 GPa and adhesive material with G_a less than 5 GPa in CFRP reinforced steel beam to achieve small interfacial shear stress.

(2) The thickness of the adhesive material is also very important for incurring the large interfacial stress at the end. Generally, the adhesive layer with 3-mm thickness can be suggested.

(3) The thinner CFRP plate can lead to larger normal stress. Therefore, the thickness of the CFRP plate is suggested to no less than 3 mm, which can be helpful to prevent the tensile fracture of the CFRP composite.

(4) The applied load is a direct factor that may lead to interfacial damage, which should be also carefully controlled. For the reinforced structures, the moving traffic loads should be strictly in charge.

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