Experimental Study on Flexural Behavior of Reinforced Concrete Beams Corroded by Chloride Ion

Trung Hieu Nguyen, Van Quang Nguyen, Phuoc Lanh Le and
Manh Hung Nguyen

July 13, 2021

Experimental study on flexural behavior of reinforced concrete beams corroded by chloride ion

Trung Hieu Nguyen[1], Van Quang Nguyen[1], Phuoc Lanh Le[1], Manh Hung Nguyen[1]

[1] National University of Civil Engineering, Hanoi, Viet nam
hieunt@nuce.edu.vn

Abstract. Corrosion of reinforcing steel in concrete is one of the primary causes of deterioration of reinforced concrete (RC) structures. This paper presents an experimental research on flexural behavior of reinforced concrete (RC) beams corroded by chloride ion Cl^-. Two identical RC beams with dimensions of 150 × 200 × 2200 mm were cast in which one beam without corrosion as control beam specimen. Accelerated corrosion test by electro-chemical corrosion method was conducted on other RC beam, until cracks, caused by corroded steel bars, appeared on the beam surfaces. Next, the control and corroded beams were subjected to a four-point bending test until failure. The obtained experimental results allow to clarify the flexural behavior of corroded RC beam when the reinforcement is corroded. Next, a load-carrying capacity model is proposed to quantitatively estimate the residual flexural strength of corroded RC beam.

Keywords: Steel corrosion, RC beam, Concrete cover, Detetioration

1 Introduction

Steel corrosion in RC structures is one of the fundamental factors which cause the failure of RC structures. Building failure caused by steel corrosion mainly happens in the areas objected to carbon dioxide gas (CO_2) such as urban environment or the areas which are affected by chemical factors such as coastal area, industrial factories using chemicals (paper or fertilizer factory…). According to the statistic of organizations across the world, steel corrosion is the leading hazard of damage to the building. Many kinds of research show that 90% of buildings in the coastal area do not guarantee the requirement of concrete cover and the number of buildings strongly damaged after 10 years of use have accounted for a considerable amount.

Fig. 1 illustrates the typical failure of a RC beams. The increasing volume of reinforcement during the corrosion process causes the fracture of the concrete cover. The corrosion might happen in a part of the cross-section (the edge of column) or a total of that. It is possible to recognize the general point of RC structures failure caused by steel corrosion is the reduction of concrete's cross-section and reinforcement's cross-section, the decreased bonding capacity between reinforcement and concrete, which leads to decreased load-bearing of that cross-section [1][2][3].

Fig. 1. Corrosion deterioration of RC beams

Evaluating the load-bearing capacity of RC structures in general and in particular RC beams damaged by corrosion is the fundamental experience for repairing and strengthening damaged structure efficiently. The article will present the experimental investigation of residual capacity of RC beam corroded by chloride ion. The experimental research is carried out at Laboratory of Testing and Construction Inspection (LCTI), National University of Civil Engineering, Vietnam.

2 Experimental research

2.1 Test specimens and materials

This test program involves 2 RC beam specimens, D-1 and D-2, with a rectangular cross-section. Reinforcement details of test beams are presented in Fig. 2. Two beam specimens were geometrically identical with a length of 2200 mm, a depth of 200 mm and a width of 150 mm and were cast using the same batch of concrete. The thickness of the concrete cover was 20 mm. All beams had two longitudinal reinforcing steel bars of 12 mm in diameter (2∅12) at the tensile side and two bars with a diameter of 10 mm (2∅8) at compression side (Fig. 2), corresponding to a tensile reinforcement ratio of 0.75 %. The transverse reinforcement in the shear span was 6 mm in diameter, which was arranged with a space of 100 mm. The reinforcing bars used in the experimental program were deformed steel bars. All the specimens were designed to be subjected to flexural failure according to Vietnamese Standard TCVN 5574-2018 [4].

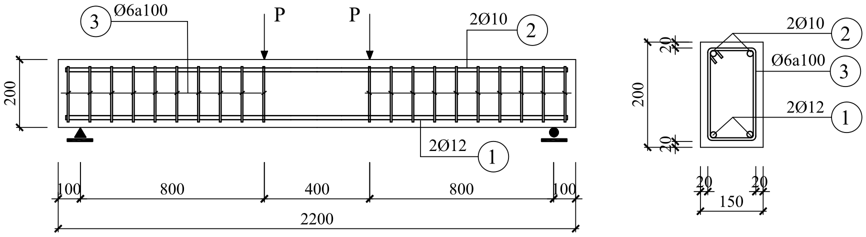

Fig. 2. Dimensions and reinforcement details of D-1 and D-2 beam specimens

Concrete mix ratio of the test specimens is shown in Table 1. The average cylinder strength at the age of 28 days is 31.5 MPa. Yield and fracture strengths of reinforcing bars with diameter ∅6 and ∅12 are 330 MPa and 515 MPa, respectively.

Table 1. Mixture proportions for 1m^3 of concrete (kg/m^3)

Cement PCB40	Sand	Coarse aggregate	Water	Average cylinder strength R28 (MPa)
305	680	1260	175	31.5

2.2 Electrochemically-accelerated corrosion test

After 28 days of curing, the D-2 beam was put into a tank with a certain amount of sodium chloride (NaCl) solution at a mass concentration of 5 %, as shown in Fig. 3. Twenty-four hours later, direct current was used in the electrochemically-accelerated corrosion test with the current density setting at 400 µA/cm^2. According to Faraday's Law, the corrosion time corresponding to a certain targeted corrosion ratio can be determined as following formula:

$$t = \frac{RFr\rho}{Mi} \tag{1}$$

where i is the current density set at 400 µA/cm^2 based on a the existing investigations [1][2][5], R is the target corrosion ratio, M is molar mass of Fe, that is, 56 g/mol, γ is rebar radius, F is Faraday constant, which is 96487 C/mol, ρ is the iron's density which is 7.8 g/cm^3, and t is theoretical duration of corrosion. With the target corrosion ratio of 10 %, based on Farraday's Law, the calculated corrosion time with 560 hours.

Fig. 3. Electrochemically-accelerated corrosion test

2.3 Flexural test setup and instruments

Fig. 4 illustrates the typical test setup for the current experimental investigation. These simply supported beams are loaded by a hydraulic jack through a two-loading-point system, creating two equal applied force P. Each loading point is 800 mm away from the beam support. One load-cell is used to measure the applied load. Three Linear

Variable Differential Transducers LVDT-1, LVDT-2, LVDT-3 are used to measure vertical displacements at two supports and at the mid-span section of the test beams. At every loading step, all test data including the applied load and vertical deformations are recorded with Data Logger TDS-530.

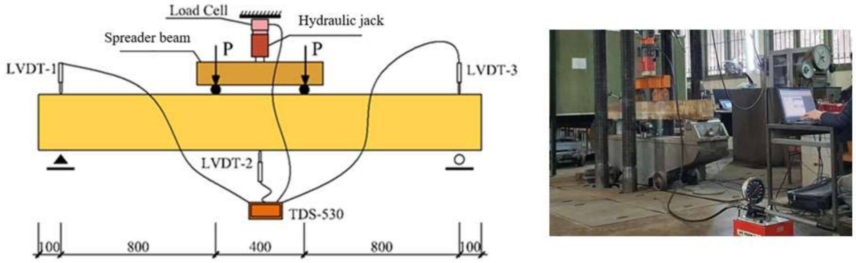

Fig. 4. Typical test setup and instrumentation

3 Test results and discusstions

3.1 Crack partent of RC beam due to corrosion and corrotion ration

After the accelerated corrosion, D-2 beam were taken out of the tank. Their surfaces were cleaned to remove all the rust. The width and length of cracks induced by corrosion were traced and measured at all sides of specimens using the crack width gauges. Fig. 5 illustrates the crack patterns on the four sides of corroded beam. It is observed that the main cracks induced by corrosion developed horizontally along the direction of tensile longitudinal reinforcement.

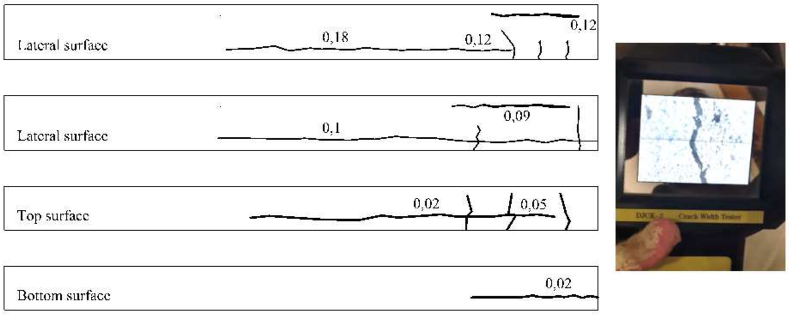

Fig. 5. Crack pattern at four side of D-2 specimen

It is well known that the corrosion degree of reinforcement, Q_{corr}, can be evaluated in terms of either mass loss, defined as follows:

$$Q_{corr} = \frac{W_0 - W_1}{W_0} \tag{2}$$

where W_0 is the original weight of reiforcement before corrosion, W_1 is the residual weight of reinforcement after corrosion. After flexural testing, all the ∅12 reinforcing bars were taken out of the tested beam and then were cleaned by steel brushes. After that, they were immersed in 10% hydrochloric acid (HCl) for 20 minutes to remove all the rust. Finally, they were measured to estimate their weight loss. In this study, the corrosion degree of ∅12 reinforcing bar was 12,6 %.

Fig. 6. Actual corrosion ratio of 7,6 % of ∅12 longitudinal reinforcement

3.2 Load-deflection curves and failure modes

Fig.7 shows the load-deflection relationships while Table 2 presents the ultimate capacitiess and deflection characteristics of two beams D-1 and D-2 obtained from flexural test. It can be seen that there are three different behavioral zones on each curve. The firstzone rep resents the stiffness off the uncracked beam D-1 and initial corrosion cracked beam D-2. The first visible crack loads were determined based on a first change in slope of the load–deflection curve. It can see that in this initial stage of loading, all specimens show almost the same stiffness. This has shown that the effect of steel corrosion is not significant when the magnitude of applied load is small.

The second zone represents the stiffness of the cracked section. For corroded beam D-2, the slope of the load-deflection curve was lower than that of the corresponding reference specimen D-1. The obtained results presented in Fig. 7 shows that the yield load (generally seen as a second change in slope of the load– deflection curve) of D-1 were higher than that of the corroded beam D-2. The third zone corresponds to a damaged beam with wide crack, yielding reinforcement and crushing of concrete in compressive zone. As shown in Fig. 7 and Table 2, the ultimate load carrying capacity of the control beam D-1 was significantly higher than that of the corroded beam D-2. Regarding the ductility of RC beams, the obtained results of deflection at the ultimate load, the obtained results showed a significant decrease in the case of reinforcement corrosion.

Table 2. Ultimate capacities and deflection characteristics of two beam specimens

Beam	Yielding load (kN)	Deflection at yielding load (mm)	Ultimate load (kN)	% Decreasing in ultimate load	Deflection at ultimate load (kN)
D-1	17.9	9.1	19.6	-	38.0
D-2	15.8	10	16.7	-15,0 %	18.6

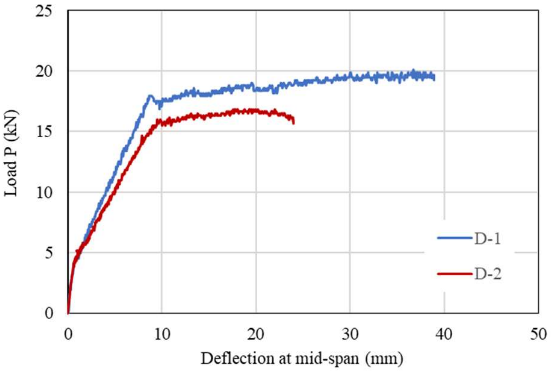

Fig. 7. Load – deflection curvres of two beam specimens

The mode of failure of the control beam and corroded beam were present in Fig. 8. All tested beams failed by yielding of steel reinforcement followed by crushing of concrete in compressive zone.

Fig. 8. Failure mode of D-1 and D-2 beams

3.3 Prediction for flexural strength of corroded RC beams

The prediction of flexural strength for RC beams with corroded longitudinal reinforcement is on the basis of the following general assumptions: (1) a plane section remains plane during bending; (2) the tensile strength of concrete is neglected; (3) the ultimate compressive strain of concrete, ε_{cu}, is equal to 0.0035.

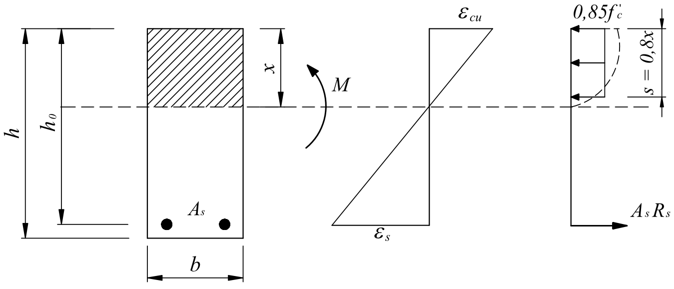

Fig. 9. Distribution of strains and stresses

In this research, the empirical formula developed by Du et al [6] to evaluate the residual strength, R_s, and the average cross-section, A_s, of corroded reinforcing bars was adopted:

$$R_s = \left(1 - 0.005Q_{corr}\right)R_{s,0} \tag{3}$$

$$A_s = \left(1 - 0.01Q_{corr}\right)A_{s,0} \tag{4}$$

where $R_{s,0}$ and $A_{s,0}$ are the intial strength and cross-section of non-corroded reinforcement, respectively. The depth of the neutral axis, x, and the ultimate moment capacity of the section, M_u, can be determined based on the following equations:

$$0.85f_c^{'}b\left(0.8x\right) = R_sA_s \tag{5}$$

$$M_u = R_sA_s\left(h_0 - \frac{0.8x}{2}\right) \tag{6}$$

The ultimate moment capacity can be transferred into the ultimate force (P_u), which is:

$$P_u = \frac{M_u}{L} \tag{7}$$

where *L* is the shear span, equals to 800 mm.

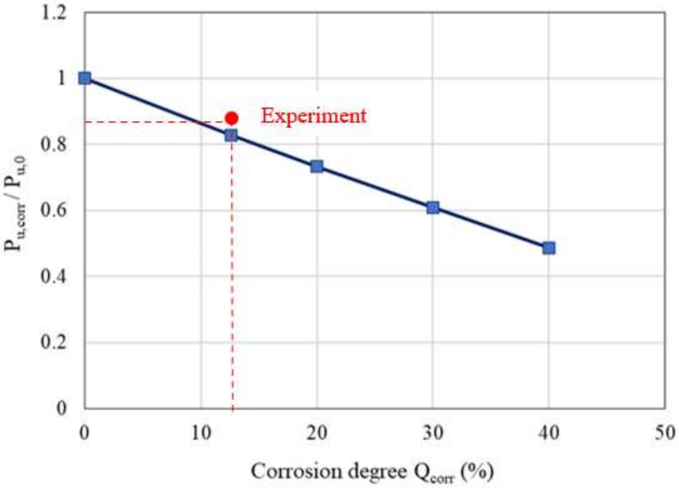

Fig. 10. Residual ultimate load of corroded RC beam D-2

Fig. 10 illustrates the residual ultimate force of corroded beam D-2 in which the vertical axis shows the ratio of the ultimate force of corroded and non-corroded beam section $P_{u,corr} / P_{u,0}$. Fig.10 indicates that the residual ultimate force of corroded beam significally decreased with an increase of the degree of corrosion. In comparison the predicted residual capacity with the experimental results at the corrosion degree of 12.6 %, it can be seen that the prediction value is consistent.

4 Conclusions

The results of the above-mentioned research have improved the understanding of the behavior of RC beams with corroded longitudinal reinforcement. Base on the obtained results in this study, the following conclusions are drawn:

- The yield and ultimate loads of corroded RC beam is smaller than that of the conventional beam. At an actual corrosion degree of 12.6 % of longitudinal reinforcement, compared with non-corroded RC beam, the ultimate capacity of corroded RC beam decreased by 15 %.
- With the increasing corrosion degree of longtitudinal reinforcement, the flexural strength and ductility of corroded RC beams degrades rapidly. Based on the experimental data and the main assumptions of flexural RC members, a prediction of the residual ultimate strength of corroded RC beam were taken. This approach consists of determining the reduction of tensile strength and cross-section of reinforcing bars.

References

[1] C. Fang, K. Lundgren, L. Chen, and C. Zhu, “Corrosion influence on bond in reinforced concrete,” *Cement and Concrete Research*, vol. 34, no. 11. pp. 2159–2167, 2004, doi: 10.1016/j.cemconres.2004.04.006.

[2] A. Castel, R. François, and G. Arliguie, “Mechanical behaviour of corroded reinforced concrete beams - Part 1: experimental study of corroded beams,” *Materials and Structures/Materiaux et Constructions*, vol. 33, no. 9. pp. 539–544, 2000, doi: 10.1007/bf02480533.

[3] J. Cairns, Y. Dut, and D. Law, “Structural performance of corrosion-damaged concrete beams,” *Magazine of Concrete Research*, vol. 60, no. 5. pp. 359–370, 2008, doi: 10.1680/macr.2007.00102.

[4] “TCVN 5574-2018. Design of concrete and reinforced concrete structures.” 2018.

[5] B. Hu, Y. Zhou, F. Xing, L. Sui, and M. Luo, “Experimental and theoretical investigation on the hybrid CFRP-ECC flexural strengthening of RC beams with corroded longitudinal reinforcement,” *Eng. Struct.*, vol. 200, no. September, p. 109717, 2019, doi: 10.1016/j.engstruct.2019.109717.

[6] Y. G. Du, L. A. Clark, and A. H. C. Chan, “Residual capacity of corroded reinforcing bars,” *Mag. Concr. Res.*, vol. 57, no. 3, pp. 135–147, 2005, doi: 10.1680/macr.2005.57.3.135.