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Bonding between high strength rebar and reactive powder concrete

Deng Zong-cai[*1], Jumbe R.Daud[2a] and Yuan Chang-xing[3b]

The Key Laboratory of Urban Security and Disaster Engineering, Ministry of Education, Beijing University of Technology, Beijing 100124 China

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Abstract. A central pullout test was conducted to investigate the bonding properties between high strength rebar and reactive powder concrete (RPC), which covered ultimate pullout load, ultimate bonding stress, free end initial slip, free end slip at peak load, and load-slip curve characteristics. The effects of varying rebar buried length, thickness of protective layer and diameter of rebars on the bonding properties were studied, and how to determine the minimum thickness of protective layer and critical anchorage length was suggested according the test results. The results prove that: 1) Ultimate pull out load and free end initial slip load increases with increase in buried length, while ultimate bonding stress and slip corresponding to the peak load reduces. When buried length is increased from 3d to 4d(d is the diameter of rebar), after peak load, the load-slip curve descending segment declines faster, but later the load rises again exceeding the first peak load. When buried length reaches 5d, rebar pull fracture occurs. 2) As thickness of protective layer increases, the ultimate pull out load, ultimate bond stress, free end initial slip load and the slip corresponding to the peak load increase, and the descending section of the curve becomes gentle. The recommended minimum thickness of protective layer for plate type members should be the greater value between d and 10 mm, and for beams or columns the greater value between d and 15 mm. 3) Increasing the diameter of HRB500 rebars leads to a gentle slope in the descending segment of the pullout curve. 4) The bonding properties between high strength steel HRB500 and RPC is very good. The suggested buried length for test determining bonding strength between high strength rebars and RPC is 4d and a formula to calculate the critical anchorage length is established. The relationships between ultimate bonding stress and thickness of protective layer or the buried length was obtained.

Keywords: HRB500 rebar; reactive powder concrete; bonding; critical anchorage length

1. Introduction

Reactive powder concrete (RPC) is a new building material with high-strength, good crack resistance, high toughness and good durability, a promising future material of high performance cement-based composites (Roux *et al*. 1996, Liu *et al*. 2009). When high strength reinforcement steel rebar is used along with RPC, the excellent performance such as high strength of both

∗Corresponding author, professor, E-mail: dengzc@bjut.edu.cn
[a]Ph.D. Student
[b]Ph.D. Student

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materials will be utilized, and would significantly improve the safety and durability of the structure, economize steel and enhance construction low-carbon buildings. The articles (Saleem 2012, Harajli 2004, Mahesh 2012, Toree 2013, Yeih 1997, Victor 2009) investigate interfacial bonding properties between high strength reinforcement steel rebar and ordinary strength concrete or high strength concrete; articles (Mingji and Meng 2007, Mahesh *et al*. 2010, Richard *et al*. 2011) compares the interface bonding properties between RPC and ordinary strength rebar or fiber reinforced polymer (FRP), but the articles on researches revolving around bonding properties between high strength steel rebar and RPC have not yet been covered by most researchers.

The effects of steel rebar diameter *d*, the thickness of the protective layer C, and rebar buried length l on the bonding properties are covered in this research. A reasonable buried length for specific bonding strength and the minimum thickness of the RPC specimens' protective layer are suggested in this article. The critical anchorage length formula, the relationships between the ultimate bond stress and thickness of the protective layer or the buried length were established herein. All these will provide a reference for engineering application and structural design.

2. Experiment introduction

2.1 Test materials and performance

HRB500 high-strength steel rebar was from Hebei Iron and Steel Group; rebar diameter and strength listed in Table 1.

The mixing ratio of RPC: cement 705.0kg/m^3, slag 471.0kg/m^3, quartz sand 1070.5kg/m^3, steel fiber 157kg/m^3, water 167.7kg/m^3 and admixture 60.1kg/m^3. Steel fiber length is 13 mm, diameter 0.22 mm, tensilze strength 2800MPa. Six cubic specimens, three of side 70 mm for measuring the compressive strength and three of side 150 mm to measure the split tensile strength, were prepared under the same conditions as the pull out specimens, where the average compressive strength was 147.1MPa and split tensile strength 19.8MPa.

Table 1 Diameter and strength of rebars

Diameter /mm	Rebar yield strength/MPa	Rebar ultimate strength/MPa
8	588.0	736.0
10	576.0	738.9
16	566.7	682.0
18	589.4	712.0

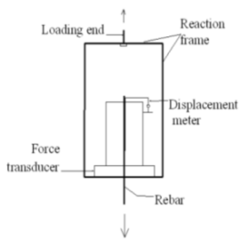


Fig. 1 Schematic representation of pull-out test setup

Fig. 2 Photo of test set-up

2.2 Specimen

Specimens listed in Table 2 are divided into two categories according to the aim of the tests. (1) influence of buried length of rebar group: the letters represent the form of specimens (L represents standard cubic specimens of side 150 mm, Z represents the central pullout test) and the first number after "-" represents rebar diameter, the number after the second "-" represents buried length of rebar. i.e., LZ-16-48 is central pullout test of cubic specimen with diameter 16 mm and buried length 48 mm. (2) Influence of thickness of the protective layer group: NZ represents prismatic specimen central pullout test, BZ represents plate type specimens central pullout test. The number after the first "-" represents rebar diameter, the number after the second "-" represents thickness of protective layer yet, i.e., LZ-16-32 is central pullout test 80 mm × 80 mm ×150 mm prismatic specimen, rebar diameter 16 mm, thickness of the protective layer 32 mm; BZ-8-6 represents plate type central pullout test specimen of length 150 mm, width 150 mm and thickness 20 mm, rebar diameter 8 mm and thickness of protective layer 6 mm.

2.3 Testing method

All specimen were cast once, specimen's top molding surface set parallel to the rebar axis, rebar are horizontally placed in the mould, the rebar and PRC are separated from each other by using a plastic sleeve at a certain length from the two ends of the templates, in order to avoid local compressive damage of RPC specimen at the loading side.

The specimen is placed on the shaking table for 2 minutes, then removed and wrapped with plastic film, placed in constant temperature and humidity curing room for two days, then dismantled from the moulds and cured for 1 day at room temperature, lastly steam cured for one day at 60℃ and next two days at 90℃. Figs. 1 and 2 show, the displacement sensor fixed to the free end of rebar to measure the relative slip between rebar and RPC, the load-displacement meter is for the correction of amount of slip at the free end. The pullout test is carried out using 1000kN hydraulic universal testing machine and test data was recorded by DH3815N static data acquisition system.

3. Test results analysis

The pullout test results are shown in Table 2, where F_{cr} is the free end initial slip load, s_u is the slip of the free end corresponding to the first peak load, and ω is volume fraction of steel fibers. The ultimate bonding stress between rebar and RPC is calculated as follows

$$\tau_m = \frac{F_u}{\pi dl} \quad (1)$$

where: F_u is ultimate pullout load value (kN), τ_m is the ultimate bonding stress (MPa), d rebar diameter (mm), l is buried length of rebar (mm)

3.1 Effect of rebar buried length on the bonding properties

Buried length directly influences the bond stress distribution between rebar and RPC and the pull-out failure mode. The load-slip curves are shown in Fig. 3.

Figs. 3(a) and (b) shows, as buried length increases from 3*d* to 4*d*, pullout load after the peak decreases faster, then increases again. Later load reaches secondary peak, which is higher than the first peak load, and the slip corresponding to the second peak load is bigger, therefore the first peak load is defined as ultimate load.

When the diameter remains constant, changing rebar buried length from 3*d* to 4*d*, the load-slip curves descend steeply at the descending stage, but later the load increases and the curve ascends again. The “gripping effect” between the rebar ribs and RPC undergoes local damage from the loading end to the free end. Stress distribution is uneven, since the tensile stress of rebar is slowly transferred from the pulling end towards the free end. Once the stress is evenly distributed in the rebar, stress redistribution effect causes the load to increase thus the curve rises again.

After the peak load, local damage increases until it causes block failure, the bond stress between rebar and RPC decreases. The longer the buried length, the more uneven bond stress becomes, and the longer the time of uniform stress redistribution process takes, which causes the post-peak pullout load to decrease more significantly. After the load decrease, the bond stress gets redistributed more evenly along the rebar, which makes the pullout load to increase again.

From Table 2 we see: (1) when the buried length is 3*d*, 4*d*, the rebar were pulled out; when buried length is 5*d*, rebar exhibit tensile fracture failure. (2) For the same rebar diameter, increasing buried length leads to increase in the free end initial slip load F_{cr}, while the free end slip s_u corresponding to ultimate load F_u decreases. This is because pullout load is transferred from the loading point to the free end. The longer the rebar buried length, the longer the load transfer path from the loading end to the free end. When the buried length increases, the free end initial slip load F_{cr} increases. As the free end begins to slip, the RPC between the rebar ribs is not completely damaged, the load is borne by the rebar throughout the buried length. F_{cr} / F_u increases with increase in buried length, and the free end initial slip increases faster from zero to s_u, so the cumulative value of s_u in this process decreases.

For the same diameter of rebar, although the pullout load increases with buried length, the ultimate bond stress decreases, as seen in LZ-18 specimens, where pullout ultimate load increased by 2.5% when buried length increased from 3*d* to 4*d*, but the ultimate bond stress reduced by 30%.

By integration of the balance equation $\tau + \frac{d}{4}\frac{d\sigma_s}{dx} = 0$ (Along the rebar buried length direction),

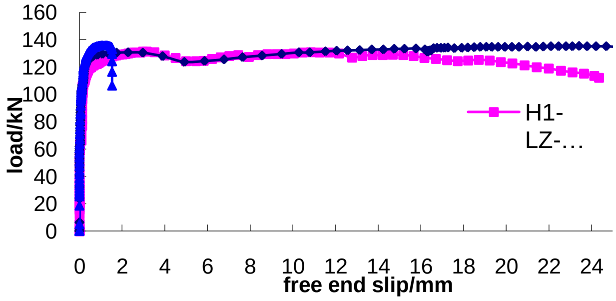
Table 2 Pull-out test results

Specimen no	l /mm	F_u /kN	τ_m /MPa	F_{cr} /kN	s_u /mm	ω /%	Failure mode
LZ-8-24	30	37.8	50.2	28.6	0.38	2	Pull off
LZ-10-30	30	51.7	54.9	24.0	1.52	2	Pull off
LZ-16-48	48	135.4	56.1	63.0	1.96	2	Pull out, vertical cracks
LZ-16-48	48	115.0	47.7	59.9	2.33	2	Pull out
LZ-16-48	48	131.0	54.3	70.2	3.15	2	Pull out, vertical cracks
LZ-16-64	64	136.3	42.4	101.3	1.04	2	Pull out, vertical cracks
LZ-16-64	64	136.1	54.3	111.3	1.24	2	Pull out, vertical cracks
LZ-16-64	64	141.0	43.9	109.0	1.11	2	Pull out, vertical cracks
LZ-16-80	80	137.1	34.1	-	-	2	Pull out, vertical cracks
LZ-16-80	80	132.8	33.0	120.3	0.02	2	Pull out,splitting
LZ-16-80	80	141.7	35.3	-	-	2	Pull off
LZ-18-54	54	170.0	55.7	102.6	1.87	2	Pull out, vertical cracks
LZ-18-54	54	168.5	55.2	89.0	1.96	2	Pull out, vertical cracks
LZ-18-54	54	164.8	54.0	29.9	2.01	2	Pull out, vertical cracks
LZ-18-72	72	172.5	42.4	141.6	1.81	2	Pull out, vertical cracks
LZ-18-72	72	170.0	41.8	118.4	1.62	2	Pull out, vertical cracks
LZ-18-72	72	173.2	42.6	125.9	1.71	2	Pull out, vertical cracks
LZ-18-90	90	181.0	35.6	162.4	0.55	2	Pull off
LZ-18-90	90	178.5	35.1	158.7	0.1	2	Pull off
LZ-18-90	90	182.7	35.9	180.6	0.02	2	Pull off
NZ-16-12	48	75.0	31.1	36.4	-	2	Pull out, splitting
NZ-16-22	48	86.8	36.0	38.7	0.16	2	Vertical through cracks
NZ-16-32	48	101.0	41.9	43.6	0.38	2	Pull out, vertical cracks
NZ-16-42	48	115.0	47.7	79.9	0.42	2	Pull out, vertical cracks
NZ-16-52	48	117.6	48.8	80.6	1.37	2	Pull out, vertical cracks
NZ-16-62	48	127.3	52.8	64.3	1.23	2	Pull out, vertical cracks
BZ-8-6	40	33.6	33.4	-	1.4	2	Pull out, scraped damage
BZ-8-8	40	35.2	35.0	-	-	2	Pull out, scraped damage
BZ-8-11	40	36.0	35.8	-	-	2	Pull out
BZ-10-10	50	49.8	31.7	-	-	2	Pull out,
BZ-10-12	50	53.0	33.8	-	-	2	Pull out, annular cracks
BZ-10-15	50	55.8	35.5	-	-	2	Pull out

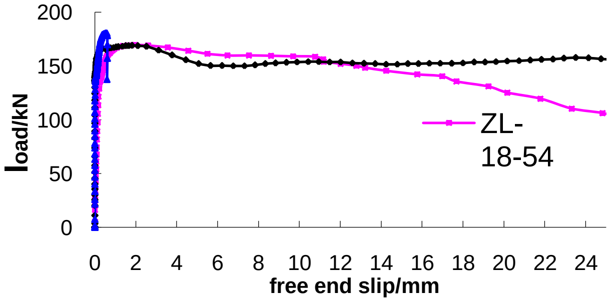
we get $\tau = \sigma_s(0)\dfrac{d}{4l}$, where $\sigma_s(0)$ is the rebar stress at the loading end, indicating that the ultimate bond stress and rebar buried length are inversely proportional, which is almost a linear relationship. From the experimental statistical regression we obtain

$$\frac{\tau_m}{f_{t,s}} = -0.46\frac{l}{d} + 4.51 (R^2 = 0.96) \tag{2}$$

where τ_m is the ultimate bond stress; $f_{t,s}$ is RPC splitting tensile strength; l is rebar buried length; d is rebar diameter.



(a) LZ-16



(b) LZ-18

Fig. 3 Load-slip curves for different rebar buried lengths

3.2 Effect of thickness of the protective layer on the bonding properties

Two types specimen were prepared to investigate the effect of thickness of the protective layer on the bonding properties. (1) Central pullout experiment on prismatic specimens to determine the relationship between thickness of the protective layer and the ultimate bond stress. (2) Central pullout test on plate-type specimens to determine the minimum thickness of the protective layer. Minimum thickness of the protective layer is mainly to ensure that the rebar strength is completely utilized when working together with RPC. The plate type central pullout test specimens are used to determine minimum thickness of the protective layer before the specimen scrap or split, also ensure maximum utilization the strengths of rebar and RPC when working jointly.

3.2.1 Central pullout test of prismatic specimens

7 groups of prismatic type central pullout specimens were prepared, where diameter of rebar is 16 mm, buried length 48mm, variable parameter is thickness of the protective layer, from 12mm to 67 mm. Test data and failure modes are all shown in Table 2, central pullout load-slip curves are shown in Fig. 3, where overall splitting occurs for specimen NZ-16-22 since the protective layer thickness is too small, and the descending segment of the curve is not abstained.

From Table 2 and Fig. 4, it's observed that increase in the thickness of protective layer leads to increase in F_{cr} and S_u, the descending segment of load-slip curve becomes gentler. The different segments of the descending section are: (1) a smaller thickness of the protective layer c < 32 mm,

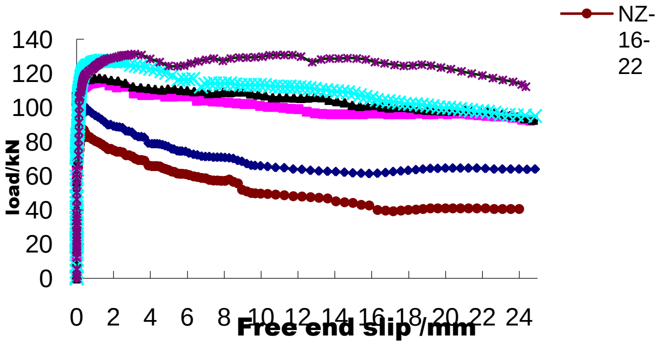


Fig. 4 Load-slip curves for different thicknesses of protective layer

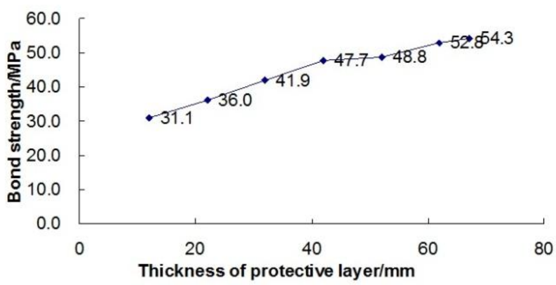


Fig. 5 Bond stress-protective layer relationship

(as in specimen NZ-16-22, NZ-16-32), after the peak load, load-slip curve descending segment becomes steep as load decreases rapidly. When the free end slip reaches 2 mm, the loads of the two specimens decrease by 14.3% and 11.9% respectively. (2) Moderate thickness of protective layer 42 mm < c < 52 mm (specimens NZ-16-42, NZ-16-52 and NZ-16-62), the effect of thickness of protective layer on the load-slip curve is small, the load-slip curves are similar, and after peak load the curve descends slowly. (3) For larger thickness of the protective specimens(such as LZ-16-48), after peak load, load-slip curve descends slightly; the free end slip reaches 5.7 mm, and the load begins to increase again and the curve ascends; when the free end slip exceeds 18 mm, the load begins to decrease.

The failure mode of cubic central pullout specimens group is shown in Table 2. When c > 22 mm, the specimens do not undergo splitting failure, but cracks form inside the specimen along the rebar extending towards the outside, crack width decreases with increase in thickness of the protective layer, cracks do not penetrate to the outer surface of the specimen. When c > 42 mm, cracks do not extend to the specimen surface but only develop around the rebar. Increasing thickness of the protective layer leads to decrease in the number of cracks and crack width. When thickness of the protective layer is small, cracks appear more easily because during rebar pull out, tension is borne by the friction between the rebar ribbed surface and RPC, thus the ribs exert pressure on RPC, causing tensile stress in RPC. When the split stress exceeds RPC tensile strength, radial cracks form along the rebar extending to the surface of the specimen. When c is increased, the number of cracks decrease. The reason for reduced crack width is, increased thickness of the protective layer increases the RPC confinement effect on the rebar, thus preventing the development of internal cracks, hence improved crack resistance of the specimen.

From Fig. 5, it is observed that for constant rebar diameter, increasing thickness of the protective layer significantly improves the ultimate bond stress, due to enhanced confinement effect of the rebar by RPC. When thickness of protective layer is increased from 12 mm to 42 mm, where ultimate bond stress τ_m increases by about 15.3% . When c is increased from 42 mm to 52 mm, τ_m only increases by 2.3%; c increased from 52 mm to 62 mm, τ_m approximately increases by 8.2%; c increased from 62 mm to 67 mm, τ_m only increases by 2.9%. When c reaches 42 mm, further increase in c makes the slope of the τ_m-c curve become more gentle, degree of increase in ultimate bond stress reduces, which means that increasing thickness of protective layer inhibits the effectiveness of increasing ultimate bond stress. Based on the experimental data, a statistical regression relationship is obtained

$$\frac{\tau_m}{f_{t,s}} = -0.05\left(\frac{c}{d}\right)^2 + 0.58\left(\frac{c}{d}\right) + 1.15 \qquad c/d < 5 \qquad (R^2 = 0.99) \tag{3}$$

where *c* is the thickness of the protective layer.

3.2.2 Plate type axial pull-out test

Plate type central pullout specimens: rebar buried lengths are all 5*d*. When rebar diameter is 8 mm, the thickness of the protective layer 6 mm, 8 mm, 11 mm; when diameter is 10mm, the thickness of protective layer 10 mm, 12 mm, 15 mm.

Pullout test for BZ-8 group specimens: specimens with 11 mm thickness of protective layer exhibit higher ultimate pull out load more than that of 6 mm thickness specimens by 7.1%. BZ-10 specimen group: specimens with protective layer thickness 15 mm improved ultimate pullout load by 12% more than that of 10 mm thick specimens. Two groups specimen thickness of the protective layers increased by 5 mm, but since the *c/d* of 8mm rebar diameter specimens is from 0.75 to 1.38 and *c/d* of 10 mm rebar diameter specimens is from 1 to 1.5, the degree of load increment by the latter is higher than that of the former. This means that when $c \geq d$, increasing the protective layer thickness leads to more significantly improved load capacity, and the bonding performance of rebar and RPC is greatly improved. From the failure pattern it is observed that in BZ-8 specimen group, specimens with 6 mm and 8 mm thickness of protective layer exhibit scraping failure when the rebar are pulled out. The specimens crack along the longitudinal steel bars penetrating internally, resulting to internal damage of RPC and exposure of rebar. When c = 10 mm, no through cracks are observed on the specimen surface. For BZ-10 group specimens, $c \geq 10$ mm, rebar pulls out, annular cracks appear along the rebar but do not penetrate to extend through the specimen. According to the test results, the minimum thickness of protective layer should be greater than the rebar diameter.

Based on the above analysis, and in reference to China "Design of concrete structures", GB 50010-2010 [12], it is recommended that the minimum thickness of the protective layer c, of plate type members should be 10 mm, when d < 10 mm, or $c \geq d$, when $d \geq 10$ mm. Since the rebar diameter in column or beam is generally large and the failure model of prismatic type central pull-out specimen with c =12 mm is complete splitting, it is recommended that the minimum thickness of protective layer should be the greater value between d and 15 mm.

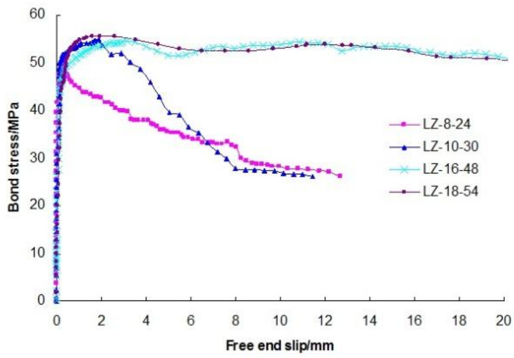


Fig. 6 Bond-slip curves of varying rebar diameters

3.3 Effect of rebar diameter on the bonding properties

When rebar buried length increases to 3*d*, the ultimate bond stress does not decrease with increasing diameter. From Fig. 6, bond stress at descending segment of bond-slip curve decrease slows with increase in diameter. When diameter $d \geq 16$ mm, post peak bond stress decreases slightly, and then increases again with increase in the amount of slip, but to a lesser extent. This shows that when rebar diameter is greater than 16 mm, bonding properties between high strength steel rebar and RPC are greatly improved.

4. Critical anchorage length

Steel rebar reaches the yield strength and the free end slip is zero, the corresponding buried length is defined as critical anchorage length.

Rebar yield tension force F_y is

$$\mathrm{F_y = f_y As = \frac{\pi d^2}{4} f_y} \tag{4}$$

The total bonding force at critical anchorage length is

$$F_\mathrm{m} = \pi d l_a \tau_u \tag{5}$$

With $F_\mathrm{y} = F_\mathrm{m}$, the critical anchorage length l_a is

$$l_a = \frac{f_y d}{4\tau_u} \tag{6}$$

where f_y is yield strength of HRB500, A_s is section-area of rebar, F_m total bond force at critical anchorage length, l_a critical anchorage length, τ_u bond strength.

In formula (6), influencing factors on τ_u are complex. From the data in Table 3, when rebar buried length is 4*d*, we can see that the free end initial slip load and rebar yield load are close (e.g. H2-LZ-16 and H2-LZ-18 specimens). When buried length is 4*d*, the load F_{cr} is more than 75% of the ultimate load F_u, which is close to or exceeds the yield load of HRB500, and further increase of buried length leads to slight decrease in τ_u, can be defined as the bonding strength between high strength rebar and RPC. The most appropriate buried length for measuring of bond strength between high strength steel rebar and RPC central pullout cubic specimens is 4*d*.

An appropriate value of τ_u is very important in the determination of l_a. Analyzing the data in Table 3, the suggested rebar buried length should not be less than 4*d*, the free end initial slip load should be greater than rebar yield load and the mean bond stress taken as bond strength. This is to guarantee the rebar reach yield load and the free end initial slip is zero. Calculation of critical anchorage length for each specimen is listed in Table 3.

In reference (GB 50010-2010), the critical anchorage length is calculated by the formula

$$l_a = 0.15\frac{f_y}{f_{t,s}}d \tag{7}$$

where *a* is rebar shape coefficient, f_t is RPC axial tensile strength.

Since measuring of the axial tensile strength of RPC is difficult, splitting tensile strength $f_{t,s}$ is used instead.

$$l_a = \alpha\frac{f_y}{f_{t,s}}d \tag{8}$$

RPC splitting tensile strength is 19.8MPa in this test. Having $\alpha = f_{t,s}/4\tau_u$ we get the approximate value of *a* as 0.13. For structural design, the yield strength f_y of HRB500 rebar is taken as 460MPa, which is less than the measured value, and for safety 0.15 is used as the value of *a*. Such that the formula for calculation critical anchorage length of HRB500 rebar and RPC is

$$l_a = 0.15\frac{f_y}{f_{t,s}}d \tag{9}$$

5. Conclusions

(1) Rebar buried length is the main factor that influences the bonding properties between high strength rebar and RPC. Increase in rebar buried length leads to increase in ultimate pull-out load F_u and the free end initial slip load F_{cr}, while ultimate bond stress τ_m and peak load slip s_u reduce. When buried length increases from 3*d* to 4*d*, load decreases faster after peak load, and then increases again. When buried length increases to 5*d*, the rebar exhibits pull fracture module.

(2) The central pullout test results of prismatic specimen show that: when the thickness of the protective layer is increased, the number of cracks and crack width reduce, load-slip curves descending segment becomes gentle, and F_u and s_u increase. The plate-type central pull-out test is used to determine the minimum thickness of the protective layer, and the protective layer thickness should be more than the rebar diameter, in order to guarantee good bonding between rebar and RPC.

(3) As rebar diameter increases, load-slip curve descending segment becomes gentle, then a secondary ascending segment appears when diameter exceeds 16 mm, the tension force can be maintained at a high level, which displays better performance of bonding properties.

(4) Compared with ordinary strength concrete, the load-slip curve of high strength rebar and

RPC, the ascending segment is quite steep while the descent stage is a little gentle.

(5) The relationships between $\tau_m / f_{t,s}$ and l / d, and $\tau_m / f_{t,s}$ and c / d were established through statistical analysis of the experimental data and the formula for critical anchorage length was suggested. The most appropriate buried length for the test measurement of bonding strength is 4*d*.

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