IMPROVING THE LOAD TRANSFER AND EFFECTIVE BOND LENGTH FOR FRP COMPOSITES BONDED TO CONCRETE

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ABSTRACT Based on a series of pull-out bond tests of FRP composites/concrete interfaces, it was found that decreasing the shear stiffness (defined as the elasticity modulus divided by the thickness) of adhesive layers could obviously improve the ultimate transferable load of the FRP composites-concrete interfaces. Further clarifying the bond mechanisms of the interfaces shows that the improved interfacial performance is contributed by increasing the effective bond length l_e as well as by alleviating the stress concentration.
KEYWORDS: FRP composites/concrete interfaces, adhesives' shear stiffness, effective bond length, interfacial load transfer

1. INTRODUCTION

Premature debonding due to stress concentration is the main problem for the FRP composites strengthening technology. The fracture of FRP composites/concrete interfaces always happens due to stress concentration. The existence of effective bond length l_e results that the interfacial load can be transferred only in a limited bond distance. Plenty of works have been done to clarify the bond mechanisms of the interfaces in the past. Although different experimental or analytical results, such as the l_e in a large range (45~275mm)[1], were reported, it can be said that the interfacial failure mechanisms have been qualified clearly in some extent. However, only few solutions have been proposed to improve the interfacial behaviors through the performance-based optimization of the interfacial materials, especially the adhesives, probably because the adhesives available commercially at present have almost the same properties. Recently, experiments on RC beams strengthened with FRP composites using soft adhesive layers have been reported for their good enhancing structural performances [2]. Herein it is necessary to understand the interfacial behaviors, such as the load transfer and the effective bond length for this new type of FRP composites/concrete interfaces containing adhesives layer with low elasticity modulus firstly. The purposes of this study are to use adhesive layers with low shear stiffness to improve the FRP composites/concrete's interfacial performances as well as clarify the improving mechanisms.

2. EXPERIMENTAL OUTLINE

2.1 EXPERIMENTAL SETUP

A pull-out bond test setup (see Fig.1) was applied in this study. The width of FRP composites in the study was 10cm. The bond length of 33cm was applied to observe the whole peeling-off procedures. Strain gages with the interval of 1.0cm were arranged along the surfaces of FRP composites to observe the local bond behaviors.

2.2 BONDING

The sheet bonding system was applied here, whereas resins used for the matrixes of FRP sheets and the bond layers were different because it was found in the authors' previous study [3] that the low Young's modulus resins as the matrix of FRP sheets decreased the strength of FRP composites harmfully. Primer was used for all specimens in order to avoid the concrete-adhesive interfacial failure.

2.3 EXPERIMENTAL MATERIALS

The material properties of FRP and adhesives are shown in Tables 1 and 2 respectively.

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Table 1 Mechanical properties of FRP materials

Fiber	Type	f_t(MPa)	E_f(GPa)	t (mm)	ε_u (%)	ρ(g/m^2)
Carbon	FTS-C1-20	3550	230	0.11	1.5	200
Glass	FTS-GE-30	1550	74.0	0.118	2.1	300
Aramid	AT-40	2520	83.6	0.223	4.6	308
	AT-90	3030	83.6	0.381	2.4	530

Note: f_t, E_f, t, ε_u, and ρ are the tensile strength, elasticity modulus, design thickness, elongation and area weight of FRP sheets respectively.

Table 2 Mechanical properties of adhesives

Adhesives	Mixing ratio by weight	Compressive modulus (GPa)	Tensile strength (MPa)
CN-100	1:1	0.35	13.0
SX-325	2:1	1.8	22.5
FR-E3P	2:1	3.17	29

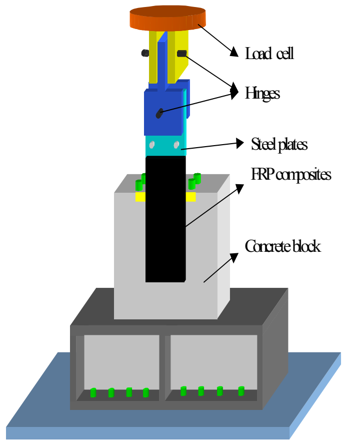


Fig.1 Test setup

2.4 SPECIMENS DETAILS

In this study 26 specimens included in four series were tested as shown in Table.3. Experimental results of series 2 are from the authors' previous study [3].

Table 3 Details of specimens and test results

Series	FRP type	$f_c^{'}$ (MPa)	Specimens code	$E_f t_f$ (GPa·mm)	L_b (mm)	P_u (kN)	σ_f (GPa)	Failure type
1	CFRP	35	CR1L1T1	25.3	330	27.0	2455	Concrete failure
			CR1L2T1	50.6	330	40.2	1827	Concrete failure
			CR1L3T1	75.9	330	42.9	1300	Concrete failure
			CR2L1T1	25.3	330	30.5	2772	Concrete failure
			CR2L2T1	50.6	330	51.0	2318	Concrete failure
			CR2L3T1	75.9	330	47.4	1436	Concrete failure
			CR3L1T1	25.3	330	31.8	2891	FRP fracture
			CR3L2T1	50.6	330	51.0	2318	FRP fracture
			CR3L3T1	75.9	330	64.8	1964	Concrete failure
2	CFRP	33.1	CR1L1T1	25.3	210	24.5	2231	Concrete failure
			CR1L1T2	25.3	210	31.1	2831	FRP fracture
			CR1L1T3	25.3	210	24.5	2231	Concrete failure
			CR1L2T1	50.6	210	33.5	1525	Concrete failure
			CR1L3T1	75.9	210	35.4	1073	Concrete failure
			CR1L3T2	75.9	210	50.4	1527	Concrete failure
			CR1L3T3	75.9	210	33.0	100	Concrete failure
3	GFRP	35	GR1L1T1	8.7	330	15.6	1320	FRP fracture
			GR1L3T1	26.2	330	28.6	806.8	Concrete failure
			GR2L3T1	26.2	330	32.7	923	Concrete failure
			GR3L3T1	26.2	330	41.0	1159	FRP fracture
			GR1L5T1	43.7	330	33.4	565	Concrete failure
4	AFRP	35	AR1L1T1 (AT-40)	18.6	330	25.5	1143	Concrete failure
			AR1L1T1 (AT-90)	31.9	330	33.6	882	Concrete failure
			AR1L2T1 (AT-90)	63.7	330	39.9	525	Concrete failure
			AR2L2T1 (AT-90)	63.7	330	47.1	618	Concrete failure
			AR3L2T1 (AT-90)	63.7	330	60.9	799	Concrete failure

Note: $f_c^{'}$, L_b, P_u and σ_f are concrete compressive strength, bond length, the ultimate interfacial load and the tensile strength of FRP sheets at ultimate load level.

*R*L*T* ——Adhesive thickness(not including primer);1,2 and 3 mean 1,2.0 and 0.5mm respectively

——The number of the FRP sheets' plies

——Adhesive type; 1,2 and 3 mean FR-E3P, SX-325 and CN-100 respectively

——FRP type, C, G and A mean carbon, glass and aramid respectively.

3. DISCUSSION ON EXPERIMENTAL RESULTS

3.1 ULTIMATE INTERFACIAL LOAD AND BOND FAILURE DESCRIPTIONS

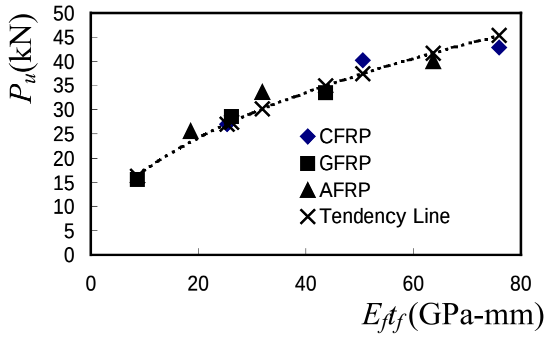


Fig2.1 Effects of the FRP stiffness on the ultimate interfacial load

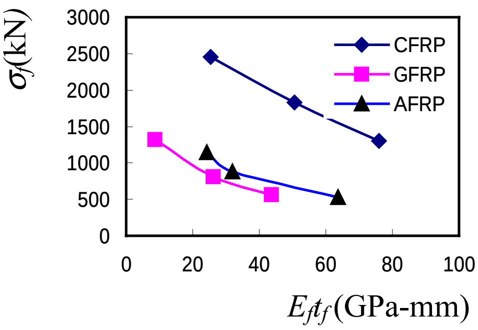


Fig2.2 Effects of the FRP stiffness on the tensile strength of FRP composites at debonding

The ultimate interfacial loads and the tensile stresses of FRP materials at debonding load level are listed in Table 3. For any type of FRP, it can be seen that the ultimate interfacial load increases with the FRP stiffness. And the ultimate loads can be regressed on one tendency line (see Fig2.1) regardless of the types of FRP, indicating that the ultimate interfacial load is only dependent on the stiffness of FRP composites and independent of the FRP types. The tensile stresses in FRP composites at bond failure decrease with the increasing of the FRP stiffness (see Fig2.2), meaning that the efficiency of FRP strength decreases. While decreasing the shear stiffness of adhesive layers through either decreasing the elasticity modulus or increasing the thickness can improve the ultimate interfacial load (see Fig.3 and Fig.4 respectively). Two failure types, FRP fracture and concrete surface bond failure were observed. The FRP fracture happened in three cases: (1) FRP composites with low stiffness (one layer of GFRP sheet); (2) 2mm thick adhesives with one layer of CFRP sheet; (3) adhesives of low elasticity modulus with one layer of CFRP and three layers of GFRP sheets, which show that using low shear stiffness adhesives can change the bond failure type from the concrete surface failure to FRP fracture one when the FRP stiffness is fairly small. The same experimental observation was reported in beam tests [2]. Meanwhile, in the cases of higher FRP stiffness, the efficiency of FRP composites is improved by using the adhesives with lower shear stiffness (see Fig.3)

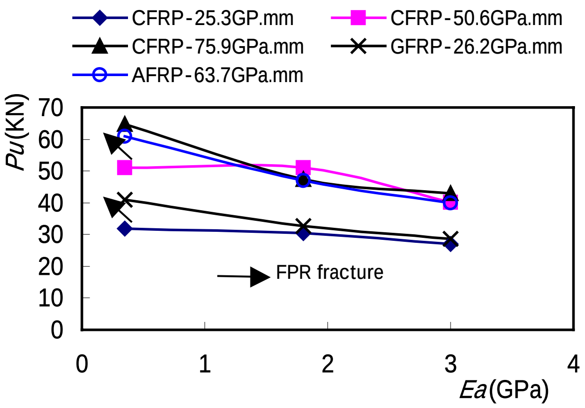


Fig.3 Effects of adhesives' elasticity modulus

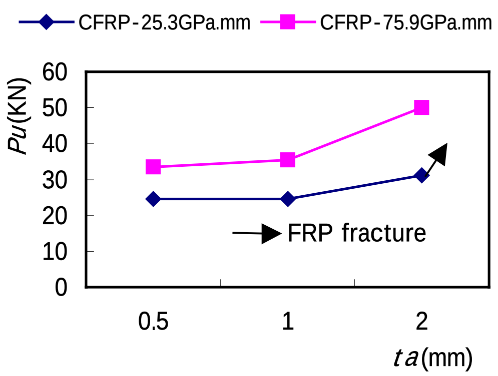


Fig.4 Effects of adhesives' thickness

3.2 LOAD-SLIP RELATIONSHIPS

Fig.5.1 to Fig.5.4 show the load-slip relationships of the specimens in four test series. The slips at loading points of bond areas were obtained through integrating the strains measured on the surfaces of the FRP composites with the interval of 1cm. With a few exceptions (the cases of FRP fracture), all load-slip curves show some ductility. Generally, the maximum value of the slips can reach 1.5~3mm. However, the reasons of the ductility are different in different cases. Generally, the load-slip curves can be divided into three stages: the linear stage till the initial peeling-off, the nonlinear or concrete softening stage, in which the pull-out loads can continue to increase till the maximum value, and the descending or peeling-off developing stage. When adhesives FR-E3P and SX-325 were used, before the third stage, big noise was always heard and the peeling-off shifted to the end zone of the bond length very quickly, resulting in big slips and the decreasing pull-out loads. At this moment if the bond length is not long enough the third stage will be finished quickly. In this study, a longer bond length was applied so that it was possible to follow the descending branch of the load-slip curves. After a fairly quick developing of the peeling off, the remaining bond length could still undertake the corresponding pull-out load. However, when the low shear stiffness adhesives CN-100 was used, no quick peeling-off phenomenon was observed. The load and slip increases linearly till the ultimate slip or the FRP fracture (see Fig.5.1, Fig.5.3 and Fig.5.4) due to the smooth strain distribution and wide range bond stress distribution, which make the effective bond length close to the test bond length. (see Fig.6.1,Fig.7, and Fig.10).

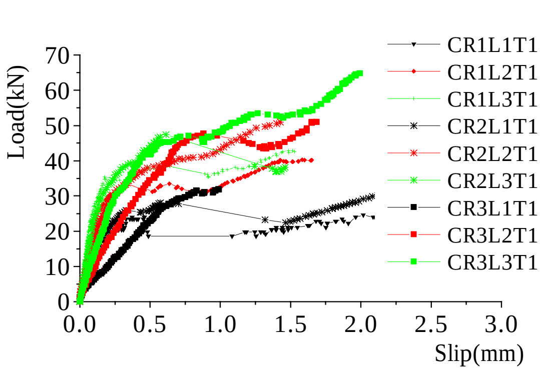


Fig.5.1 Load-slip curves of Series 1 speicmens

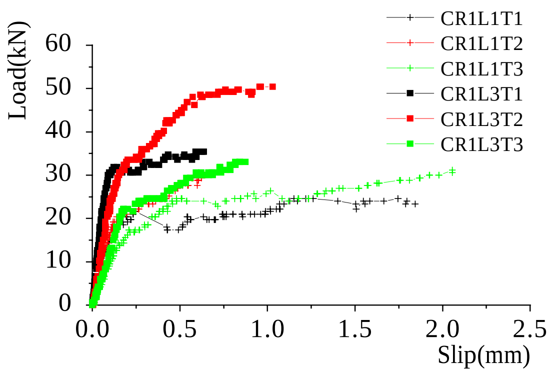


Fig.5.2 Load-slip curves of Series 2 speicmens

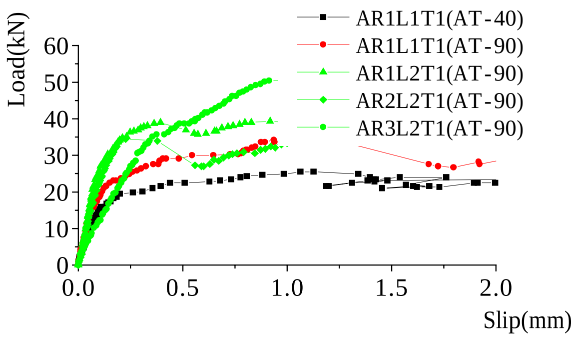


Fig.5.3 Load-slip curves of Series 3 speicmens

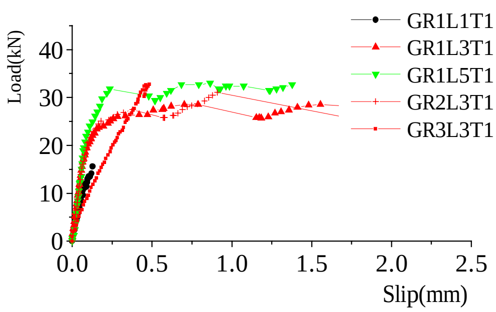


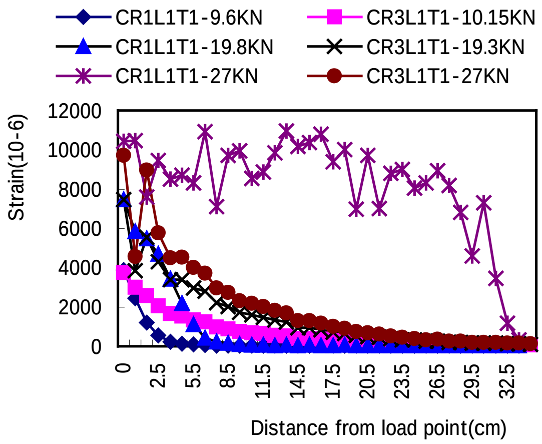
Fig.5.4 Load-slip curves of Series 4 speicmens

3.3 INTERFACIAL STRAIN AND STRAIN DISTRIBUTION

Figures 6.1 and 6.2 indicate the strain distributions of CFRP composites/concrete interfaces with the different adhesives and different FRP stiffness. Comparing the specimens CR1L1T1 (with adhesives FR-E3P) and CR3L1T1 (with adhesive CN-100) (see Fig.6.1), it can be seen that using low elasticity modulus adhesives CN-100 makes the value of strain distribution gradient $d\varepsilon_x / dx$ much smaller. The load transfer length (supposed to be the distance from the initial load point of bond area to the point with very small strain) is increased obviously. Comparing the specimens CR1L1T1 (with 1 layer of FRP sheet) and CR1L3T1 (with 3 layers of FRP sheets), increasing the FRP stiffness makes the $d\varepsilon_x / dx$ smaller as well at a given load level, however, the load transfer length has very small change (see Fig.6.2).

As a result of the smooth strain distribution contributed by the low shear stiffness of adhesives, the interfacial bond stresses could be distributed along a longer bond length. Fig.7 shows a comparison of the local bond stress distributions between specimen CR1L1T1 (with adhesive FR-E3P) and CR3L1T1 (with adhesive CN-100). Obviously using the low shear stiffness adhesives CN-100 makes the bond stress distribute in a much wider distance along the loading direction. And also, it can been seen in Fig.7 that the peeling off of specimen CR1L1T1 shifted quickly toward the load-free end with the little increasing of the pull-out load. Comparatively, the peeling-off procedure of specimen CR3L1T1 developed smoothly and was terminated by the fracture of FRP composites.

3.4 MAXIMUM BOND STRESS AND THE EFFECTIVE BOND LENGTH



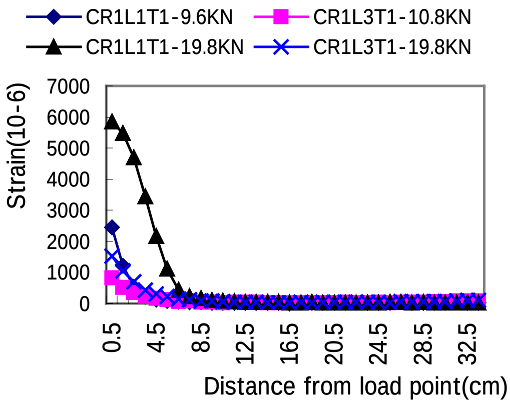
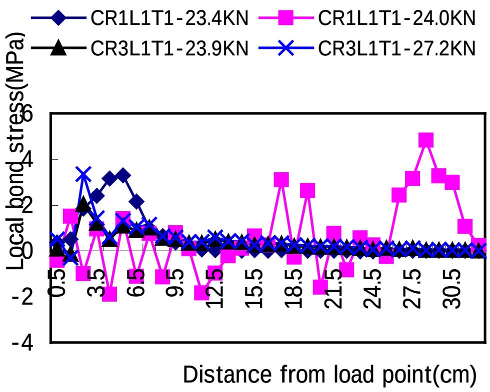


Fig6.1 Strain distribution affected by the adhesives **Fig6.2 Strain distribution affected by FRP stiffness**



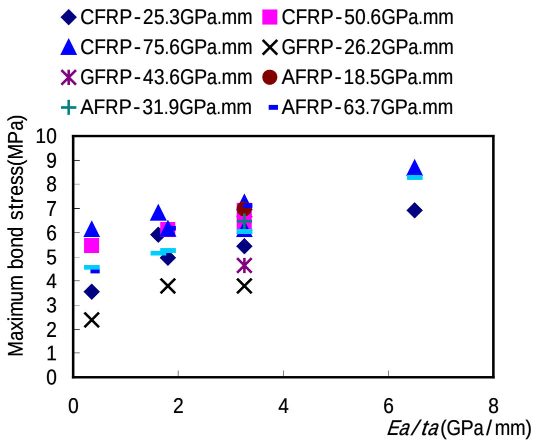


Fig.7 Adhesives' effects on bond stress distribution **Fig.8 Adhesives' shear stiffness' effects on bond stress**

In general, the local interfacial bond stress can be obtained from the following equation:

$$\tau_x = E_f t_f \cdot d\varepsilon_x / dx \tag{1}$$

When low shear stiffness adhesives are used, the decreasing $d\varepsilon_x / dx$ and constant $E_f t_f$ make the local bond stress be decreased at a given load level. When the stiffness of FRP composite is increased, the $d\varepsilon_x / dx$ is decreased as well, however, its effects on local bond stress will be different because the value of $E_f t_f$ is increased as well. As it is widely known, the interfacial peeling-off is caused by a thin concrete surface failure. Therefore, the concrete strength would be the main factor, which affects the maximum bond stress. It was found in this study that the maximum bond stress is influenced by the shear stiffness of adhesives for the cases of concrete failure, in which the concrete strengths were same (see Fig.8). And also, it can be seen from Fig.8 that the higher FRP stiffness results in higher maximum bond stress as other researchers reported [4,5]. When CFRP and GFRP composites with the same stiffness were applied, in which the thickness and the elasticity modulus of FRP composites were different, the observed ultimate interfacial loads are almost same (see Fig.2.1). Whereas the maximum bond stresses show some differences between the cases. At present, it is difficult to quantify the relationships among the maximum bond stress and all test variables, as well as the different locations along the pull-out direction or different loading boundary conditions [6]. Further detailed study should be carried out to clarify the reason why the same type of concrete failure causes different ultimate bond stresses.

The wider strain or stress distribution could be described quantitatively using the effective bond length. Figure 9 indicates the definition of the effective bond length, which is recommended by JCI TC952 [7]. Through that, the effective bond length can be obtained from the observed local bond stress distribution of each specimen. The calculated effective bond lengths from the experimental results are shown in Fig.10. It can be seen that the effective bond length increases from from10 to 25cm when the shear stiffness decreases from 3.0 to 0.35GPa/mm. Whereas, the FRP stiffness has less effect on the effective bond length than the adhesives do. Here it should be noted that improving the effective bond length has effects on both sides. One of them is the enhancement of the ultimate load transfer. The other one is that the longer anchorage length is needed to ensure the expected pull-out length. It can be seen with the increasing of thickness (CR1L1T1 and CR1L3T2 in Fig.5.2), especially with the decreasing of elasticity modulus (CR3L1T1, CR3L2T1, CR3L3T1 in Fig.5.1, AR3L2T1 in Fig.5.3 and GR3L3T1 in Fig.5.4) of adhesive layers, the initial stiffness of load-slip curves is decreased. That means that, to reach same strengthening effects, the actual structure elements should be permitted to have larger deformation due to larger slip in comparison with the cases of using normal adhesives. It has been found that increasing the thickness of adhesives (with the elasticity modulus of 1MPa) only takes into effects when the thickness is smaller than a specific value in the case of beam strengthening [2], which means that decreasing the shear stiffness should have a lower limit. Therefore using adhesives with low shear stiffness is a selectable way for the interfacial design and should be optimized based on structural performances.

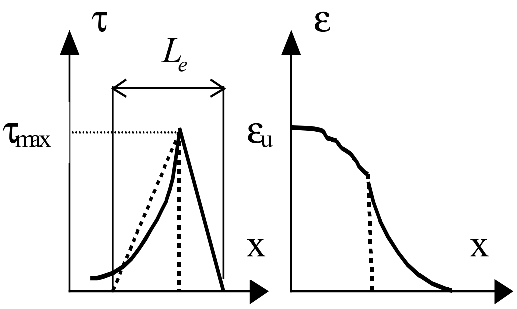


Fig.9 Definition for the effective bond length

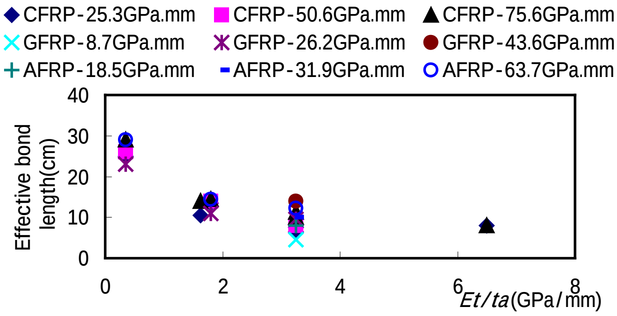


Fig.10 Adhesives' effects on the effective bond length

4. CONCLUSIOINS

Through the experimental work in this study, the following conclusions can be drawn up:

1. Using adhesives with low shear stiffness, which is introduced by either increasing the thickness or decreasing of the elasticity of adhesives, can improve the ultimate load transfer ability of FRP composites/concrete interfaces.
2. Decreasing the shear stiffness of adhesives reduces the interfacial strain distribution gradient as well as increases the effective bond length significantly. Increasing the FRP stiffness also leads to smaller strain gradient but has comparatively less improvement on the effective bond length.
3. Different from increasing the FRP stiffness, decreasing the shear stiffness of adhesives leads to lower interfacial maximum bond stress, although both ways increase the ultimate load transfer. In actual structural strengthening, decreasing the shear stiffness of adhesives should have a lower limit based on the analysis of overall structural performance to reach optimum interfacial design.

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