

Analysis on Influence Factors of Grouted Anchorages for CFRP Bars

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Abstract. Force mechanism of CFRP reinforced anchorage is discussed in this thesis, where epoxy resin is used as adhesive agent. Taking the length of anchorage, the load, the thickness of resin and elastic modulus etc. as the main parameters, the shearing stress on the interface between tendons and resin were analyzed in light of finite element method. Finally, the suggestions for the design of the CFRP reinforced anchorages and the methods of improving adhesive agent are put forward.

Introduction

CFRP bars characterized by high specific strength, corrosion resistance, fatigue resistance, etc., can not be clamped by anchorage clip because of their low radial compressive strength, low shear strength between the carbon fiber layers . Anchoring of prestressed CFRP bars which is one of the most important technique should be developed in a safe, practical and economical way. Anchorage types can be summed up to steel plate clamp type, clip type and bonding anchorage based on the research. Among them, bonding anchorage with high efficiency is divided into two types, one of which is resin glue, the other is high strength and micro-expansion cement mortar. Harada and Lees applied the mortar to bonding anchorage in 1995 and 1996 respectively. While EMPA and BBR from Switzerland developed a bonding anchorage with resin, which is blended into alumina particles coated by epoxy resin to achieve a gradient of resin elastic modulus, with the anchoring efficiency being up to 92%, which was later applied to the Stock cable-stayed bridge in Zurich, Switzerland [1]. Research on CFRP reinforced anchorage have begun since the late 1990s in China. Many science research institutes have studied on the three types of anchorage shown above[2-6]. CFRP reinforced group anchorage was developed in Southeast University in 2004, which was applied to a bridge for the first time in China[4]; Experimental study on the CFRP reinforced anchorage performances was carried out through different bonding mediums in Hunan University, including the performances under Reactive Powder Concrete(RPC), epoxy iron sand, epoxy quartz sand and ordinary concrete were analyzed respectively[6]. The influence factors and practical calculation methods of the bond bearing capacity still need to be further studied. Taking CFRP bars and resin grouted type anchorage as the research object, this paper will study on the bonding interface shear stress distribution patterns by the finite element method to obtain a practical and simplified calculation method for the bond bearing capacity.

Preliminary judgment on strength of the bonding interface

When the resin adhesive bonds, the member bonded is infiltrated, through which an interface is formed by the physical and chemical reactions between the adhesive liquid and the bonded member in the process of curing. This bonding mode is a kind of the mechanical bonding and physical adsorption.

CFCC(Carbon Fiber Composite Cable) consists of twisted CFRP wires with small diameter, it can be divided into 7 strands, 19 strands and 37 strands, etc. with diameter changed from 9mm to 40mm, whose surface shape is conducive to mechanical interlocking and can be glued adequately. In the process of tensioning or holding, the average shear stress between the CFRP bars and the colloid,

the average shear stress between the colloid and the steel sleeve can be calculated by the following formula.

$$t_i = \frac{T}{pd_il} \quad (i=1,2) . \quad (1)$$

where T is the tensile force of the tendons, d_1 is the diameter of CFRP bars, d_2 is the diameter of the steel sleeve, and l is the length of the sleeve.

$d_1 < d_2$, we can get $\tau_1 > \tau_2$. Obviously, interface between the CFRP bars and colloid is the control interface of grouted anchorage. Actually, shear stress on interface is not uniformly distributed. As Khin et al.[8] observed in the experiment, when the tensioning force is small, maximum shear stress occurs at the loading end, when the force increases, stress peak moves gradually to the other end of the anchorage, and the magnitude of the peak is essentially invariant. The following research will be carried out by the finite element method.

Analysis on the influence factors of shear stress

With epoxy resin as binder, the grouted type anchorage model is shown in Fig. 1.

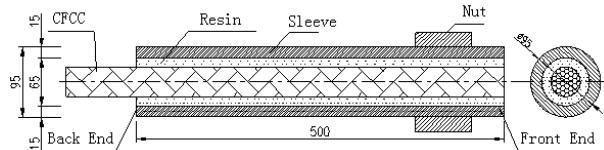


Fig.1 CFRP bars and grouted type anchorage

The basic assumptions of FEM analysis are as follows: firstly, the colloid is a homogeneous quality or a segmented homogeneous material, which bonds well with the steel sleeve and CFRP bars; CFRP bars is elastic and anisotropy, its elastic modulus and Poisson's ratio is 137GPa and 0.22 in the direction of fiber, 13.7GPa and 0.02 in the radial direction. Colloid is considered as elastic-plastic material, the stress-strain curve of epoxy glue is approximately linear when the stress is small, however, when the stress reaches the ultimate strength, colloid softens, the strain increases rapidly while the stress decreases. Its tensile stress-strain curve is represented by formula (2).

$$s = \frac{2(e/e_0)}{1+(e/e_0)^2} f_t^*. \quad (2)$$

Where, f_t^* is ultimate tensile strength of epoxy resin colloid, the trial average value can be adopted. e_0 is the tensile strain corresponding to the epoxy colloid peak of f_t^* . For a LICA type of structural glue made in China, we draw a stress-strain curve shown in Fig. 2.

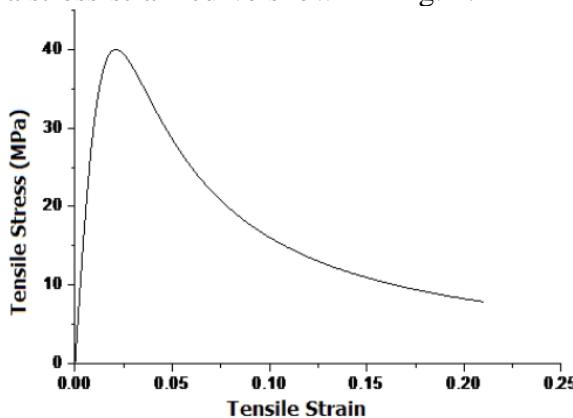


Fig.2 Tensile stress-strain curve of epoxy resin colloid

A plane model is built according to the axial symmetry of anchorage and analyzed by ANSYS procedure. The influence of anchorage length, colloidal elastic modulus, colloidal thickness etc. on the shear stress distributing between the resin colloid and CFRP bars ("colloid-bar" interface). are analyzed as follows.

Influence of the tensile load. Shear stress distribution on the "colloid-bar" interface is related to the tensile load. Shear stress distribution map (Fig.3a) obtained from FEM analysis shows that when the tensile load is smaller, the peak of shear stress occurs close to the back end of the anchorage, and shear stress near the front end is smaller. But when the load increases gradually, plastic softening happens at the interfaces near back end, where the shear stress falls and the peak position will gradually move to the front end of anchorage, while the peak value basically keep unchanged; there will be a peak zone under the ultimate load. The case is similar to what Khin had observed from bonding anchorage tests, shown in Fig.3.

It is predicted that the strength of "colloid-bar" interface determines the bearing capacity of the anchorages. The failure process on "colloid-bar" interface is basically divided into two stages. First, shear stress of interface increases with the increasing of tensile force, the colloid is in elastic state. Second, when bond stress reaches the maximum, the colloid in some zone falls into the plastic softening stage, shear stress decreases gradually, defects in the "colloid-bar" interface may cause micro-cracks; when shear strain reaches its limit value, CFRP bars and colloid disengage, and the anchorage fails.

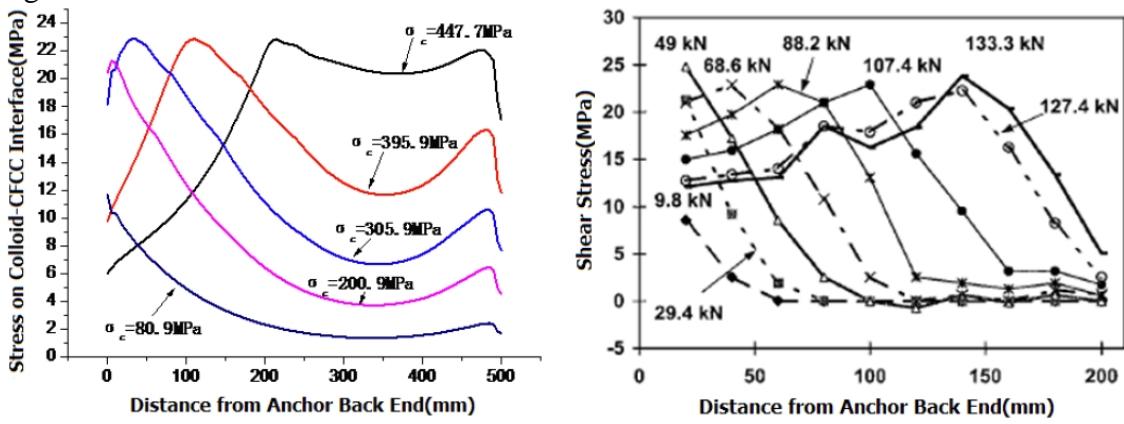


Fig.3 Relationship between the shear stress distribution of interface and tensile load

Influence of the anchorage length. Considering bridge design, short anchorage facilitates anchorage arrangement and tensile construction. While in view of supporting, long anchorage is better.

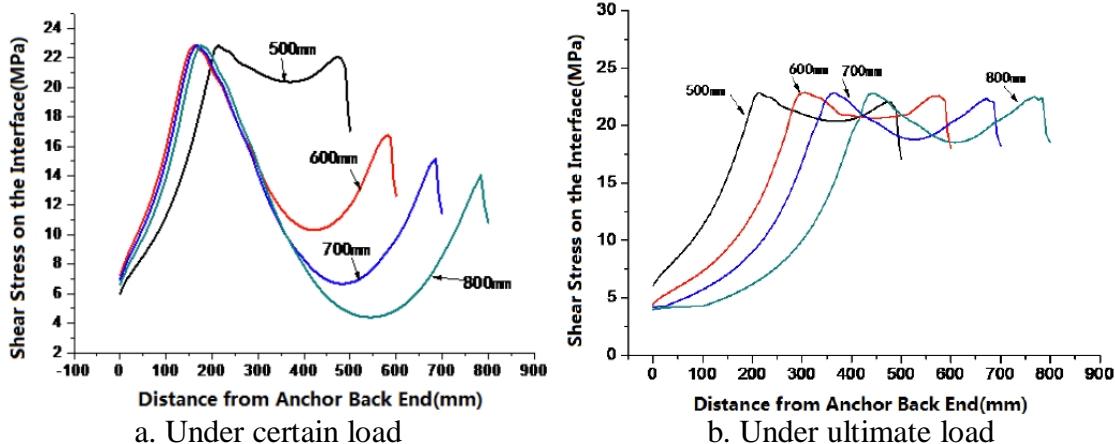


Fig.4 Influence of anchorage length on shear stress distribution of "colloid-bar" interface

Seen from Fig.4a, when the anchorage length increases under the same load, the value and position of stress peak near the back end of anchorage almost have no changes, while the shear stress near the front end decreases, that is the load shared by the zone around the front end of anchorage will reduce. Seen from Fig.4b, although the anchorage length is different, the shear stress distribution of “colloid-bar” interface is almost the same and the peak have no changes at ultimate limit state; the length of peak roughly ranges from $0.4L$ to $0.6L$, and the displacement distance is equal to the increment of anchorage length. The ultimate load of anchorage increases when its length increases, for the anchorage length of 500mm, 600mm, 700mm, 800mm, the corresponding bearing capacities are 348kN, 387kN, 419kN, 449kN respectively. Obviously, it is not economical to increase bearing capacity by increasing the anchorage length. It is suggested the anchorage length should be 12-14 times of the diameter of CFRP tendon.

Influence of the colloid thickness of the anchorage. The thickness of epoxy resin colloid is determined by the diameter of CFRP bars and the inner diameter of the anchorage. In Fig. 5a, when the thickness of epoxy resin colloid increases under the same tensile load, the length of the softening zone decreases, and the value and position of shear stress peak (23Mpa) near the back end of the anchorage have no changes, while the shear stress peak near the front end decreases. The reason is that the thicker the colloid is, the larger deformation it allows, then the shear strain decreases with the increasinge of the colloid thickness under the same load, so that the colloidal softening zone near the back end becomes shorter, and the total displacement of CFRP bars will increase along the tension direction under the same load. When the thickness continues to grow, the influence of colloid thickness becomes smaller.

The bearing capacity of anchorage increases slowly with the colloid thickness. When the colloid thickness is 12.5mm, 15mm, 17.5mm and 20mm respectively, the bearing capacity of bonding anchorage are 348kN, 360kN, 368kN and 374kN accordingly. As shown in Fig.5b, the colloid thickness has a small effect on the stress distribution, the shear stress peak zone is almost the same under the ultimate limit state. The difference is, with the increase of the colloid thickness, the residual stress near the back end increases. It is suggested that the thickness of the colloid should be $1/3\sim1/2$ of diameter of the CFRP bars or cables.

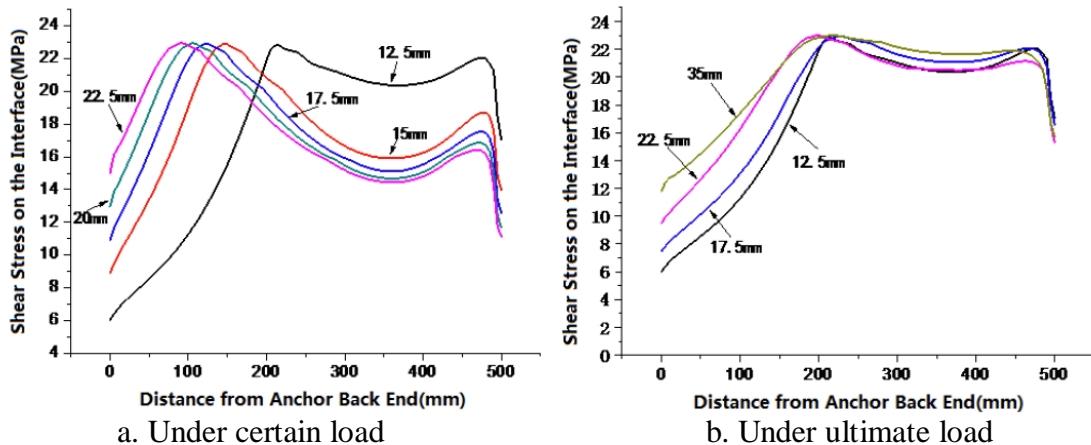
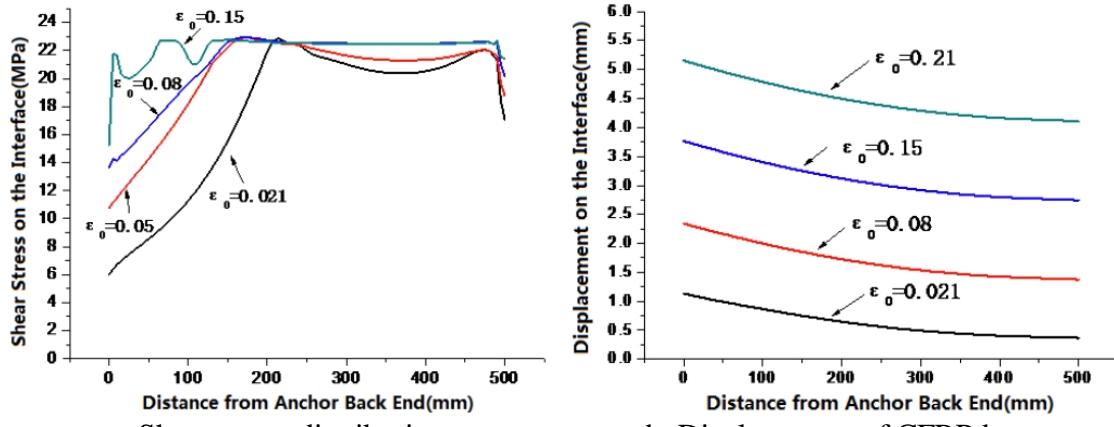


Fig.5 Influence of colloid thickness on the shear stress distribution of “ colloid-bar” interface

Influence of colloid elastic modulus. The colloid elastic modulus can be represented by the tensile strain ε_0 opposite to the ultimate tensile strength, shown in formula (2). When tensile strength remains unchanged, four cases $\varepsilon_0=0.021, 0.05, 0.08$ and 0.15 are compared, the shear stress distribution along the anchorage length is shown in Fig. 6a. With the decreasing of the colloid elastic modulus, the deformation capacity of the epoxy resin increases, the length of the plastic softening zone decreases, and the distribution of the shear stress tends to be uniform. Displacement of cable is shown in Fig.6b, the maximum displacement is near the back end, and with the decreasing of the elastic modulus, the displacement of CFRP bars along the tensioning direction increases accordingly as shown in Table 1. Considering prestressed loss, the colloid elastic modulus should not be reduced alone even if it can enhance the bearing capacity of the anchorage.



a. Shear stress distribution

b. Displacement of CFRP bar

Fig.6 Influence of colloidal elastic modulus on shear stress distribution and displacement of bar

According to the above analysis, we can reduce the plastic softening zone length by decreasing the colloid elastic modulus at back end appropriately. In order to control the displacement of CFRP bars, the elastic modulus of colloid close to the front end anchorage should be large enough. That is, the colloid can be made up of two parts with different elastic modulus. According to Fig.6a, two layers are divided both of which are in a distance of $0.4L$ from the back end, where L is the length of the anchorage. Two cases are analyzed below: ①the peak strain ϵ_0 of the two parts are 0.021, 0.08 respectively; ②the peak strain ϵ_0 of the two parts are 0.021, 0.05 respectively.

Table. 1 Influence of colloid elastic modulus on the anchorage ultimate limit state

ϵ_0	0.021	0.05	0.08	0.15	0.021_0.08	0.021_0.05
Maximum shear strain	0.259	0.322	0.348	0.369	0.115	0.204
Maximum displacement of bar [mm]	1.45	2.09	2.8	4.18	1.73	1.79
Bearing capacity of anchorage [kN]	349	401	424	444	411	431

As shown in Fig.7, when the colloid of anchorage are made up of different elastic modulus parts, the plastic softening problem at the back end is alleviated. Seen from Tab.1, the maximum displacement of CFRP bars along the tensile direction reduces too. Compared with 0.021 of ϵ_0 , the bearing capacity of anchorage is greatly improved by combined colloid.

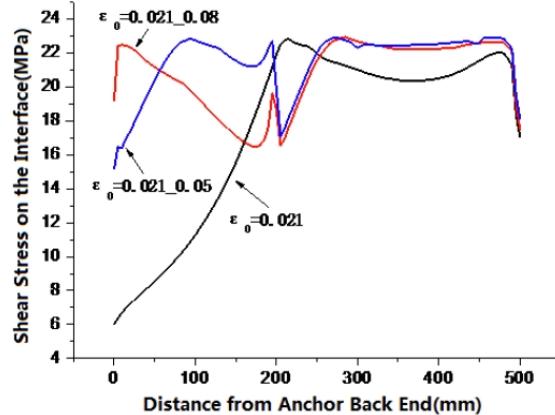


Fig.7 Influence of colloid elastic modulus

Influence of the end block. The end block at the back end is shown in Fig.8, which can restrain the shear deformation of colloid, through which the bearing capacity of anchorage will be improved. However, concentrated stress will occur in the CFRP bars at back end if the end block is set inappropriately, which will cause the damage of CFRP bars. So it is better to keep 2 ~ 3mm of gap

between the end block and the CFRP bars surface to hold a flexible polyethylene sheet to reduce or avoid the blade damage of CFRP bars caused by end block edge.

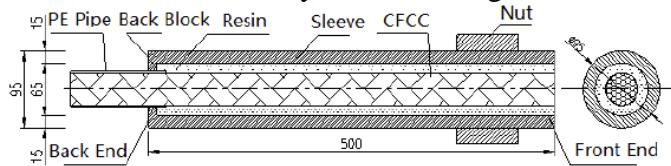


Fig.8 The design of grouted anchorage with end block

From the comparison of the cases with and without end block shown in Fig.9, the main difference is that there are one more shear stress peak near the back end with end block, and the bearing capacity of anchorage increases greatly, which is shown in Tab.2.

Tab.2 Influence of end block on anchorage at ultimate limit state

Anchorage form	With end block	Without end block
Maximum shear strain	0.200	0.259
Maximum displacement of bar [mm]	1.80	1.45
Bearing capacity of anchorage [kN]	620	349

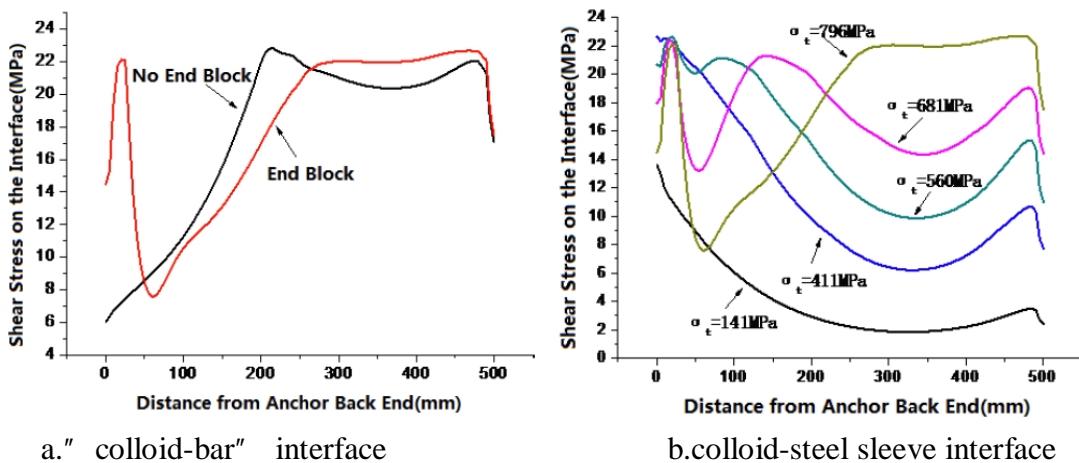


Fig.9 Influence of the end block

Seen from Fig.9b, under smaller tensile load, the shear stress distribution of "colloid-bar" interface with the end block is similar to that without end block. When the load increases to a certain value, the end block begins to play an important role, an stress peak appears near the back end and becomes clear with the load increasing.

Summary

Based on analysis of the above CFRP reinforced bonding anchorage, we draw the following conclusions:

The shear stress of " colloid-bar" interface near the front end of the anchorage increases as the tensile load increases, the shear stress peak appears first close to the back end of the anchorage, where plastic softening starts when the tensile force reaches to a certain level. Stress peak zone appears near the front end until the anchorage reaches the ultimate limit state.

The bearing capacity can not be improved efficiently only by increasing the length of the anchorage.

With the increasing of the colloid thickness, the displacement of CFRP bars increases too under the same load, but the bearing capacity of anchorage increases slowly. With the decreasing of the

elastic modulus of colloid, the bearing capacity of anchorage and the displacement of CFRP bars along the tension direction both correspondingly increase. The method of gradually increasing elastic modulus from back end to the front end can improve bearing capacity of anchorage and reduce displacement of CFRP bars at the same time.

The end block improves the bearing capacity of bonding anchorage. It is recommended that the grouted anchorage set end block, and the length of anchorage be 12~14 times of bars diameter, the thickness of colloid be 1/3~1/2 of tendons diameter.

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