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AN EXPERIMENTAL STUDY ON THE SHEAR CAPACITY OF CORRODED REINFORCED CONCRETE BEAMS WITHOUT SHEAR REINFORCEMENT

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Abstract

The effect of corrosion on the structural behavior of reinforced concrete (RC) beams without stirrups was experimentally investigated. A total of eight medium-scale RC beams were constructed without stirrups. The beams were 150 mm in width, 200 mm in depth, and 1100 mm in length. Test variables included three distinct degrees of corrosion (0%, 3.13%, 4.11%, and 4.93% by mass loss of steel rebar). Six beams were subjected to an accelerated corrosion test, while two beams served as non-corroded control beams. All beams were tested under four-point loading failure after the corrosion stage. The effect of various small degrees of corroded longitudinal reinforcements has been observed for the shear capacity. Test findings found that all tested beams had a brittle failure with tested corrosion degrees. Moreover, corroded beams that are exposed to 3% and 4% average corrosion degree reported having a larger shear capacity of approximately 7% compared to control beams. Lastly, beams with a corrosion degree of about 5% showed a decrease of 10% shear strength and a different failure mechanism with distinguished cracking patterns due to the formation of corrosion cracks along the longitudinal reinforcements.

Keywords: reinforced concrete beam; reinforcement corrosion; shear strength; no stirrups.

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1. Introduction

Corrosion of steel rebar is the most significant deterioration problem faced by reinforced concrete (RC) structures, especially for RC members without shear reinforcement (e.g. deck slabs, T-beam bridges). It leads to complex distributions of strains and stresses, highly nonlinear, path-dependent behavior of corroded elements. Corrosion products occupy more volume than the original steel thus resulting in cracking and spalling of the concrete cover. Corrosion of the steel reinforcement results in loss of bond between steel and concrete and a reduction in cross-sectional area of the reinforcing rebar.

The corrosion inflicts damages which induce a decrease in the performance as well as safety of RC structures [1]. In order to rehabilitate efficiently the damaged RC structures due to corrosion, the residual strength and failure mechanism of these structures must be determined. The majority of the previous studies have investigated mainly on the flexural behavior of corroded RC structures [2–4],

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but the effect of reinforcement corrosion on shear performance has not been given much attention. Recently, researchers have gradually focused on the shear strength of corroded beams [5–7], because the corrosion of reinforcement had altered the failure mode from bending for non-corroded beams to shear for corroded beams [8]. Therefore, it is necessary to design RC beams with a higher shear capacity to avoid such sudden failure.

Moreover, shear behavior of RC beams is a complex phenomenon that is still not very well understood. In general, shear mechanism and failure mode of RC beams depend on the shear span to depth ratio (a/d). The loads applied to RC beams are expected to be sustained by either beam mechanism, or by tied-arch mechanism. According to ACI 318-19 [9] and CEB-FIB Model Codes 2010 [10], the beams that have a/d ratios smaller than 2.0 are considered as deep beams. In general, deep beam can sustain high shear strength because of the tie-arched mechanism which distributes the load directly to the support through concrete compressive struts. This type of beam usually fails by shear compression failure which occurs at the tip of the shear crack when the compressive strength of the concrete is exceeded in the compression area. Meanwhile, the beams with the a/d ratios greater than 2.0 are slender beams. In slender beam, the beam mechanism plays a more important role. This is because the tied-arch mechanism has been weakened by the long distance between the loading point and the support. After the failure of beam mechanism, the diagonal cracks propagate rapidly to the loading point with the sudden breakdown of aggregate interlock which causes diagonal tension failure. Because of those different failure mechanisms, the international current design codes of RC structure have the recommendation on the design of shear in deep beam and slender beam separately while the Vietnamese standard TCVN 5574:2018 has not yet addressed such a significant and essential problem [11].

A number of studies have been reported to investigate the influence of cracking along the longitudinal reinforcing rebars on the shear capacity of corroded slender RC beams without stirrups. Firstly, a study of Toongoenthong and Maekawa [12] on spatially localized cracking and pre-induced damage along the longitudinal reinforcement of RC beam fabricated without shear reinforcement by simulating the corrosion effect has shown that the corrosion cracking does not necessarily always bring a non-favorable effect on the structural behavior of corroded RC members because of the steel and concrete bond performance. With the sufficient anchorage performance, the bond deterioration caused by corrosion cracks in the shear span may lead to tied-arch action with the increasing of shear capacity. Furthermore, it shares the same agreement with the research work conducted by Han et al. [13], in which the tension reinforcement was properly anchored using the hook details, the RC beams subjected to less than 5% corrosion degree showed about 40% enhancement in shear resistance capacity due to the transfer mechanism shifting from beam action to tied-arch action, regardless of the reduction in bond performance.

The shear behavior of RC beam without shear reinforcement, on the other hand, has been mainly relied on the bond behavior between longitudinal steel rebars and concrete, this is because of its important role in the load-carrying mechanism. Moreover, corrosion is one of the well-known reasons for the severe deterioration of bond strength in RC beams in the serviceability stage. Therefore, it is necessary to conduct the research findings of an experimental study on the structural behavior of shear-critical reinforced concrete (RC) beams subjected to chloride-induced corrosion in the flexural reinforcement with the beam fabricated without stirrups. This paper has experimentally investigated a total of eight RC specimens that were carefully designed and fabricated with the main objective is to evaluate the effect of corrosion of longitudinal reinforcement without anchorage on the structural behavior of corroded RC slender beams without stirrups, in which the corrosion degrees ranging from

0, 3.13%, 4.1%, to 4.93% were considered to be the main variables of the experimental test.

2. Experimental program

2.1. Materials

Table 1 presents the compositions of the concrete used consisting of Portland cement PCB30, river sand, crushed stone with a maximum diameter of 20 mm and water. The water-cement ratio is 0.42. The compression test was carried out on a group of three cubic specimens with the dimensions of 150 × 150 × 150 mm at 28-day. The results show that the average compressive strength of concrete is equal to 25.1 MPa, with a standard deviation of 0.4 MPa and a coefficient of variation of 1.5%.

Table 1. Concrete mix

Cement PCB30 (kg)	Fine aggregates (kg)	Coarse aggregates (kg)	Water (liter)	W/C
439	622	1211	185	0.42

The longitudinal reinforcements in the experimental beams are ribbed rebars with a nominal diameter of 16 mm. In the laboratory, the tensile strengths of steel rebars were also determined by the tension test, with the yield tensile strength and ultimate tensile strength are equal to 328.5 and 528.8 MPa on average, respectively. All steel rebars have been measured the length and the initial mass before corrosion.

2.2. Test specimens

In this study, each experimental beam was made of concrete having a compressive strength of B20 strength grade according to the Vietnamese standard TCVN 5574:2018 [11] and two longitudinal steel rebars with a nominal diameter of 16 mm at the bottom layer, without shear reinforcements (stirrups). The concrete cover depth is 42 mm from the bottom face of the beam. In the laboratory, there were 8 experimental beams with the dimensions of 150 × 200 × 1100 mm that were fabricated in the same batch and exposed the indoor environmental conditions. The layout of a typical experimental beam is illustrated in Fig. 1. Fig. 2 shows the concrete casting and the experimental beams and cubic specimens in the mold.

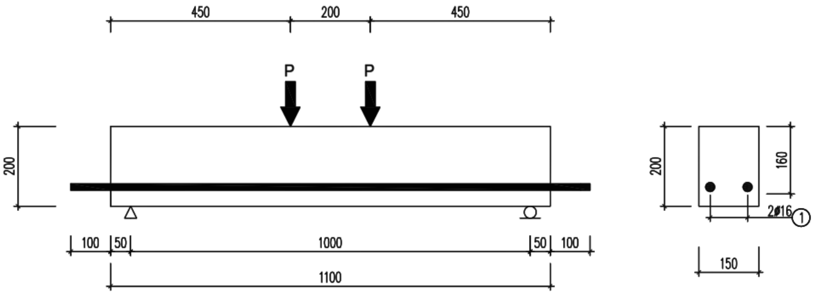


Figure 1. Layout of a typical experimental beam

(a) Concrete casting (b) Test specimens after concreting

Figure 2. Fabrication of the experimental beams in the laboratory

2.3. Accelerated corrosion test

After 28 days of curing, six beams were subjected to an accelerated corrosion test as illustrated in Fig. 3. The steel rebars were connected to the anode of the power supplier while the cathode is connected to a copper rebar embedded in the sodium solution with the concentration of 3.5%. Only the bottom face of the experimental beams is in contact with the solution. The solution level is maintained approximately 2 cm from the beam bottom. The steel rebars were not immersed in the solution to avoid locally corrosion at outer rebars.

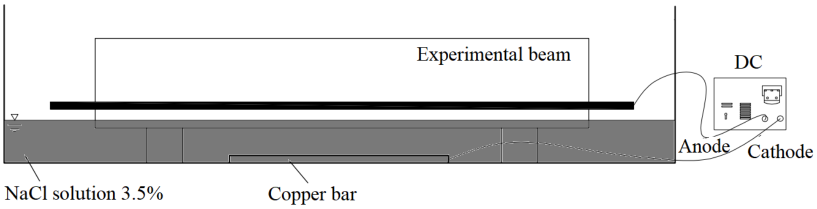


Figure 3. Detail of accelerated corrosion test

For longitudinal rebars, the corrosion degree of the beam tested was determined based on the mass loss of the metal. Before doing the corrosion experiments, the steel rebars were weighed to determine the initial mass (m_0). After the corroded beams were subjected to monotonic loading to fracture, and the corroded reinforcement was removed to assess corrosion measurement. Firstly, the reinforcement was cleaned by a bristle brush to eliminate concrete adhering to the surface of the rebars. The reinforcement is then immersed for one day with 3.5 g hexamethylenetetramine in a 3.5% HCl solution and then washed to eliminate corrosion products. The cleaning technique was also applied without corrosion to a control steel bar. The procedure was found to result in an insignificant loss of the control steel rebar. Therefore, to assess the remaining mass (m), the rebars were weighed. The corrosion degree of the reinforcement, c (%) is defined by Eq. (1), with m_0 (g) being the steel mass before corrosion, m (g) being the steel mass after corrosion, and Δm (g) being the steel mass loss by corrosion.

$$c\,(\%) = \frac{m_0 - m}{m_0} \times 100 = \frac{\Delta m}{m_0} \times 100 \tag{1}$$

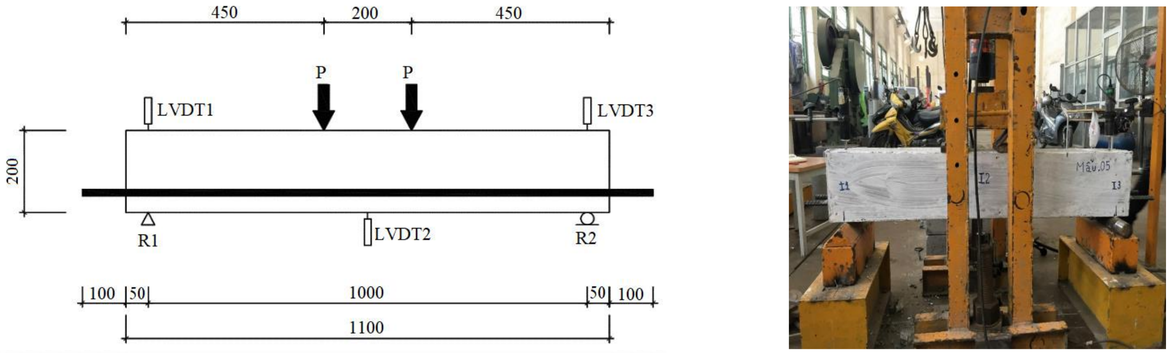
Table 2 shows the results of the determination of reinforcement corrosion degree for all testing beams. For each corroded beam, the corrosion degree is the average value of the two corroded rebars at the bottom layer (D16 steel rebars). The eight tested beams were divided into four groups named C0, C3, C4 and C5, respectively. Group C0 consisted of two control beams. Group C3, C4 and C5 had two corroded beams. Each experimental specimen was designated with two numbers: the first number indicating the average degree of corrosion (0%, 3.13%, 4.1% and 4.93%) whereas the second number stands for the numerical order of the beam.

Table 2. Determination of corrosion degrees of D16 steel rebars

Test group	Beams notation	Initial mass (g)	Remaining mass (g)	Mass loss (g)	Corrosion degree (%)	Average degree (%)
C0	C0-1	1987	1987	0	0	0
	C0-2	1956	1956	0	0	
C3	C3-1	1964	1909	55	3.16	3.13
	C3-2	1881	1822	59	3.10	
C4	C4-1	1993	1932	61	4.27	4.1
	C4-2	1950	1888	62	3.94	
C5	C5-1	1947	1865	82	4.99	4.93
	C5-2	1872	1797	75	4.87	

2.4. *Four-point loading test setup*

The experimental beams were all 150 mm wide, 200 mm deep, and 1100 mm long, with two d16 mm longitudinal reinforcing rebars. In order to consider a shear span to depth ratio of 2.5 for all beams, the shear span and effective depth were kept constant at 400 mm and 160 mm, respectively.



(a) (b)

Figure 4. Details of test specimens and loading arrangement of four-point loading test

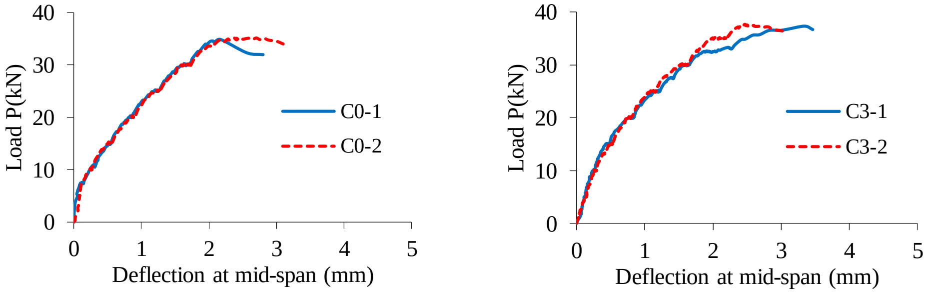
The test specimens were subjected to monotonic loading as illustrated in Fig. 4 to investigate the structural performance following the electrochemical accelerated corrosion of corroded beams and at least 28-day of curing with non-corroded beams. Over a clear span of 1100 mm, the beams were simply supported with two concentrated loads, which were both 400 mm apart from the supports R1 and R2. In order to calculate the vertical displacement of each beam measured, three Linear Variable Deformation Transducers (LVDTs) were mounted. The displacement transducer sets (LVDT1 and LVDT3) were used to calculate the displacement of the supports. In order to measure the displacement at the mid-span of the beam, the LVDT2 displacement transducer was used. A TDS-530 data-logger and a computer were connected to all displacement transducers to automatically collect measurement data to determine the relationship between the applied load and displacement.

The loading diagram and arrangement of the measuring instruments is shown in Fig. 4(a) while Fig. 4(b) shows a photo of the test carried out on a typical experimental beam. The applied load was continuously increased during the experiment until the beam failed. At the same time, to detect the presence of the first concrete crack, each test beam was carefully observed. The growth of concrete cracks was highlighted on the testing beams surface.

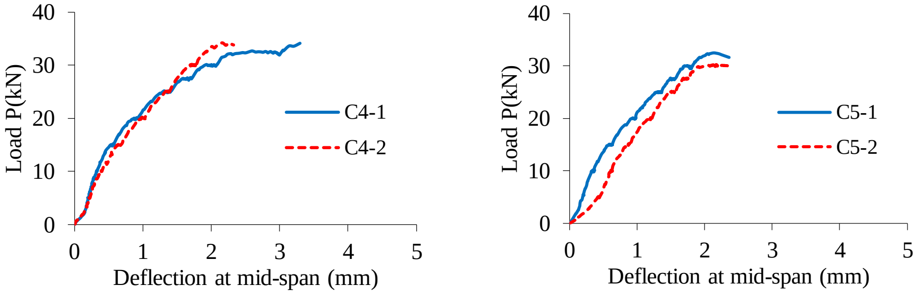
3. Results and discussions

3.1. Experimental shear capacity

A total of eight experimental beams were fabricated and tested in the laboratory. Six beams belong to groups C3, C4 and C5 were subjected to accelerated corrosion and the remaining two beams of group C0 were retained as non-corroded control beams. All beams were without compression



(a) Group C0 (b) Group C3



(c) Group C4 (d) Group C5

Figure 5. Load – deflection curves of the experimental beams

and transverse shear reinforcement. Test variables included the different degrees of corrosion of 0%, 3.13%, 4.1% and 4.93% on average. The shear responses of the experimental beams are shown in Fig. 5. For the control beams, three distinct phases will characterize the load - deflection response, as follows: (i) the first phase represents the action of an un-cracked beam with a gross inertia moment; (ii) the second phase represents the first shear crack with a reduced inertia moment; (iii) the third phase is the post-peak phase after failure. In the control beams C0-1 and C0-2, the first crack was observed at the load of approximately 7.5 kN, and shear failure occurred at the ultimate load of 34.8 and 35.1 kN, respectively. The corroded beams belong to the groups C3 and C4 exhibited shear behavior similar to that of the control beams. However, in the case of the beams C3-1 and C3-2 having the target corrosion degree of 3.16% and 3.10%, respectively, the shear strength was increased by approximately 7% (37.5 kN versus 35 kN on average) while in the case of the beams C4-1 and C4-2 the maximum capacity is nearly equal to the result of the control beams in group C0. These results can be explained that the bond stress between steel and concrete increases in the experimental beams having the corrosion degree smaller than 4% regardless of the corrosion crack occurred along the longitudinal rebars that is mentioned in the literature [13, 15].

The higher corrosion degree beams C5-1 and C5-2 displayed lower initial stiffness than the other tested beams with no clear shear crack was found in the beam web but the flexural cracks during testing. It is stated that the width of the splitting cracks gradually increased with load increase after the splitting cracking formed along the longitudinal reinforcing rebars, and failure occurred at 32.5 kN and 30.2 kN corresponding to a decrease of 10% in comparison with those of the control beams.

This is because the bond-loss between reinforcement and concrete dominates the failure mechanism of these corroded RC beams as the corrosion degree increases before sufficient tensile forces are developed in the longitudinal reinforcement to resist the external flexural moment.

Table 3. Summary of test results

Beam notation	Degree of corrosion c (%)	Ultimate load P (kN)	Failure mode
C0-1	0	34.8	Diagonal tension failure
C0-2	0	35.1	Diagonal tension failure
C3-1	3.16	37.3	Diagonal tension failure
C3-2	3.10	37.6	Diagonal tension failure
C4-1	4.27	35.4	Diagonal tension failure
C4-2	3.94	34.2	Diagonal tension failure
C5-1	4.99	32.5	Shear tension failure
C5-2	4.87	30.2	Shear tension failure

Table 3 synthesizes the main results obtained using the four-point loading test for each experimental beam, characterized by the corrosion degree of longitudinal reinforcements, ultimate load and failure mode. For each test group, the average value of the ultimate load is calculated and shown in Fig. 6 in order to compare the shear strength between the beams with different degrees of corrosion.

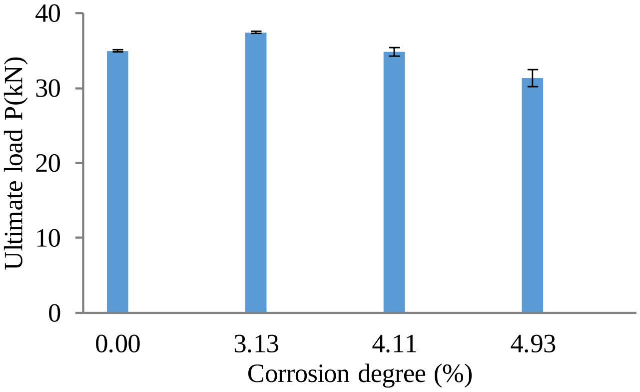


Figure 6. Comparison of average ultimate load between experimental beams

3.2. *Change in failure mode according to the corrosion degree*

The cracking patterns of the control beams and corroded beams are shown in Fig. 7 consisting of corrosion cracks marked red line and loading cracks (i.e. flexural cracking in loading process and shear crack at failure). For the test groups C0, C3 and C4, the corrosion cracks propagated for a limited length along longitudinal rebars, meanwhile they propagated for the total length of the corroded beams in group C5.

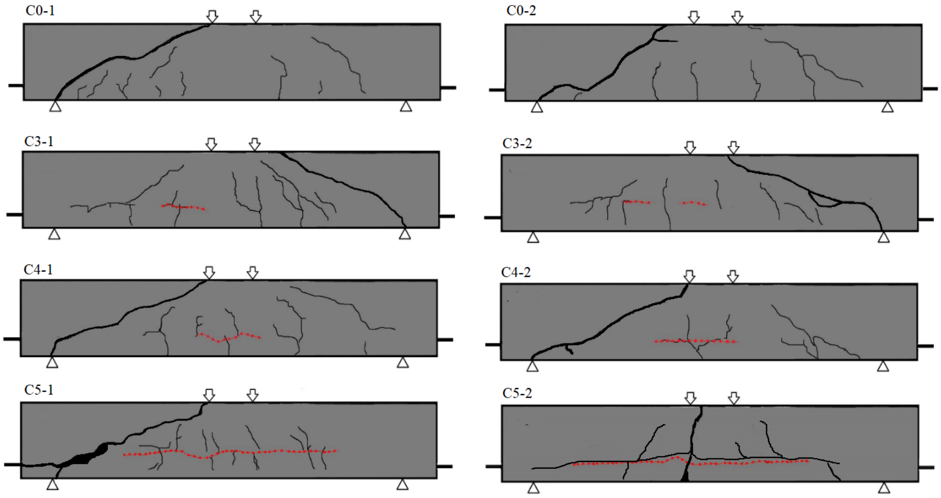


Figure 7. Crack pattern on the experimental beams

For the control beams C0-1 and C0-2, they showed typical diagonal tension failure mode which is a sudden failure of concrete in shear. In group C3, the development of vertical cracks (flexural cracks) at the bottom of the beam due to flexural tensile stress has led to diagonal tension failure. If the load on the beam increases, as it propagates from the support point of the beam towards the loading point, these cracks expand both in width and length and bend in a diagonal direction. The beams in groups C3 and C4 exhibited a similar failure mode and shear crack pattern to those of the reference specimen. The corroded beams C5-1 and C5-2, which have higher corrosion degrees, showed the different failure mode. In particular, as the degree of corrosion reached 5%, the C5-2 had a shear tension failure at final stage and illustrated a tendency that the width of the splitting cracks caused by corrosion increased significantly as the external load increased. Moreover, the diagonal cracks propagate horizontally along the rebars, it is mainly because of inadequate anchorage of the longitudinal rebars, and the specimen failed abruptly with the occurrence of the nearly vertical critical shear cracks at the maximum load-carrying capacity.

3.3. Comparison of the experimental and calculated results

In this section, the shear strengths of all experimental beams are calculated using prediction models given in the design standards. In the ACI 318-19 Code [9], the shear strength (denoted V_c) of corroded RC element without shear reinforcement is expressed as Eq. (2).

$$V_c = \left[0.66\lambda_s(\rho_w)^{1/3}\sqrt{f_c'} + \frac{N_u}{870A_g}\right]b_w d \tag{2}$$

where λ_s is the size effect modification factor that is calculated by $\sqrt{2\Big/\left(1+\dfrac{d}{254}\right)} \leq 1.0$; f_c' (MPa) is specified compressive strength of concrete. In this study, f_c' is taken as 20 MPa that is based on the compressive strength measured on cubes at 28 days; ρ_w is the longitudinal reinforcement ratio that is calculated as $A_s(1-c)/(b_w d)$, with A_s is the cross-sectional area of non-corroded steel rebar, c (%) is the corrosion degree calculated by mass loss, b_w is the smallest width of the cross-section in the tension area, and d is the effective depth of concrete section; A_g is the gross section area; N_u is the axial load taken as zero in this study.

In the European Code EC2 [14], the shear strength of RC element without shear reinforcement, denoted $V_{Rd,c}$, is calculated by Eq. (3), where $k = 1 + \sqrt{\dfrac{200}{d}} \leq 2.0$, $C_{Rd,c}$ is taken as 0.18 and not divided by the partial factor for concrete ($\gamma_c = 1.5$), ρ_l is the longitudinal reinforcement ratio that is calculated by the same formula in ACI 318-19 [9] for both non-corroded and corroded steel rebar, f_{ck} (MPa) is characteristic compressive cylinder strength of concrete that is taken as 20 MPa for the concrete used, k_1 is recommended to be 0.15, σ_{cp} (MPa) is compressive stress in the concrete from axial load or prestressing taken as zero in this study.

$$V_{Rd,c} = \left[C_{Rd,c}k(100\rho_l f_{ck})^{1/3} + k_1\sigma_{cp}\right]b_w d \tag{3}$$

According to the Vietnamese standard TCVN 5574:2018 [11], there is no recommendation for the shear strength calculation of corroded RC beams with or without shear reinforcements, as well as the differences in working mechanism of shear-critical RC beams with the varying a/d ratios. In general, the shear capacity of a RC beam, denoted Q, obtained from the shear force bearing by concrete (Q_b) and the shear force bearing by the shear reinforcement (Q_{sw}) on the inclined-section, as expressed in formula (4). Q_b is calculated by Eq. (5), with φ_{b2} being the coefficient concern the effect of longitudinal reinforcement, bond stress on the inclined-section with the value of 1.5; R_{bt} being the calculated tensile strength of concrete, b being the beam width, h_0 being the effective depth of the beam, and C being the projection length of the most dangerous inclined section on the longitudinal axis of RC member. Q_{sw} is calculated by Eq. (6), with φ_{sw} being the coefficient concern the decrease of the internal forces along the length C taken as 0.75; q_{sw} being the axial force in the stirrups over a length unit. For calculating the shear capacity of the non-corroded beams without stirrups, Q_{sw} is equal to zero, meanwhile Q_b ranges between $0.5R_{bt}bh_0$ and $2.5R_{bt}bh_0$ when the length C decreases from $3h_0$ to h_0. Based on the crack pattern of the experimental beams (cf. Fig. 7), the length C is essentially near to $2.5h_0$. Therefore, it is taken as $3h_0$ in the calculation. The calculated tensile strength of concrete is deduced from the measured compressive strength and taken as 1.35 MPa (not divided by the partial factor for concrete). Furthermore, it is limited to predict the shear capacity of the corroded beams with considering the reductions in tensile strength of concrete, cross-sectional area due to corrosion cracking.

$$Q \leq Q_b + Q_{sw} \tag{4}$$

$$Q_b = \frac{\varphi_{b2} R_{bt} b h_0^2}{C} \tag{5}$$

$$Q_{sw} = \varphi_{sw} q_{sw} C \tag{6}$$

Table 4. Experimental and calculated results of the shear strength

Average degree of corrosion c (%)		0	3.13	4.11	4.93
Average shear strength	TCVN 5574	16.2	-	-	-
	ACI 318-19	18.1	17.9	17.9	17.8
	EC2	27.9	27.6	27.5	27.4
	Test	35.0	37.5	34.8	31.3

The calculated results are summarized in Table 4. Fig. 8 presents a comparison for the shear strength of the experimental beams between the test results and the calculated values using the analytical models in the current design codes such as ACI 318-19 [9], TCVN 5574:2018 [11], and EC2 [14]. All models used have shown an underestimation in the prediction of shear strength for corroded beams without stirrup reinforcement. This leads to awareness in the procedure of design calculations for such elements. The calculated values by the EC2 model are nearer to the experimental results. Meanwhile, the results obtained from the analytical model from TCVN 5574:2018 shared the largest distinction in comparison with the experimental results, this is because the design code does not have any specific recommendation regarding the cases of shear-critical RC beam without shear reinforcement. Normally, the calculated shear strength is reduced with increasing the corrosion degree of longitudinal reinforcement, because the models in the design codes consider only the decrease of reinforcement ratio based on the mass loss uniformly along the length of the steel rebar. As consequence, the reduction in calculated shear strength is negligible, approximately 2% for the tested range of the corrosion degree, meanwhile there was 10% in the test results. Thus, it is necessary to account the reduction of the concrete compressive strength and the width of the cross-section in the tension area due to corrosion cracks, as well as the spatial variability of steel rebar mass loss in order to obtain more precision when predicting the shear strength of corroded RC beam without shear reinforcement.

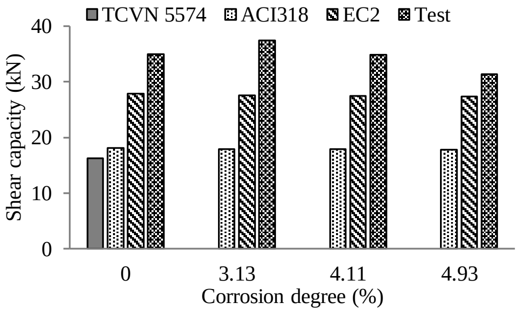


Figure 8. Comparison of the test and calculated results

4. Conclusions

This paper presents the experimental results obtained from the four-point loading test carried out on the eight experimental beams with the dimensions of 150 × 200 × 1100 mm having the average corrosion degrees ranging from 0% to 5% that determined based on the mass loss of corroded steel rebars using accelerated corrosion test. The results allow for assessing the shear response of the control and corroded beams without stirrups. Some conclusions can be given as follows:

- When the tension reinforcement was not properly anchored, the shear strength of corroded RC beams without stirrups decreased by 10% with the corrosion degree equal to or larger than 5%. The failure mode of corroded specimens tends to shift from diagonal tension failure which is casually seen in shear test to shear tension failure. This is because the bond strength between the tension reinforcement and surrounding concrete decreases rapidly due to the corrosion cracks forming along the tension reinforcement. Therefore, sufficient tension force in the longitudinal reinforcement cannot be developed fully.

- In the corroded beam group C3 in which the tension reinforcement subjected to corrosion degree smaller than 4%, specimens showed about 7% enhancement of shear strength, compared with control beam group C0. Even with 4% degree of corrosion in tension reinforcement, the maximum shear capacity of corroded beams C4-1, C4-2 was similar compared with that of the beams C0-1 and C0-2 due to the increase in bond stress between steel and concrete regardless of limited crack-mouth opening occurrence due to corrosion.

- The prediction models in the ACI 318 and EC2 codes can underestimate the reduction in shear strength for corroded RC beams without shear reinforcement because they consider only the decrease of the cross-sectional area of corroded longitudinal rebar in the formula.

- Currently, it is limited to predict the shear capacity of corroded RC beams using the model mentioned in the Vietnamese standard TCVN 5574:2018. Thus, it is necessary to investigate influencing parameters of deteriorated structures under corrosion, such as mechanical properties of damaged concrete (e.g. compressive strength, tensile strength), loss of steel-concrete bond strength and steel cross-section due to corrosion, as well as their spatial variability for improving the precision of predicted values.

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