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Study on the effects of bonded-stress between concrete and corroded rebar

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KEYWORDS

bond- slip relationship, corrosion, corroded RC structures, pull-out

ABSTRACT

In this study, the bond stress between steel bar with a diameter of 12 mm and concrete was examined with the effect of different corrosion levels and different concrete grades. A steel bar was inserted in a concrete block with a size of $20 \times 20 \times 20$ cm. The compressive strength of concrete was 25.6 MPa, 35.1 MPa, and 44.1 MPa. These specimens were soaked into solution NalCl3.5 % to accelerate the corrosion process at a different time and corrosion levels. The pull-out test was conducted. Results showed that the bond strength of the corroded steel bar was higher than that predicted from CEB-FIP [1]. Slip displacement and the range of slip displacement at the bond strength were reduced when the concrete compressive strength was increased.

1. Introduction

Reinforced concrete (RC) structures have been widely used in civil engineering because of their flexibility, durability, and economy [2] . After several years of service, RC structures are generally degraded. Many reasons are causing the deterioration in RC structures. One of the reasons is steel corrosion, especially in concrete structures in the marine environment. In Japan, a study showed that 90 % of the buildings exposed to the marine environment with the protective concrete layer were not large enough and that the structures that were only ten years old have been damaged in a large proportion. In the United States, based on the monitoring of 586000 expressway bridges, 15 % of the structure has deteriorated, mainly due to the strong development of corrosion. In Vietnam, the low quality of concrete in the corrosion environment causes steel corrosion in concrete structures that reduce its capacity. Many RC structures with corroded steel bars are shown in Figure 1. 45 % of steel bars in RC structures are seriously corroded. Many stirrups are destroyed and broken, the protective concrete layer is spalled and disappeared [3].

Generally, steel bars in RC structures are protected by concrete cover thickness. However, the deterioration of concrete as carbonation makes water (H_2O) and oxygen (O_2) or ion chloride (Cl-) penetrate through a protective concrete layer and causing the corrosion of steel bars. In the non-corrosive environment, RC structures could be operated sustainably for their service time. However, in hot and humid climate conditions containing high ionic content, the RC structures show different corrosion levels. Therefore, corroded concrete structures do not save the life of the project [4, 5]. In an aggressive environment as a marine environment, The RC structures with corroded steel bars only operate within 10 to 30 years. Corrosion of the steel reinforcement bars reduces the area of the steel bar and the bond stress between the steel bars and around concrete. It affects the anchorage of straight reinforcing bars, cracking control and section stiffness [6]. That then reduces the capacity of concrete structures [7, 8, 9]. Collected data shows the frequency and cost of building repairs for deterioration and damage caused by corrosion [10].

(a) Cua Cam Port in Hai Phong after 30 years

(b) Trade Port in Vung Tau after 15 years

Figure 1. Current status of reinforcement corrosion on some real projects [3].

orrosion protection of concrete layer in RC structures depends on the level of environmental cavitation and the quality of materials such as concrete strength, types of cement, type reinforcement, design, construction quality, maintenance, and so on. The pull-out test of the steel bar inserted in a concrete block was carried out. The concrete block size was 20 × 20 × 20 cm. Design compressive strength was 25 MPa, 35 MPa, and 45 MPa. A steel bar with a diameter of 12 mm inserted in a concrete block was corroded in the laboratory in a short time using the electrochemical corrosion acceleration method. In this study, the bond stress between steel bar and concrete was examined with the effect of different corrosion levels and different concrete grades.

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2. General bond behaviour

The relationship between bond stress and slip of steel bars around concrete according to the CEB-FIP model [1] is shown in (Figure 2). The maximum bond stress, τ_{max} is calculated as follows Eq. (1):

$$\tau_{max} = k\sqrt{f_c'} \quad (1)$$

Where k is a factor taken by 2.5, f'_c is the compressive strength of concrete (MPa). Bamonte và Gambarova [11] proposed the maximum bond stress of $0.45f'_c$. Using Eq (1), k value suggested by Bamonte và Gambarova to predict the maximum bond stress is 3.74. It means that the maximum bond stress has been predicted with the value from other researchers. The maximum bond stress between steel bar and concrete by CEB-FIP [1] is accepted as constant within slip from s_1 to s_2. The value of s_1 and s_2 for pull-out failure mode is 1mm and 2 mm, respectively. The bond stress from an experiment is calculated by Eq. (2):

$$\tau = \frac{P}{\pi d l} \quad (2)$$

Where P is the load from the experiment, d is the nominal diameter of the steel bar, and l is the anchorage length of steel bars.

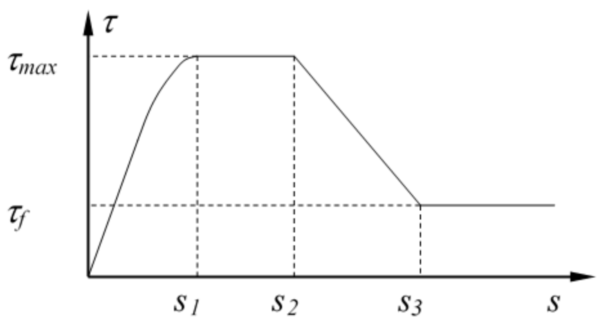


Figure 2. Bond stress and slip relationship by CEB-FIP [1].

3. Test program

3.1. Steel bars

Normal reinforcement bar using in this study is a deformed bar with a diameter of 12 mm. The length of bars of 600 mm was prepared (Figure 3). A segment was about 10 cm accelerated corrosion was embedded in the concrete block. Other parts of the embedded bar in the concrete block were protected by plastic tubes. Concrete blocks with embedded bar were soaked into the corrosion environment NaCl soluble. The end of the steel bar close to the concrete block was protected carefully. Its yield and tensile strengths were 400 MPa and 570 MPa, respectively. Its elongation is about 14 %.

(a) Cuting steel bars

(b) Determining corroded segment

Figure 2. Preparing steel bar for fullout test.

3.2. Concrete

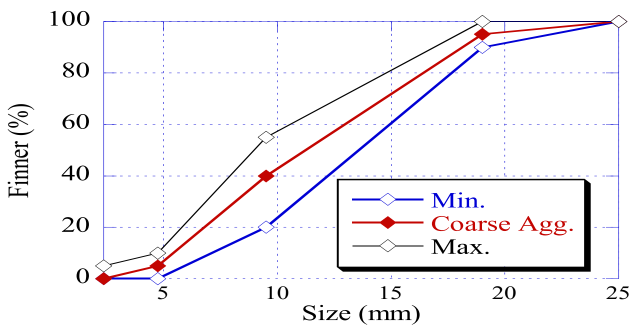
Concrete includes aggregate, sand, cement, and water. Coarse and fine aggregates (Figure 4) are in the local market. It was evaluated by sieving analysis based on ASTM C136-01 [12]. The maximum size of the coarse and fine aggregates was 25 mm and 4.75 mm, respectively. Size distribution curves of coarse and fine aggregates satisfied ASTM C33M-18 [13] (Figure 5). Cement is PCB40 in the market with a density was 3.11 ton/m^3. Concrete mixtures were designed based on ACI [14]. Its desired compressive strength at 28 days was 25 MPa, 35 MPa, and 45 MPa. The mix proportions were tabulated in Table 1. Each compressive strength at 28 days predicted by an average of three-cylinder specimens (Figure 6) was also tabulated in Table 1.

Table 1.

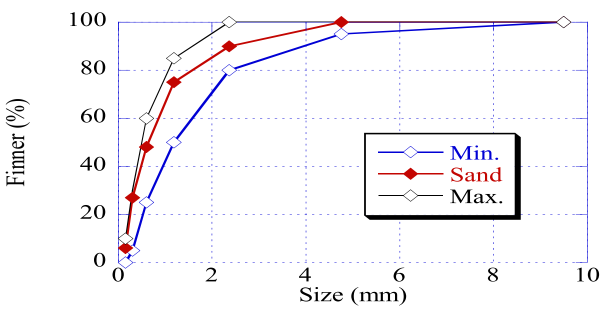
Concrete mix proportions

Design strength (MPa)	Cement (kg)	Sand (kg)	Aggregate (kg)	Water (l)	Compressive strength at 28 days (MPa)
25	350	660	1200	170	24.6
35	465	650	1150	186	35.1
45	550	645	1100	210	44.1

Figure 4. Coarse and fine aggregates.



(a) Coarse aggregate



(b) Fine aggregate

Figure 5. Size distribution curves of coarse anf fine aggregates.

(a) cylinder specimens (b) Testing compressive strength

Figure 6. Determining compressive strength of concrete at 28 days.

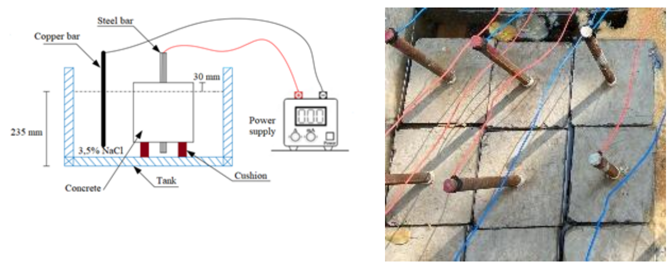
3.3. Specimens and corrosion process

Formwork for specimens was made from wooden plates. The steel bar was located in the center of the formwork. It was fixed carefully to ensure perpendicularly to the surface of the concrete block (Figure 7). Concrete was cast on the formwork (Figure 8). The top surface of specimens was made as flat as possible because this top surface will be placed on the bottom plate of the jig on testing. After casting, concrete blocks were cured by covering wet clothes for six days. Water was provided three times a day. After one week, the formwork was removed. The specimens were then put in laboratory conditions.

At 28 days, all specimens were soaked in solution *NalCl* 3.5 % (35 *g/l*) to accelerate the corrosion process. The specimen setting for testing is illustrated in Figure 9. The samples are connected simultaneously with the terminals of the transformer according to a parallel circuit diagram. The negative pole of the transformer is connected to a copper rod placed in solution *NalCl* 3.5 %. Saltwater has a salinity equivalent to seawater in Vietnam and around the world, and in the experiment acts as a liquid solution. Transformer allows to convert alternating current to direct current (Figure 10), amperage can be fixed in advance.

Figure 7. Set up steel bars.

Figure 8. Casting specimens.



(a) Setting up model

(b) Experiment

Figure 9. corrosion acceleration experiment.

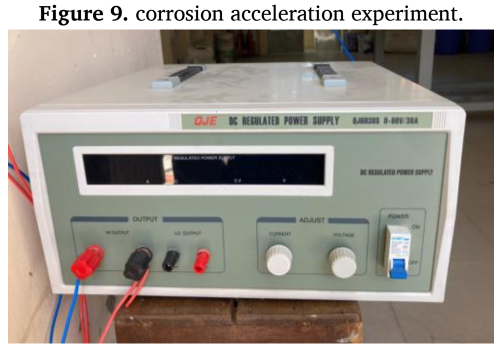


Figure 10. DC power for corrosion test.

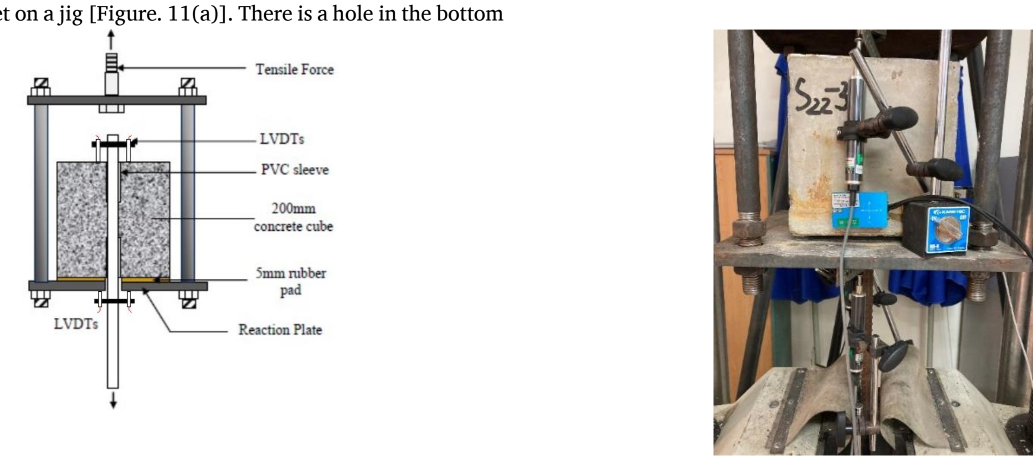
When the concrete was 28 days, the specimens were soaked in the solution *NalCl* 3.5 % within three days to be fully saturated by chloride ions. The top of the surface solution *NalCl* 3.5 % was far from the top of concrete blocks around 3cm (Figure 9). Steel bars were connected electric power parallelly circuit diagram. During the soaking, the amperage was adjusted and recorded every 12 hours. Corroded steel bars were set up to 5 %, 15 %, and 25 % to investigate bond behavior between a corroded steel bar and concrete. Electrolysis time is predicted simply according to Faraday's law Eq. (3):

$$M_{th} = \frac{W \times T \times I_{app}}{F} \tag{3}$$

Where M_{th} is a theoretical mass of rust per unit surface area of the bar (*g*), *W* is the equivalent weight of steel which is taken as the ratio of the atomic weight of iron to the valency of iron 27.925 (*g*), *Iaap* is applied current density (*Amp*), *T* is the duration of induced corrosion (*sec*), *F* is Faraday's constant 96487 (*Amp/sec*). Based on equation Eq. (3), the time to soak specimens to corrode steel bars of 5 %, 15 %, and 25 % was soaked in solution *NalCl* 3.5 % within 51 hours, 154 hours, and 255 hours, respectively. When the soaking was finished, specimens were taken out of solution *NalCl* 3.5 % for pulling out tests.

3.4. Experimental method

A specimen was set on a jig [Figure. 11(a)]. There is a hole in the bottom plate of the jig. Therefore, a steel bar was put through to connect to the loading machine. The top plate of the jig is connected to a bolt with thread to create a high bond to the jig and loading machine. To measure slip between the steel bar and the concrete block in each specimen, two transducers type of CDP25 were set up at two locations on the steel bar close to the top and bottom of the concrete block. A K-gauge and pi-gauge were pasted on concrete at the middle of two sides of the concrete block to detect crack and crack width. All measurement devices were connected to Data Logger TDS630 (Figure 12). The loading machine was controlled with a load speed of 0.1 kN/s.



(a) Diagram of seting up sample (b) Seting up instrument measurment

Figure 11. Layout of test samples on tractors and support device.

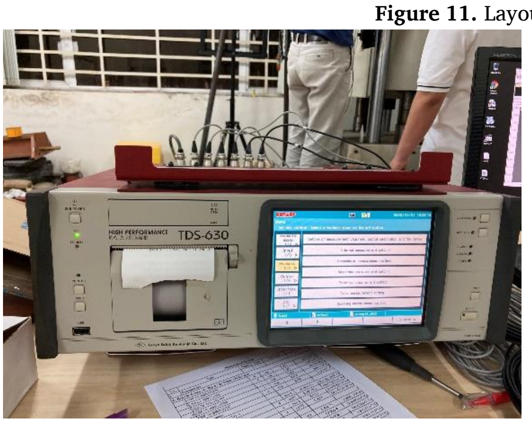


Figure 12. Data Logger TDS630.

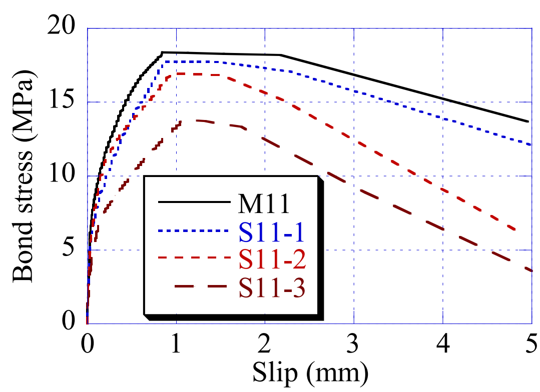


Figure 13. Bond stress and sliping cuvre in concrete of 24.6 Mpa.

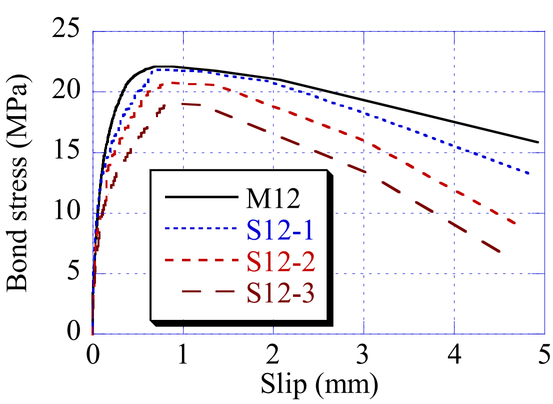


Figure 14. Bond stress and sliping cuvre in concrete of 35.1 MPa.

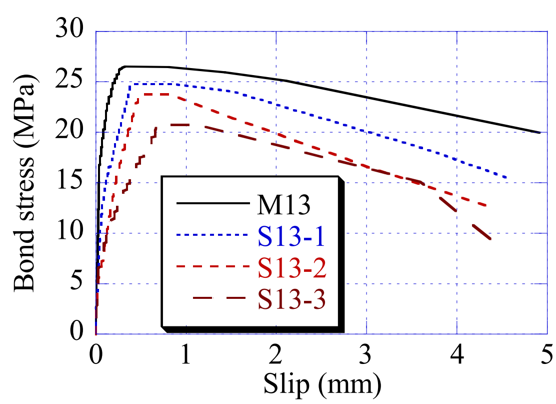


Figure 15. Bond stress and sliping cuvre in concrete of 44.1 Mpa.

2. Results and discussion

Tested compressive strengths of concrete were approximate the designed values. The relationships between bond stress and slip of steel bar were expressed in Figure 13-15. The bond stress reduced when the level of corrosion increased in each compressive strength. The corrosion level was also evaluated after testing by losing weight. The corrosion level was not the same as the designed values. The higher compressive strength it was, the lower the corrosion level it was. The same design corrosion level of 5 %, compressive strength of concrete of 24.6 MPa, 35.1 MPa, and 44.1 MPa, the corrosion level in the experiment showed 1.76 %, 0.55 %, and 1.11 %, respectively. Table 2 shows all testing results of specimens.

Figure 16 showed that compressive strength was affected bond stress between steel bar and around concrete. The bond stress increased when compressive strength increased. Bond strength from this experiment was much higher than that was predicted from CEB-FIP MC2020. Based on the compressive strength of concrete of 24.6 MPa, 35.1 MPa, and 44.1 MPa, the maximum bond strength based on Eq. (1) was 12.4 MPa, 14.8 MPa, and 16.6 MPa, respectively. However, the maximum bond strength from the experiment was calculated as 18.4 MPa, 22.1 MPa, and 26.5 MPa, respectively. Based on the experimental results, the k value to predict the maximum bond stress in Eq. (1) was approximately 3.8. This value was closer to the k value proposed by Bamonte và Gambarova [11].

The values s_1 and s_2 in the experimental results were not the same as the slip values in the bond-slip model proposed by CEB-FIP [1]. The experimental results showed that s_1 and s_2 were lower than those suggested CEB-FIP [1]. The compressive strength affected the values s_1 and s_2 (Figure 17). The range between s_1 and s_2 was also reduced when compressive strength was increased. At the failure stage, concrete around the steel bar on the top of the concrete block was spalled out. No crack propagated to the edges of concrete blocks in all specimens. Therefore, specimens were considered as pull-out failure modes (Figure 18).

Table 2: Test results.

Specimens	f'_c (MPa)	Corrosion level (%)	P (kN)	τ (MPa)	s_1 (mm)	s_2 (mm)	w (mm)	Failure type
M_{11}	24.6	0	41.55	18.37	0.838	2.168	0.03	Pull out
S_{11}-1		1.76	40.15	17.75	0.863	1.512	0.15	
S_{11}-2		4.14	38.25	16.91	0.930	1.502	0.30	
S_{11}-3		12.93	31.25	13.81	1.070	1.728	0.35	
M_{12}	35.1	0	50.05	22.13	0.688	1.353	0.01	
S_{12}-1		0.51	49.35	21.82	0.671	1.256	0.03	
S_{12}-2		3.36	47.05	20.08	0.814	1.354	0.30	
S_{13}-3		5.05	43.10	19.05	0.872	1.202	0.30	
M_{13}	44.1	0	60.15	26.51	0.326	0.805	0	
S_{13}-1		1.11	58.95	24.82	0.406	0.849	0.01	
S_{13}-2		2.05	53.80	23.79	0.482	0.821	0.30	
S_{13}-3		4.79	46.95	20.76	0.702	1.125	0.35	

Note: f'_c :compressive strength; P: peak load; t: bond stress; s_1: w crack with

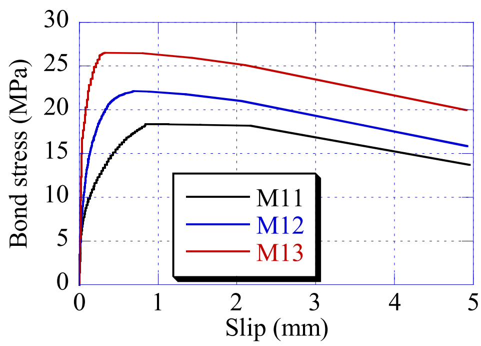


Figure 16. Effect of compress strength on bond stress without corrosion

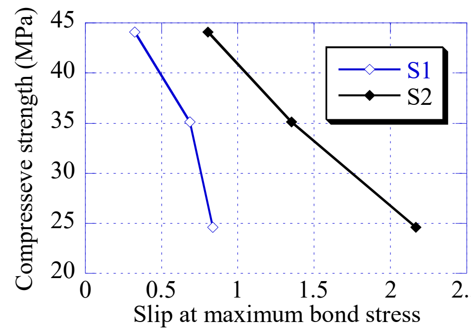


Figure 17. Effect of compressive strength on value of s_1 and s_2

Figure 18. Corrosion-induced cracks of reinforcement D12.

4. Conclusions

In this research, bond stress between a steel bar and concrete was investigated from pull-out tests with the effect of concrete grades and corrosion levels. Steel bars were electrochemical corrosion acceleration method. The following conclusions can be taken from the findings of this paper:

- The *k* value to predict the maximum bond strength between corroded steel bar and around concrete in the pull-out test was approximately 3.8. The bond strength from this experiment was much higher than that was predicted from CEB-FIP MC2020.
- Slip displacement and the range of slip displacement at the maximum bond stress were reduced when the concrete compressive strength was increased.

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