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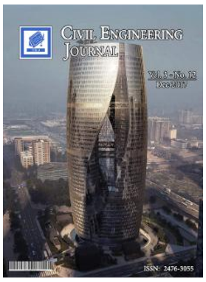

Experimental and Numerical Study of Nano-Silica Additions on the Local Bond of Ultra-High Performance Concrete and Steel Reinforcing Bar

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Abstract

Micro-silica is widely used as an additive to cement in producing high performance concrete. This matter is used to enhance the strength and efficiency of concrete. Recently, due to the development of advanced nano-technology, nano-silica has been produced with particle sizes smaller than micro-silica and higher pozzolanic activity. Studies show that addition of nano-silica into cement-based materials improves their mechanical properties. Considering the unique characteristics of nano-silica, it seems that this material can be used in ultra-high performance concrete (UHPC). Therefore, further studies are needed on how the local bond and bond stress of steel reinforcing bar and UHPC containing nano-silica would be effected. In the present study, after preparing the mix designs and proposed specimens, the effects of various parameters on the local bond of steel reinforcing bars and UHPC containing nano-silica were examined by pullout experiments. In this research, we have numerically investigated the bond strength using numerical methods and calibration of the ABAQUS results in addition to its experimental study of ultra-high performance concrete and steel reinforcement. In numerical analysis, the concrete damage plasticity method was used to simulate the nonlinear behavior of concrete and its strain softness. Comparing between numerical and experimental analysis results shows that numerical analysis with high precision can predict the bond stress, bond load, and concrete specimen fracture mode.

Keywords: Ultra-High Performance Concrete; Nano-Silica; Local Bond; Bond Stress; Pullout Experiment.

1. Introduction

The ultra-high performance concrete (UHPC) has many advantages. Due to its better mechanical properties and low permeability, this type of concrete is gradually replacing conventional concrete. Because of its considerable properties, this type of concrete can either be used in structures to resist loads, or in large bridges and several constructions due to being affected by environmental conditions. Micro-silica is widely used as an additive to cement in producing high performance concrete. This matter is used to enhance the strength and efficiency of concrete. Several experiments have shown that replacing a part of cement with micro-silica, improves sulphate and acid resistance of concrete and reduces chlorine permeability. By addition of micro-silica to concrete or cement mortar, due to being fine grained, it fills the space between cement particles, so the existing pores will become smaller. Moreover, due to the reaction between silica and calcium hydroxide remained from cement hydration process, more C-S-H gels are produced and, as a result, more capillary cracks will be covered [1]. Recently, considering the unique characteristics of nano-silica, it seems that this material can be used in ultra-high performance concrete. Therefore, further research is needed on how to use it in concrete mix designs. To this end, the present study used Pullout test to assess the effect of nano-silica on the bond stress between steel reinforcement and ultra-high performance concrete. Pullout test is the oldest, simplest, cheapest and less time-consuming way to measure local bond stress of concrete. In this test, a reinforcement is placed into a cylindrical

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or cube shaped concrete specimen, and then while the concrete is fixed in place, the reinforcement is pulled out. Since the reinforcement is under tension and concrete is under compression, the resultant relative strain will lead to relative slip. Many researchers have studied the bond between steel reinforcement and ultra-high performance concrete. Alkaysi, M., El-Tawil, S. (2016) conducted an experimental study on the bond stress between ultra-high performance concrete and steel reinforcement. They calculated the bond stress between 13, 16 and 19 mm reinforcements and ultra-high performance concrete in the pullout test. The average compressive strength of the ultra-high performance concrete made in these experiments was 190 MPa [2]. Carbonell Munoz, M.A. et. al. (2014) examined the bond stress between conventional and ultra-high performance concrete and steel reinforcement. The conventional concrete with a compressive strength of about 50 MPa and the ultra-high performance concrete with a compressive strength of about 150 MPa were made for these experiments [3]. Engstrom, B. et. al. (1998) presented the effects of concrete confinement and cover, on bonding in high strength concretes. They showed that with reducing the thickness of concrete cover up to 16 mm (equal to the diameter of reinforcement) resulted in a 25% reduction in the maximum bond stress compared with the well-confined specimen (with sufficient concrete cover). When using a 32 mm cover, the loading will be same as that of well-confined concrete [4]. Kim, S. et. al. (2016) conducted an experimental study on the bond stress between ultra-high performance concrete and 10, 13 and 19 mm steel reinforcements [5]. Cake, K.H. et. al. (2010) conducted an experimental study on the bond stress between ultra-high performance concrete and high strength steel reinforcements. The pullout test based on RILEM standards was used in this study [6]. Finally, these experiments showed that the bond stress of ultra-high performance concrete is 5-10 times higher than conventional concrete. Roy, M. et. al. (2017) used pullout test to determine the bond stress between ultra-high performance concrete and steel reinforcements. In this study, the strength of reinforcements was 415 MPa, and the compressive strength of the concrete was considered between 122.6 MPa to 176.1 MPa. Finally, sliding diagrams of reinforcement in concrete-force were plotted for all specimens [7]. Xing G. et.al. (2015) performed the pullout test to determine the bond stress between ultra-high performance concrete and steel reinforcement [8]. Guizani, L. et. al. (2017) conducted a Local bond stress-slip model for reinforced concrete joints and anchorages with moderate confinement. Guizani, L. et. al. in their paper presented a summary of an experimental investigation and the derivation of a bond-slip model for reinforcing steel embedded in moderately confined concrete under monotonic and cyclic loadings [9]. Yan, C. and Mindes, S. (1994) conducted a bond test between epoxy-coated reinforcing bars and concrete under impact loading [10]. Duchesneau, F., et. al. (2011) conducted a monolithic and hybrid precast bridge parapets in high and ultra-high performance fiber reinforced concretes [11].

2. Pullout Test

Pullout test (Figure1) is the oldest, simplest, cheapest and less time-consuming way to measure bond stress. In this test, a steel reinforcing bar is placed into a cylindrical or cube shaped concrete specimen, and then while the concrete is fixed in place, the steel reinforcing bar is pulled out. Since the steel reinforcing bar is under tension and concrete is under compression, the resultant relative strain will lead to relative slip. This test can present a good comparison between bond strength and corresponding anchorage length. However, the test shows a bond stress greater than the actual bond stress generated in a flexural beam. This can be due to longitudinal compression generated in concrete and the friction on the support surface [12,13]. Therefore, it can be said that although pullout test is the easiest way to study the effects of various parameters on the concrete-steel reinforcing bar bond, but as mentioned in ASTMC234-91a, this experimental method is not suitable in order to determine bond values for design purposes [14]. Pullout test has been used by many researchers to study the effects of various parameters on the bond strength. In this test, short anchorage lengths are used to generate uniform bond stress along the steel reinforcing bar which is called local bond.

Figure 1. Pullout Test

3. Study Plan

To study the bond stress between UHPC and steel reinforcing bar, some specimens were made based on RILEM standard [15]. To consider the ideal targets for experiments, the specimens were used to investigate the effect of different parameters on bond strength. The steel reinforcing bars with the diameters 16 mm, Figure 2. As this Figure shows, to adjust the bond length between steel reinforcing bar and concrete, a plastic pipe is put on the surface of steel reinforcing bar. The anchorage length can vary by changing the pipe length put between the steel reinforcing bar and concrete.

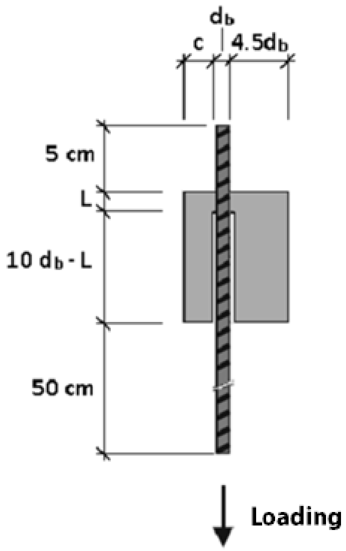

Figure 2. RILEM Specimens dimensions [15]

To do the pullout test, a grip shown in Figure 3 was made to be installed on the jack at the Structural Dynamic laboratory of Sichuan University. The jack and loading conditions are shown in Figure 3. The loading is fully con-trolled and recorded by load cells. The LVDT is put at the end of steel reinforcing bar to record its movement. All the gathered information would be automatically stored in a defined computer.

Figure 3. Pullout test grip

3.1. Steel Reinforcing Bar Properties

Steel bars having diameters 16mm were used in determining the ultra-high performance concrete-steel bond strength. Some properties of these steel bars, obtained through tensile test, are given in Table 1.

Table 1. Material properties of the steel reinforcing bar

Diameters (mm)	Elastic modulus (MPa)	Yield strength (MPa)	Ultimate strength (MPa)	Fracture strain (%)
16	198616	563	682	11.03

3.2. The UHPC Mix Materials

In this section, we discuss the mix design, mixing process and thermal curing required for producing UHPC in order to reach its maximum strength capabilities. The materials to make UHPC are as follows: Portland cement, micro-silica, quartz powder, quartz sand, superplasticizer, water. Since each of these components are effective in optimizing characteristics of this type of concrete, in the following sections we will discuss the effects of these materials individually.

3.3. Mix Design

Several mix designs have so far been offered for UHPC. After studying and testing several mix designs and assessing feasibility of producing them in laboratory, the mix design proposed by Schneider Jianxin was selected to be used in this study. In specimens containing nano-silica, micro-silica was replaced by nano-silica equivalent to 2.5, 4.5 and 6.5 weight% cement. The mix designs used in the present study are given in Table 1 in kilograms per cubic meter [16]. Type I cement with a strength class of 525 was used in this research. The micro-silica used in this study was purchased from Zhikava company and its chemical composition is presented in Table 3. The superplasticizer was purchased from Silcrete company. This poly carboxylate-based superplasticizer is available with the brand Pema. The nano-silica used in this study were purchased from Lima Nano Pars company and its chemical composition is also given in Table 3.

Table 2. The UHPC mix designs

Design type	Cement	Quartz sand	Quartz powder	Micro-silica	Nano-silica	Water	Superplasticizer
1	665	1020	285	200	0	178	23
2	665	1020	285	183.375	16.625	178	23
3	665	1020	285	170.075	29.925	178	23
4	665	1020	285	156.775	43.225	178	23

Table 3. Chemical composition of Micro and Nano-silica

Element (%)	SiO2	SiC	C	Fe2O2	K2O	P2O5	SO3	Cl	Al2O3	CaO	MgO	Na2O
Micro-silica	93.6	0.5	0.3	0.37	1.01	0.16	0.1	0.04	1.32	0.49	0.97	0.31
Nano-silica	99	0	0	0	0	0	0	0	0	0	0	0

Before the main experiments, compressive strength test was performed using standard cubic specimens at ages of 7, 28, 90 and 180 days, by breaking three specimens of each mix design per day. Compressive strength test results obtained for these ages are illustrated in Figure 4 and Table 4.

Table 4. Compressive strength test results for ages of 7, 28, 90 and 180 days.

No of Days	Mix design 1	Mix design 2	Mix design 3	Mix design 4
7-day specimen	66.84	81.72	100.32	114.36
28-day specimen	99.072	112.332	129.12	136.32
90-day specimen	121.8	136.68	144	147.72
180-day specimen	130.8	142.44	151.08	160.92

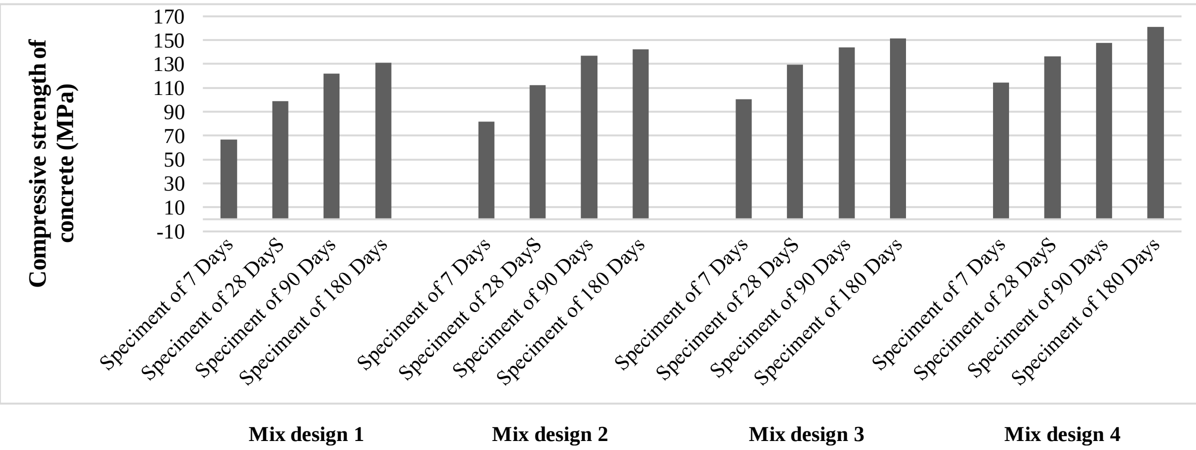

Figure 4. Bar graph of the compressive strength for ages of 7, 28, 90 and 180 days

3.4. Specimens

In this paper, 48 specimens were studied to assess the effect of nano-silica on local bond between UHPC and steel reinforcing bar. In order to complete the research, 4 of the tested specimens were modeled using finite element software

ABAQUS at the Structural Dynamics Laboratory of Sichuan University. Finally, after model validation, we achieved a suitable numerical method for estimating the bond stress of UHPC. In this test, we measured the bond stress between UHPC and steel reinforcing bar for steel bars of No. 16 with the anchorage lengths and concrete covers of d_b, $2d_b$, $3d_b$ and $4d_b$, Pullout test was used to measure the bond stress. In this test, a steel reinforcing bar is placed into a cube shaped concrete specimen, and then while the concrete is fixed in the grip shown in Figure 3, the steel reinforcing bar is pulled out. Specimen naming is so that e.g. in the specimen R16C3L3, R16 means that tests were conducted based on RILEM standards and the steel reinforcing bar No. 16 was tested. C3 represents concrete cover in cubic specimens. According to considering four values of d_b, $2d_b$, $3d_b$ and $4d_b$, for concrete covers, C3 represents the third cover which is equal to $3 \times 16 = 48$ mm for this specimen. L3 shows the steel reinforcing bar-concrete anchorage length in cubic specimens. According to considering four values of d_b, $2d_b$, $3d_b$ and $4d_b$, for the steel reinforcing bar-concrete anchorage length, L3 refers to the third anchorage length which is equal to $3 \times 16 = 48$ mm for this specimen. The Specimens properties are presented in Table 5.

Table 5. Specimens properties

Specimen name	d_b	Concrete Cover	Anchorage length
R16C1L1	16	16	16
R16C1L2	16	16	32
R16C1L3	16	16	48
R16C1L4	16	16	64
R16C2L1	16	32	16
R16C2L2	16	32	32
R16C2L3	16	32	48
R16C2L4	16	32	64
R16C3L1	16	48	16
R16C3L2	16	48	32
R16C3L3	16	48	48
R16C3L4	16	48	64
R16C4L1	16	64	16
R16C4L2	16	64	32
R16C4L3	16	64	48
R16C4L4	16	64	64

4. Results and Discussion

The summary tables 6 to 9 present the results obtained from testing RILEM standards specimens. Each specimen was produced 3 times in 3 different days at the Structural Dynamics Laboratory of Sichuan University and the average of results are presented in the following tables. Specimens were collected from the produced concrete every 3 days and the average results of the 28-day compressive strength are given in the following tables. In all the tables presented in this chapter, u, u_{ave}, $u/\sqrt{f'_c}$, and $(u/\sqrt{f'_c})_a$ represent the bond stress, the mean average bond stress for similar specimens, the normalized average bond stress, and the mean normalized average bond stress for similar specimens in each category, respectively.

Table 6. Specimens properties containing UHPC with 6.5% nano-silica

Specimen name	28-day compressive strength of the concrete $f'_c\ (MPa)$	Tensile strength of the concrete $f'_{ct}\ (MPa)$	Concrete cover (mm)	Bond length (mm)	Bond load (kg)	Bond stress $(\frac{kgf}{mm^2})$	The Normalized average bond stress $(u/\sqrt{f'_c})$
R16C1L1	136.32	6.42	16	16	14609.33	18.17	1.56
R16C1L2	136.32	6.42	16	32	28052.16	17.44	1.49
R16C1L3	136.32	6.42	16	48	41523.31	17.21	1.47
R16C1L4	136.32	6.42	16	64	54624.51	16.98	1.45
R16C2L1	136.32	6.42	32	16	19737.35	24.54	2.10
R16C2L2	136.32	6.42	32	32	38925.59	24.20	2.07
R16C2L3	136.32	6.42	32	48	57881.71	23.99	2.05
R16C2L4	136.32	6.42	32	64	76596.55	23.81	2.04
R16C3L1	136.32	6.42	48	16	23232.24	28.89	2.47
R16C3L2	136.32	6.42	48	32	46405.09	28.85	2.47
R16C3L3	136.32	6.42	48	48	66712.35	27.65	2.37
R16C3L4	136.32	6.42	48	64	88242.06	27.43	2.35
R16C4L1	136.32	6.42	64	16	25767.00	32.04	2.74
R16C4L2	136.32	6.42	64	32	51278.83	31.88	2.73
R16C4L3	136.32	6.42	64	48	76676.98	31.78	2.72
R16C4L4	136.32	6.42	64	64	---	---	2.71

Table 7. Specimens properties containing UHPC with 4.5% nano-silica

Specimen name	28-day compressive strength of the concrete f'_c (MPa)	Tensile strength of the concrete f_{ct} (MPa)	Concrete cover (mm)	Bond length (mm)	Bond load (kg)	Bond stress $(\frac{kgf}{mm^2})$	The normalized average bond stress $(u/\sqrt{f'_c})$
R16C1L1	129.12	6.25	16	16	14218.28	17.68	1.56
R16C1L2	129.12	6.25	16	32	27505.27	17.10	1.50
R16C1L3	129.12	6.25	16	48	40751.23	16.89	1.49
R16C1L4	129.12	6.25	16	64	52501.29	16.32	1.44
R16C2L1	129.12	6.25	32	16	19209.05	23.88	2.10
R16C2L2	129.12	6.25	32	32	37960.49	23.60	2.08
R16C2L3	129.12	6.25	32	48	56482.32	23.41	2.06
R16C2L4	129.12	6.25	32	64	74376.83	23.12	2.03
R16C3L1	129.12	6.25	48	16	22610.39	28.11	2.47
R16C3L2	129.12	6.25	48	32	44828.77	27.87	2.45
R16C3L3	129.12	6.25	48	48	66181.54	27.43	2.41
R16C3L4	129.12	6.25	48	64	87180.45	27.10	2.38
R16C4L1	129.12	6.25	64	16	25077.30	31.18	2.74
R16C4L2	129.12	6.25	64	32	49332.56	30.67	2.70
R16C4L3	129.12	6.25	64	48	72888.97	30.21	2.66
R16C4L4	129.12	6.25	64	64	96574.07	30.02	2.64

Table 8. Specimens properties containing UHPC with 2.5% nano-silica

Specimen name	28-day compressive strength of the concrete f'_c (MPa)	Tensile strength of the concrete f_{ct} (MPa)	Concrete cover (mm)	Bond length (mm)	Bond load (kg)	The normalized average bond stress $(u/\sqrt{f'_c})$
R16C1L1	112.332	5.83	16	16	13261.79	1.56
R16C1L2	112.332	5.83	16	32	25928.95	1.52
R16C1L3	112.332	5.83	16	48	38555.64	1.51
R16C1L4	112.332	5.83	16	64	50699.78	1.49
R16C2L1	112.332	5.83	32	16	17916.81	2.10
R16C2L2	112.332	5.83	32	32	35209.97	2.07
R16C2L3	112.332	5.83	32	48	52501.29	2.05
R16C2L4	112.332	5.83	32	64	69261.81	2.03
R16C3L1	112.332	5.83	48	16	21089.34	2.47
R16C3L2	112.332	5.83	48	32	41676.12	2.44
R16C3L3	112.332	5.83	48	48	61935.12	2.42
R16C3L4	112.332	5.83	48	64	81422.04	25.31
R16C4L1	112.332	5.83	64	16	23390.30	29.08
R16C4L2	112.332	5.83	64	32	46453.35	28.88
R16C4L3	112.332	5.83	64	48	68594.29	28.43
R16C4L4	112.332	5.83	64	64	90719.14	28.20

Table 9. Specimens properties containing UHPC without nano-silica

Specimen name	28-day compressive strength of the concrete f'_c (MPa)	Tensile strength of the concrete $f_{ct}(MPa)$	Concrete cover (mm)	Bond length (mm)	Bond load (kg)	Bond stress $(\frac{kgf}{mm^2})$	The normalized average bond stress $(u/\sqrt{f'_c})$
R16C1L1	99.072	5.47	16	16	12454.49	15.49	1.56
R16C1L2	99.072	5.47	16	32	24127.43	15.00	1.51
R16C1L3	99.072	5.47	16	48	35612.09	14.76	1.48
R16C1L4	99.072	5.47	16	64	46485.52	14.45	1.45
R16C2L1	99.072	5.47	32	16	16826.14	20.92	2.1
R16C2L2	99.072	5.47	32	32	32684.63	20.32	2.04
R16C2L3	99.072	5.47	32	48	48278.99	20.01	2.01
R16C2L4	99.072	5.47	32	64	63278.21	19.67	1.98
R16C3L1	99.072	5.47	48	16	19805.55	24.63	2.47
R16C3L2	99.072	5.47	48	32	38941.67	24.21	2.43
R16C3L3	99.072	5.47	48	48	57905.84	24.00	2.41
R16C3L4	99.072	5.47	48	64	76628.72	23.82	2.39
R16C4L1	99.072	5.47	64	16	21966.43	27.31	2.74
R16C4L2	99.072	5.47	64	32	43316.78	26.93	2.71
R16C4L3	99.072	5.47	64	48	64347.86	26.67	2.68
R16C4L4	99.072	5.47	64	64	84960.73	26.41	2.65

Tables 6 to 9 provide the results of bond stress between the reinforcement No. 16 and UHPC containing 2.5%, 4.5% and 6.5% of nano-silica and without nano-silica. As it is evident, the increase in nano-silica percentage has increased the compressive strength of the concrete, so that the bond load and bond stress have also increased. The bond load has not been achieved in specimen R16C4L4 with 6.5% nano-silica due to the high bond length, high strength of the concrete and the reinforcement failure. In specimens R16C1L2, R16C1L3 and R16C1L4 containing ultra-high performance concrete with 6.5% nano-silica, due to the bond length increase, the bond stress decreased by 1.4%, 5.3% and 6.6%, respectively, compared to the specimen R16C1L1. In specimens R16C2L1, R16C3L1 and R16C4L1 containing 6.5% nano-silica, due to increasing the concrete cover, the bond stress increased by 35%, 58% and 76%, respectively, compared to the specimen R16C1L1. It can be concluded that concrete cover has a significant influence on the bond stress between UHPC and steel reinforcement.

5. Description of the Numerical Model

In this study, the bond stress between UHPC and steel reinforcement was investigated by conducting the pullout test for reinforcement No. 16. In order to completing the studies, we will discuss the results of the pullout test with modeling and analysis in ABAQUS finite element software. Four specimens of R16C1L1, R16C1L2, R16C1L3 and R16C1L4 were modeled in ABAQUS and all of them have 16 mm concrete covers and 16, 32, 48, and 64 mm bond lengths, respectively. The dimensions of each cubic specimen were considered as 160 mm. The 28-day compressive strengths for modeling these specimens were 136.32 MPa.

ABAQUS Version 2017 [17] software was used for three-dimensional modeling and nonlinear analysis of specimens. In the modeled specimens, the C3D8R element was used to model the concrete. Mesh of specimens was selected so that concrete size in each specimen be equal to 10 × 10 mm. The T3D2 element was used for meshing steel reinforcing bars. Figure 5 illustrates the specimens modeling in ABAQUS software.

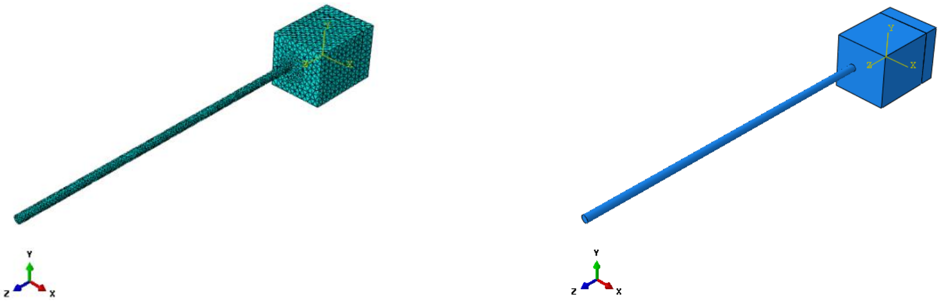

Figure 5. Specimen modeling and meshing

5.1. Model Verification

The bond loads resulted from experimental analysis and numerical analysis are compared with each other and presented in Table.13. As shown in the above table, the results obtained from numerical and experimental analyses are in relatively good agreement with each other, so that the results obtained from numerical analysis are up to about 0.3% more conservative than the results obtained from experimental analysis.

As can be seen from the numerical analysis results, the bond stress corresponding to the bond load is reduced by increasing the bond length and thus increasing the bond load corresponding to each specimen. In the specimens R16C1L2, R16C1L3 and R16C1L4 the bond stress has decreased by 4.4%, 5.5%, and 6.7%, respectively, compared to the R16C1L1 specimen.

Table 10. Bond loads and Bond stress of specimens

Specimen name	28-day compressive strength of the concrete f'_c (MPa)	Concrete cove (mm)	Bond length (mm)	Bond load resulted from experimental analysis (kg)	Bond load resulted from numerical analysis (kg)	Bond stress resulted from numerical analysis u $(\frac{kgf}{mm^2})$	$\frac{f_{num}}{f_{exp}}$
R16C1L1	136.32	16	16	14609.33	14687.21	18.26	1.0053
R16C1L2	136.32	16	32	28052.16	28111.1	17.47	1.002
R16C1L3	136.32	16	48	41523.31	41651.3	17.26	1.003
R16C1L4	136.32	16	64	54624.51	54764.4	17.02	1.0025

5.2. Cracks

According to the test observations, failure of the specimens can be divided into three main modes of pullout, split, and bar yielding. In the mode of pulling the reinforcement out of the concrete by removing the concrete keys between reinforcement treads as much as concrete shear capacity, the keys are slipped off and the reinforcement is pulled out of concrete. In this case, the concrete specimen remains intact without any cracks or damage indicating destruction. This failure mode was observed in highly coated specimens. In the split mode, due to the reaching of hoop tensile stresses to the ultimate tensile strength of concrete, failure is done with wide radial cracking and splitting the specimen into two or more parts (Figure 6, 7). The reinforcement bar yielding mode occurs due to the long bond length or high strength of concrete. In this case, before the bond zone reaches the ultimate capacity, the reinforcement yields.

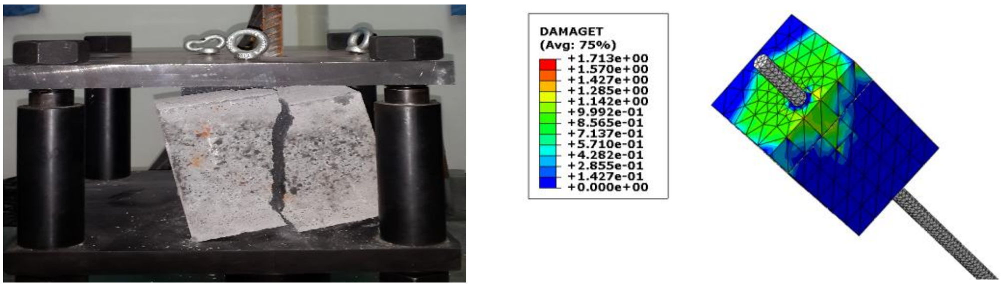

Figure 6. R16C1L4 cracking

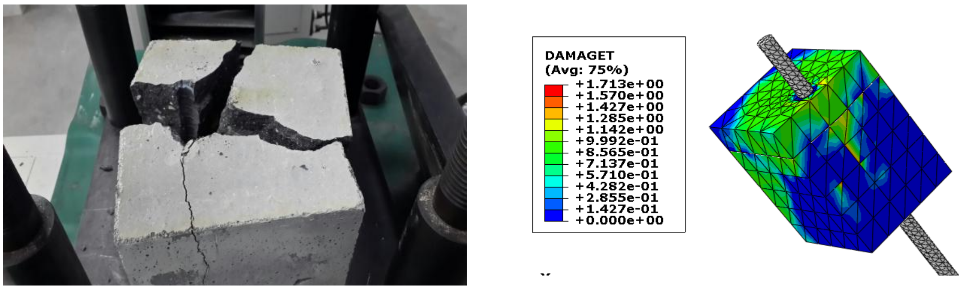

Figure 7. R16C1L2 cracking

6. The Correction of Local Bond Stress Formulas

Tepfers theory was developed by Esfahani and Rangan in 1998 [1], which described the local bond stress of UHPC.

$$u_c = 4.9\frac{\left(\frac{c}{d_b}+0.5\right)}{\left(\frac{c}{d_b}+3.6\right)} fct : f_c' \leq 50Mpa \tag{1}$$

$$u_c = 8.6\frac{\left(\frac{c}{d_b}+0.5\right)}{\left(\frac{c}{d_b}+5.5\right)} fct : f_c' \succ 50Mpa \tag{2}$$

In these equations, u_c shows the bond stress, c the minimum concrete cover on steel reinforcing bar, d_b the steel reinforcing bar diameter, f_c' the compressive strength of concrete and $f_{ct} = 0.55\sqrt{f_c'}$.

To revise and correct the Equation 2, the initial value of f_b is used.

$$f_b = \frac{\frac{c}{d_b}+0.5}{1.75} f_{ct} \tag{3}$$

In Equation 3, c the minimum concrete cover on steel reinforcing bar, d_b the steel reinforcing bar diameter, f_c' the compressive strength of concrete and $f_{ct} = 0.55\sqrt{f_c'}$. By using Equation 3 in Equation 2:

$$u_c = 1.75(c_1 \times \frac{f_b}{\left(\frac{c}{d_b}+c_2\right)}) \tag{4}$$

In Equation 4, c_1 and c_2 are used as the constant coefficients. Equation 4 can be simplified to a linear Equation 5.

$$\frac{c}{d_b} = 1.75 \times c_1 \times \left(\frac{f_b}{u_c}\right) - c_2 \tag{5}$$

The values of $\frac{f_b}{u_{test}}$ and $\frac{c}{d_b}$ are calculated for all specimens and the averages of each group are presented in Figure 8. In this figure, the values of $\frac{c}{d_b}$ versus $\frac{f_b}{u_{test}}$ are plotted for the UHPC containing 6.5% nano-silica.

The line equation drawn in Figure 6 is:

$$\frac{f_b}{u_c} = 0.07\frac{c}{d_b} + 0.2427 \tag{6}$$

By using the equation (6), equation (2) would be corrected for UHPC as:

$$u_c = 8.163\frac{\frac{c}{d_b}+0.5}{\frac{c}{d_b}+3.467} f_{ct} : f'_c \succ 110Mpa \tag{7}$$

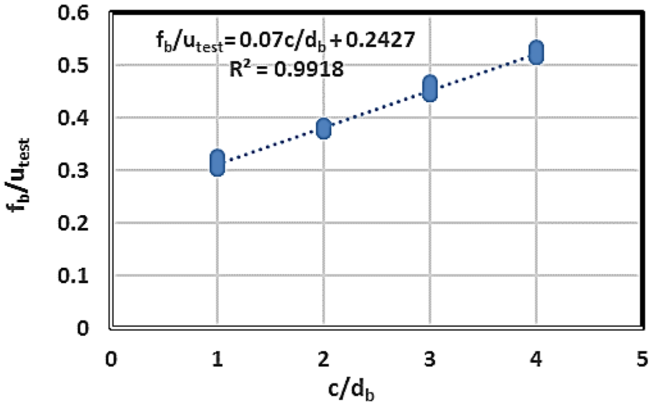

Figure 8. The experimental values of $\frac{f_b}{u_{test}}$ v.s. $\frac{c}{d_b}$ for the steel reinforcing bar no.16 and the concrete containing 2.5, 4.5 and 6.5 % nano-silica

7. Conclusions

In this research, we conducted the experimental and the numerical investigation of the local bond stress between the ultra-high performance concrete and steel reinforcement No. 16. The results of this research show that the bond stress formula can be revised as follows:

$$u_c = 8.163\frac{\frac{c}{d_b}+0.5}{\frac{c}{d_b}+3.467} f_{ct} : f'_c \succ 110Mpa \tag{8}$$

The increasing of bond length between steel reinforcing bar and UHPC would decrease the average bond stress and the increasing of concrete cover of steel reinforcing bar, would increase the ultimate average bond stress. In specimens R16C1L2, R16C1L3 and R16C1L4 containing ultra-high performance concrete with 6.5% nano-silica, due to the bond length increase, the bond stress decreased by 1.4%, 5.3% and 6.6%, respectively, compared to the specimen R16C1L1. In specimens R16C2L1, R16C3L1 and R16C4L1 containing 6.5% nano-silica, due to increasing the concrete cover, the bond stress increased by 35%, 58% and 76%, respectively, compared to the R16C1L1. It can be concluded that concrete cover has a significant influence on the bond stress between UHPC and steel reinforcement.

Also Simultaneously increasing bond length and steel reinforcing bar cover by the values of d_b, $2d_b$, $3d_b$ and $4d_b$, leads to increased average bond stress and simultaneously increasing bond length and steel reinforcing bar cover by the values of d_b, $2d_b$, $3d_b$ and $4d_b$, increases the ultimate average bond stress. By adding nano-silica into UHPC, the normalized ultimate bond stress is increased. The results obtained from numerical and experimental analyses are in relatively good agreement with each other, so that the results obtained from numerical analysis are up to about 0.3% more conservative than the results obtained from experimental analysis.

Finally, with respect to numerical analysis results, the bond stress corresponding to the bond load has also been decreased with the increase of the bond length and consequently the bond load corresponding to each specimen. So that the bond stress in specimens R16C1L2, R16C1L3 and R16C1L4 decreased by 4.4%, 5.5% and 6.7%, respectively, compared to the specimen R16C1L1.

8. References

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