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Bond behavior of corroded reinforcing bar and ultra high toughness cementitious composites (UHTCC)

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ABSTRACT: Ultra High Toughness Cementitious Composites (UHTCC), featured with its strain hardening characteristic and outstanding crack controlling capacity under tensile conditions, could greatly enhance the durability of reinforced concrete structures and prolong the service life of infrastructures. By means of accelerated corrosion test and direct pull-out test, bond behaviors between corroded rebar and UHTCC with different corrosion ratios (from 0 to 5%) were investigated, did the same for corroded rebar and ordinary concrete while other conditions being the same. The average bond stress-slip relationship with different corrosion ratios were presented and simulated with a constitutive curve model, and fitted well. The relationship between maximum average bond stress and corrosion ratio indicated that the maximum average bond stress of rebar and UHTCC increased linearly before corrosion ratio up to 3%, then remained constant till to 5%, while the maximum average bond stress between rebar and concrete decreased rapidly when the corrosion ratio exceeded 2%. The results proved that UHTCC could still restrict the rebar under higher corrosion ratio.

1 INTRODUCTION

Ultra High Toughness Cementitious Composites (UHTCC) has been developed increasingly all over the world these two decades because of its unique strain hardening characteristic and excellent crack-controlled capacity. The applications of UHTCC have been grown rapidly with the mechanics principles and test methods of UHTCC driven to maturity stage (Xu S. & Li H. 2008). The combination of UHTCC and conventional building materials, such as concrete and reinforcing bar, could exert the advantages of each material at the structural level considering the optimization of function and cost. In the case of reinforced UHTCC, numerous multiple cracks of small width were formed due to its strain hardening behavior and compatible tensile deformation with steel (Zhang X. & Xu S. 2008). The constitutive relationship of bond stress and relative slip between reinforcing bar and concrete had been investigated by Xu S. & Wang H. (2008), providing the foundation for finite element analysis of reinforced UHTCC members or structures. Their bond behaviors determined the utilizing of the strength of UHTCC and reinforcing bar. Zhang X. & Xu S. (2008) investigated flexural performance of steel reinforced ultra high toughness cementitious composites (RUHTCC) beams through theoretical analysis and experiment. The results showed that UHTCC had good compatibility with reinforcing bar and RUHTCC beam could improve both flexural bearing carrying capacity and ductility index compared to controlled RC beams. What is more, the crack controlling capacity of UHTCC could improve the durability of structures with loading.

Corrosion of reinforcing steel bars is the main reason for deterioration of reinforced concrete structures or members in ingressive environment. Reinforcing steel bars embedded in concrete are usually protected against corrosion by high alkalinity of pore water around reinforcing bars because the steel bars' surface is passivated. However, the reinforcing bars are inevitably depassivated when the chloride ions concentration reaches threshold level in chloride environment or pH of pore water around steel bars drops below critical value due to carbonation. Once corrosion is initiated, active and continuous corrosion will result in concrete cover cracking, rusty spot, decreasing of bond between reinforcing bar and concrete, reduction of reinforcing bar's section, etc. These problems will bring out bearing capacity decreasing of RC structures or members, even give rise to integral structural failure (Auyueng Y. et al. 2000). Former researches revealed that the test values of RC members bearing capacity with corroded reinforcing bars were less than the calculated values only considering reinforcing bars section reduction and yield strength decreasing due to corrosion, so the bond characteristics between reinforcing bar and concrete have crucial effects on the bearing carrying capacity of RC structures or members when the reinforcing bars are corroded. UHTCC has been applied into new construction and for repair/retrofit of deteriorated structures benefited from its tensile strain hardening characteristic with tensile capacity in excess of 3% and multiple cracking patterns. UHTCC could improve durability of RC structures for its tight cracks and large strain capacity under tensile or flexural loadings preventing ingressive substances, like chloride ions, sulfate, etc, penetrating into structures or prolonging this procedure. Corrosion of reinforcing bars is an inevitable problem for RC structures under chloride environment taking long service time, so the bond behaviors between UHTCC and corroded reinforcing bar is required brought to light for exactly evaluating the service life of RC structures incorporating UHTCC. The objective of this study is to investigate the bond behaviors between UHTCC and corroded reinforcing bar. The bond characteristics of UHTCC and corroded reinforcing bar under different corrosion ratios (0~5%) were investigated experimentally after the reinforcing bars were corroded through accelerated corrosion test in laboratory. The average bond stress-slip relation of corroded reinforcing bar and UHTCC under different corrosion ratios, the relation of maximum bond stress and corrosion ratio were analyzed and discussed. The results were also compared with bond behaviors of normal concrete and corroded reinforcing bar under the same test condition.

2 SPECIMEN PREPARATION

UHTCC in this study was consisted of cement, mineral admixtures, fine sand, water, super plasticizer and fibers. A PVA fiber (KURALON-II REC15) was selected for test and the basic physical and mechanical properties were listed in Table 1. The tensile stress-strain curves and the multiple-cracking pattern of UHTCC were showed in Figure 1 and Figure 2 respectively. Controlled normal concrete was prepared for comparison. The basic mechanical properties of UHTCC and normal concrete were listed in Table 2. The nominal diameter of steel rebar was 12 mm and its yield stress was 380 MPa.

Table 1. Basic physical and mechanical properties of PVA fiber.

Length	Diameter	Tensile strength	Elongation	Tensile elastic modulus	Density
mm	μm	MPa	%	GPa	g/cm^3
12	39	1620	7	42.8	1.3

Table 2. Basic mechanical properties of UHTCC and concrete.

Properties	Compressive Strength (28 days)	Limit tensile trength	Limit tensile strain
	MPa	MPa	%
UHTCC	40.2	4.75	4.2
Normal concrete	36.8	—	—

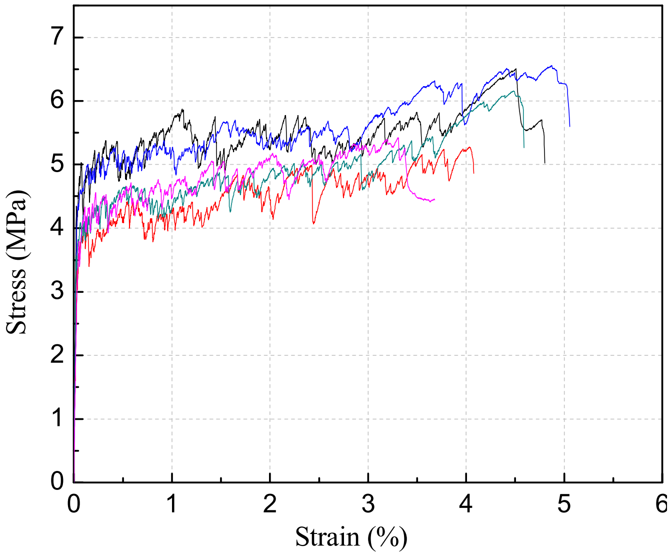


Figure 1. Tensile stress-strain curves of UHTCC.

Figure 2. Crack pattern of UHTCC under tensile loading.

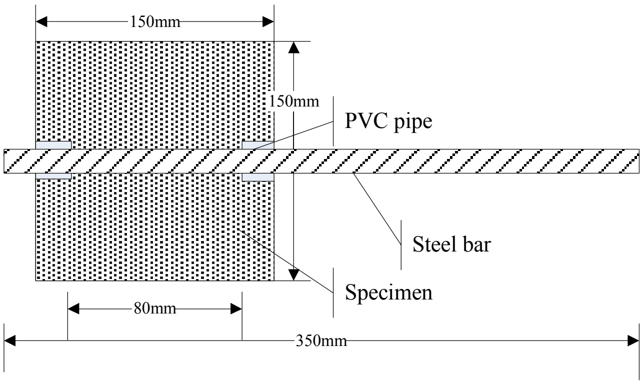


Figure 3. Sketch map of pull-out specimen.

Direct pull-out test was applied in this study for determining the bond characteristics of UHTCC and corroded steel rebar. The form and dimension of test specimen is showed in Figure 3, which the embedded length was 80 mm, the two sides of the anchoring segment were protected by PVC pipes and sealed by silicon sealant. The specimens were cured for 28 days after demold, then were connected with copper wires at one end of the rebars and sealed by epoxy resin.

3 TEST PROCEDURE

3.1 *Accelerated corrosion test*

An electrolyte corrosion technique was used to accelerate the rebar corrosion. The sketch map of accelerated corrosion procedure is showed in Figure 4. The prepared specimens were immersed in a 3.5% NaCl solution in a plastic tank. The rebar was connected with the positive of power supply and the stainless steel plate next to the specimen was connected with the negative of power supply. Every group included six specimens, with three UHTCC specimens and three normal concrete specimens. The specimens were set up an electric circuit after immersed for three days. The current density from 1~3mA/cm^2 was chosen for the electrolyte corrosion process, and the current was adjusted with the test processing. The mass loss of rebar was estimated theoretically by Faraday's Law and the actual mass loss was measured after pull-out test finished. The theoretical corrosion ratio and actual mass loss with corrosion time were listed in Table 3.

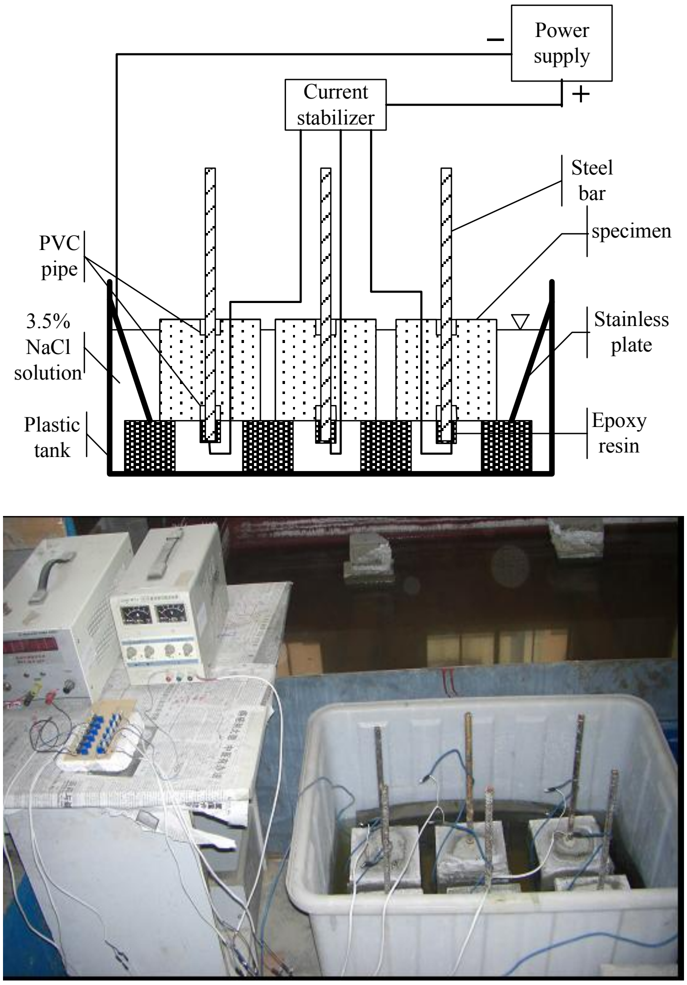


Figure 4. Sketch map of accelerated corrosion.

3.2 *Direct pull-out test*

When the accelerated corrosion test finished, the specimens were taken out and dried in natural conditions. The sketch map of direct pull-out test is showed in Figure 5. Two external linear variable differential transducers (LVDTs) were mounted to the free end of the rebar, and two displacement gages were mounted to the loading end of the rebar for measuring the relative clip between the matrix (UHTCC/concrete) and the rebar. The loading rate of 0.5mm/min was used and loading-displacement data were collected using IMC device.

Table 3. Program of accelerated corrosion test.

Specimen number	Current density	Time	Theoretical corrosion ratio	Actual corrosion ratio
	mA/cm^2	h		
CON-0 /UH-0	0	0	0	0
CON-1 /UH-1	1	23	1%	1.13%
CON-2 /UH-2	1	45	2%	2.25%
CON-3/ UH-3	1	68	3%	3.31%

4 TEST RESULTS AND DISCUSSIONS

4.1 *Test results*

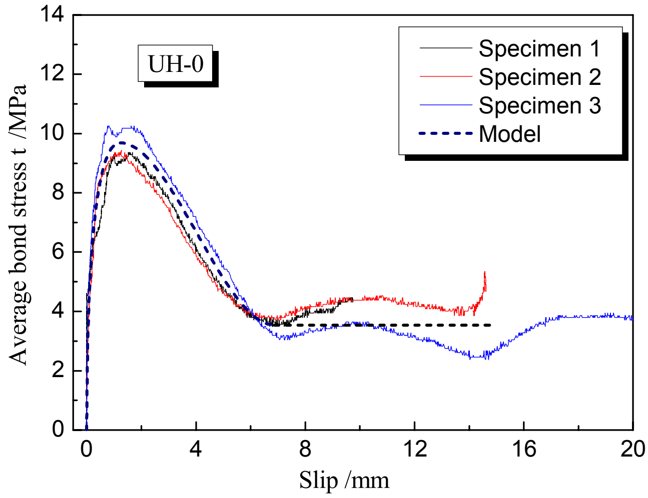
4.1.1 *Test phenomenon and average bond stress-slip relation*

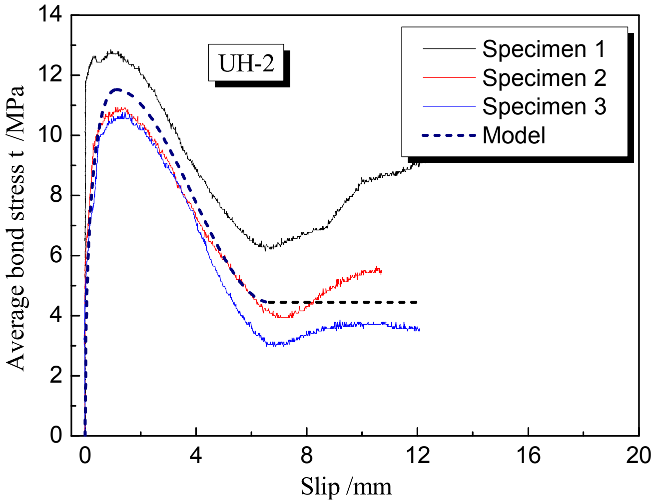
The failure patterns of direct pull-out tests were all typical shear failure patterns between corroded steel bars and concrete/UHTCC for the ratio of cover thickness and diameter of rebar was large (c/d>5). The failure patterns revealed well ductile characteristic.

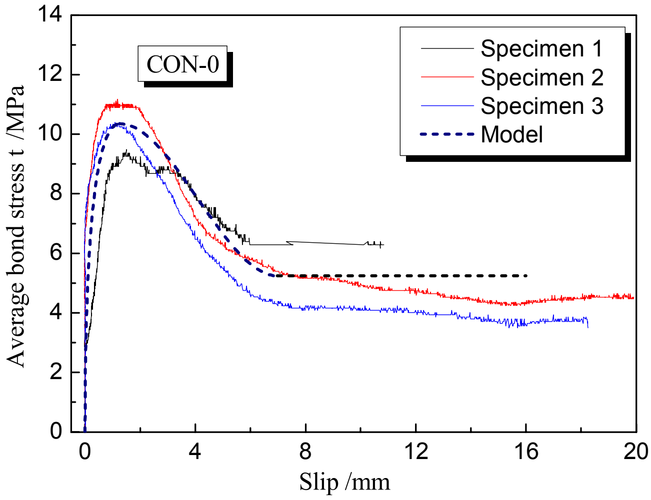
The relation curves of average bond stress and slip are showed in figure6, including UHTCC and normal concrete specimens. Like normal concrete, the curves of average bond stress and slip about UHTCC specimens could also divide into three parts, covering ascending branch, descending branch and residual branch within test range. Unlike normal concrete, the residual branch of UHTCC was not smooth, but had 1~2 hardening stages. The corrosion ratio of rebar higher, the hardening stage was smoother.

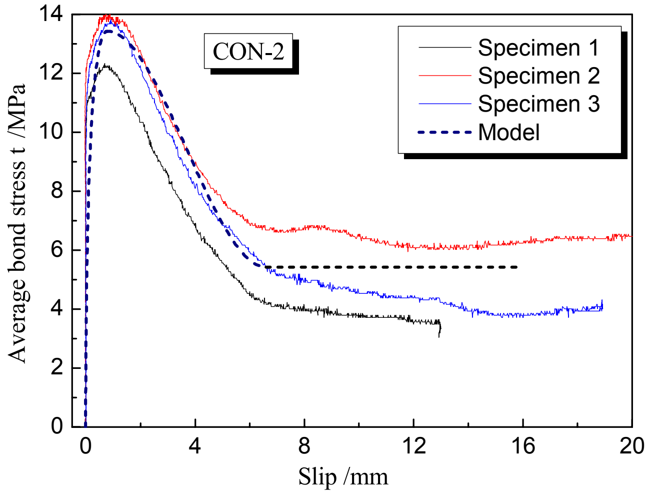
4.1.2 *Relation of corrosion ratio and maximum average bond stress*

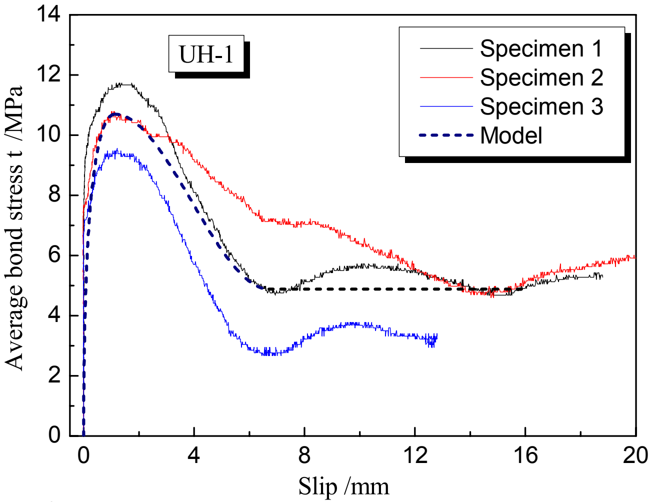
The relation of maximum average bond stress and steel bar corrosion ratio about UHTCC and normal concrete is showed in Figure 7. It's showed that the maximum average bond stress of normal concrete and corrosion rebars increased with the rebar corrosion ratio increasing firstly and then decreased. The maximum average bond stress increased with corrosion ratio before the corrosion ratio up to 2%, and then decreased promptly with the corrosion ratio increasing. Unlike concrete specimens, the maximum average bond stress of UHTCC and corroded steel bar increased slightly with the corrosion ratio increasing, and remained almost unchanged for the corrosion ratio from 3% to 5%.

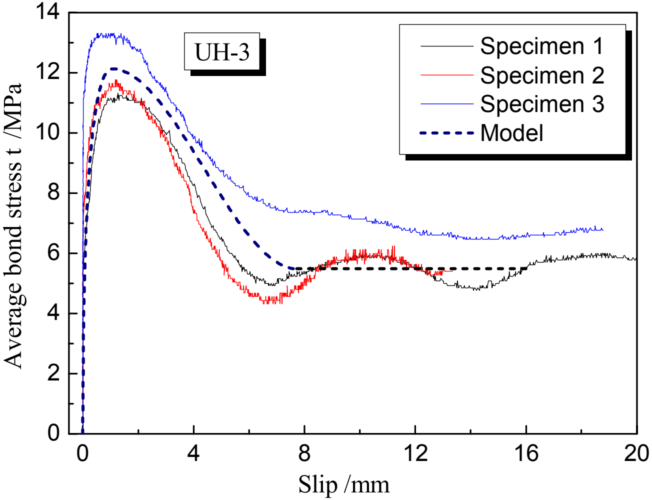

UH-0
Specimen 1
Specimen 2
Specimen 3
Model
Average bond stress t /MPa
Slip /mm
0 2 4 6 8 10 12 14
0 4 8 12 16 20

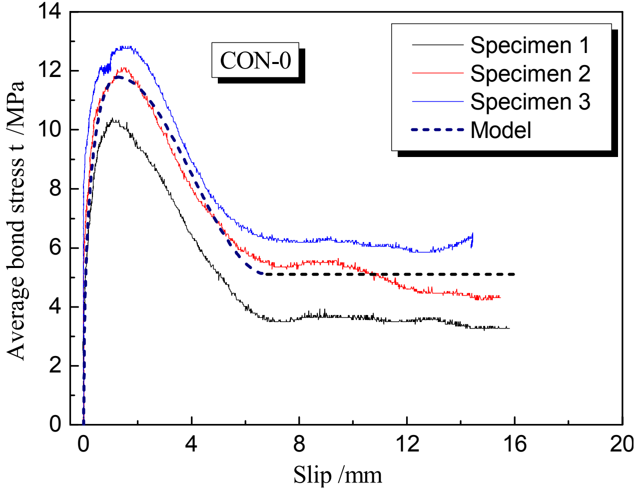

UH-2
Specimen 1
Specimen 2
Specimen 3
Model
Average bond stress t /MPa
Slip /mm
0 2 4 6 8 10 12 14
0 4 8 12 16 20

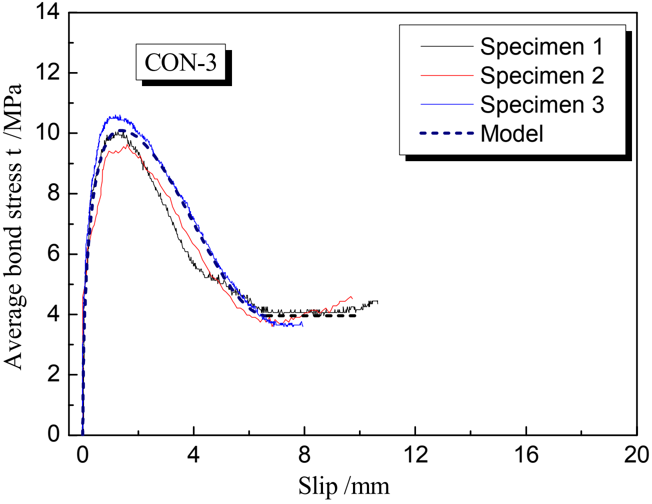

CON-0
Specimen 1
Specimen 2
Specimen 3
Model
Average bond stress t /MPa
Slip /mm
0 2 4 6 8 10 12 14
0 4 8 12 16 20


CON-2
Specimen 1
Specimen 2
Specimen 3
Model
Average bond stress t /MPa
Slip /mm
0 2 4 6 8 10 12 14
0 4 8 12 16 20


UH-1
Specimen 1
Specimen 2
Specimen 3
Model
Average bond stress t /MPa
Slip /mm
0 2 4 6 8 10 12 14
0 4 8 12 16 20


UH-3
Specimen 1
Specimen 2
Specimen 3
Model
Average bond stress t /MPa
Slip /mm
0 2 4 6 8 10 12 14
0 4 8 12 16 20


CON-0
Specimen 1
Specimen 2
Specimen 3
Model
Average bond stress t /MPa
Slip /mm
0 2 4 6 8 10 12 14
0 4 8 12 16 20


CON-3
Specimen 1
Specimen 2
Specimen 3
Model
Average bond stress t /MPa
Slip /mm
0 2 4 6 8 10 12 14
0 4 8 12 16 20

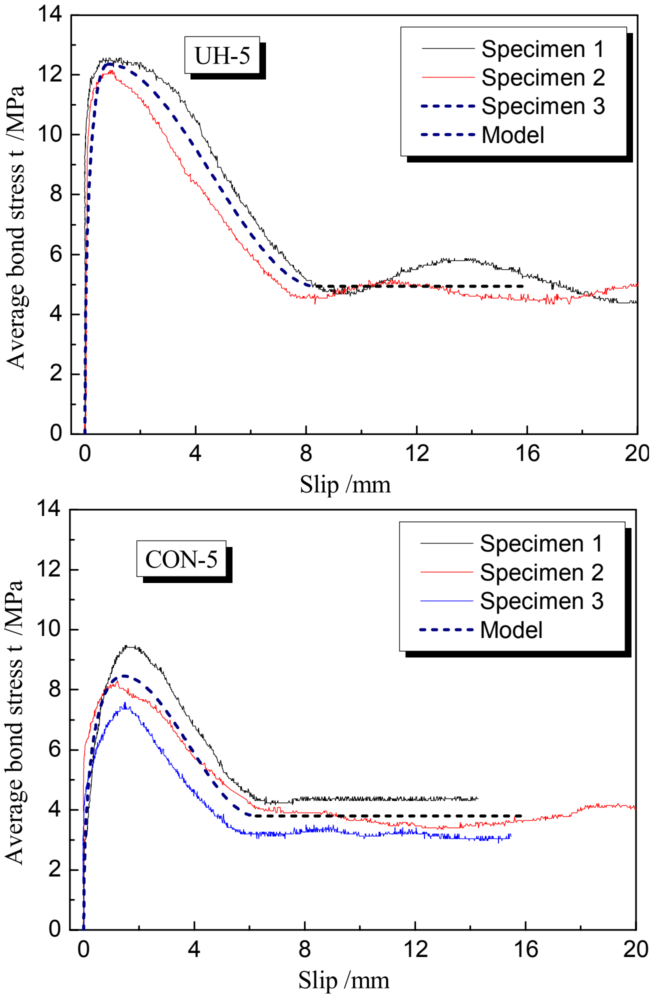


Figure 5. Bond stress-slip curves with different corrosion ratio.

4.2 *Discussions*

UHTCC has superior corrosion resistance compared with mortar in terms of corrosion propagation time, tight crack width, and higher retention stiffness and flexural load due to its high tensile strain capacity, strain hardening and multiple cracking behaviors (Kanda T. et al. 2003). The bond behaviors of UHTCC and corroded rebar have significant effects on the structural response of RC structures incorporated with UHTCC.

4.2.1 *Bond-slip relation of UHTCC and corroded rebar*

The bond-slip curve of rebar and matrix is an overall reflection of the bond behaviors of rebar and matrix. The relation of bond and slip is a crucial factor while the crack width, the rotation capacity of plastic hinge, shear failure and structural responses via nonlinear finite element method was investigated.

The bond-slip relation of UHTCC and rebar could be expressed by a continuous model (Gao D. et al. 2003) according to the results of bond-slip relation of concrete and rebar. This model is illustrated in figure8, and the relation could be written by the following expressions,

OA stage:

$$\frac{\tau}{\tau_0} = 2\sqrt{\frac{s}{s_0}} - \frac{s}{s_0}, 0 < s \le s_0$$

AE stage：

$$\tau = \tau_0 \frac{\left(s_u - s\right)^2 \left(2s + s_u - 3s_0\right)}{\left(s_u - s_0\right)^3} + \tau_u \frac{\left(s - s_0\right)^2 \left(3s_u - 2s - s_0\right)}{\left(s_u - s_0\right)^3}$$

$, s_0 < s \le s_u$

EF stage： $\tau = \tau_u, s > s_u$

Knowing the values of τ_0, s_0, τ_u, s_u, the continuous model could be determined. The test values of τ_0, s_0, τ_u, s_u were listed in table4. The continuous model with different corrosion ratios could be determined by putting these test values into the model. It is showed that the curves of test and the curves of model are fitted well (see Fig. 6), so it is reasonable to apply this model for expressing the average bond stress-slip relation of UHTCC with different corrosion ratio.

Table 4. Key bond parameters with different corrosion ratio.

Matrix	Corrosion ratio	τ_0	s_0	τ_u	s_u
		MPa	mm	MPa	mm
Concrete	0	10.35	1.259	5.24	6.978
	1%	11.78	1.272	5.11	6.802
	2%	13.42	0.784	5.42	6.602
	3%	10.10	1.347	3.95	6.656
	5%	8.45	1.424	3.80	6.243
UHTCC	0	9.69	1.220	3.54	6.869
	1%	10.70	1.134	4.88	6.708
	2%	11.52	1.124	4.45	6.652
	3%	12.13	1.052	5.49	7.723
	5%	12.36	0.829	4.94	8.386

4.2.2 *Effect of corrosion of steel bar on maximum average bond stress*

Like the bond characteristics of rebar and normal concrete, the bond stress of steel bar and UHTCC is attributed to the chemical bond force of UHTCC, the mechanical force of UHTCC and steel bar's ribs and the frictional force of UHTCC and rebar (Lee H.S. et al. 2002). The decreasing of bond stress between concrete and steel bar is primarily caused by the following reasons, (1) The abrasion of rebar's ribs; (2) The reduction of frictional force between concrete and rebar by virtue of the flake corrosion products on the surface of rebar. (3) The weakening of concrete active restriction to rebar because of longitudinal cracking while corrosion. Similarly, corrosion of rebar could also lead to the abrasion of rebar's ribs and reduction of the frictional force between UHTCC and rebar, and these might reduce the bond stress of UHTCC and rebar. However, due to its particular tensile behaviors, including strain-hardening and multiple-cracking characteristics for the steady state crack propagation, UHTCC behaves ductile failure patterns with saturated multiple cracking different from concrete's brittle failure pattern with only one large crack when subjected to tensile/flexural loads (Kanda T. et al. 2003); accordingly, the longitudinal cracking due steel bar corrosion could not be occurred, and the rebar is still restricted by UHTCC effectively.

In this study, the maximum bond stress and corrosion ratio relation within 3% of the corrosion ratio could be expressed by

$$\tau_{\max} = 0.8167\Delta_{\mathrm{r}} + 9.7798,\ 0 < \Delta_{\mathrm{r}} \le 3,\ \mathrm{R}^2 = 0.987$$

When the corrosion ratio exceeds 3%, the maximum bond stress of UHTCC and rebar remains practically unchanged in this study.

Serving as the compared ones, the relation between the maximum bond stress and steel bar to the corrosion ratio of normal concrete is expressed by

$$\tau_{\max} = 1.5438\Delta_{\mathrm{r}} + 10.305,\ 0 < \Delta_{\mathrm{r}} \le 2,\ \mathrm{R}^2 = 0.998;$$

$$\tau_{\max} = 18.409 \cdot \Delta_{\mathrm{r}}^{-0.495},\ 2 < \Delta_{\mathrm{r}} \le 5,\ \mathrm{R}^2 = 0.961$$

From the test results, it is obtained that the maximum bond stress between concrete and steel bar increased with the corrosion ratio increased below 2% of the corrosion ratio, and decreased rapidly from then on. These results were similar with the former research (Auyueng Y. et al. 2000). It is generally recognized that the load carrying capacity of structures would increase slightly with the corrosion ratio of steel bar below 1.5%, and decrease with the corrosion ratio from then on. Once the concrete cover cracks due to corrosion of rebar, the load carrying capacity of structures would decrease immediately.

However, the maximum bond stress development of UHTCC and steel bar with the corrosion ratio is different from ordinary concrete according to this study and the reasons may be as follows: (1)Unlike normal concrete with brittle failure with only one large crack, the failure pattern of UHTCC was ductile with tight and multiple cracking due to its steady state crack propagation; so the cover would not split; (2)Unlike normal concrete with losing load carrying capacity when reaching the tensile strength with low strain, UHTCC could retain its load carrying capacity until reaching the maximum tensile strain (up to 3% even higher) due to its unique strain hardening characteristic.

Actually, the expansion force induced by corrosion of steel bar was a tensile load for outer matrix about structures. For reinforced concrete structures, the concrete cover would crack once the circumferential stress induced by corrosion expansion exceeded the tensile strength of concrete, and the crack extended till longitudinal cracking or scaling of the cover occurred. For the structures substituting UHTCC for concrete as cover in order to protect steel bars, the corrosion had positive effect on the bond of UHTCC and steel bar below 3% corrosion ratio according to this study. While the corrosion exceeded 3%, the maximum average bond stress remained constant approximately. The test result revealed that the corrosion of steel bar would not lead to the constant decreasing of the bond stress between UHTCC and steel bar which was different from concrete and steel bar. This is in accordance with the result discussed in bond behaviors between steel bar and concrete restricted with stirrups. The characteristics of UHTCC, including higher tensile strain capacity and saturated multiple cracking behavior, prevented or prolonged the micro cracks induced by corrosion expansion propagating outer, as well as avoided the micro cracks connecting, thereby still retained restricted effect on steel bar with higher corrosion ratio and ensured enough bond stress between UHTCC and steel bar. With the help of an anti-spalling test, the literature (Kanda T. et al. 2003) simulated anti-cracking and anti-spalling performance of UHTCC against re-bar corrosion, indicating that UHTCC might be less vulnerable to corrosion cracking than normal concrete, and was thus capable of a longer service life in heavy chloride environment.

5 CONCLUSIONS

This study aimed at investigating the bond behaviors between UHTCC and steel bar making an attempt to demonstrate the substantial potential of UHTCC for resisting steel bar corrosion in heavy chloride environment, then compared with normal concrete. The direct pull-out test presented the average bond stress-slip relation of UHTCC and corroded steel bars, and compared with normal concrete before be subjected to accelerated corrosion test. The test curves were simulated by a continuous bond-slip model under different corrosion ratio, and fitted well. The results showed that the average bond stress of concrete and steel bars increased below 2% of corrosion ratio and then decreased rapidly, but didn’t for UHTCC. After 3% of corrosion ratio, the average bond stress of UHTCC and steel bars didn’t decrease with the corrosion ratio increased, but retained at a stable value. This study suggest a substantial potential of UHTCC as the cover of RC structures in heavy chloride environment to resist corrosion expansion for prolonging the service life of members or structures.

ACKNOWLEDGEMENT

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