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EXPERIMENTAL STUDY ON THE BEHAVIOR OF ECCENTRICALLY COMPRESSED CORROSION-DAMAGED REINFORCED CONCRETE COLUMNS

Nguyen Manh Hung[a], Nguyen Trung Hieu[a,*], Nguyen Van Tuan[b], Pham Xuan Dat[a]

[a]*Faculty of Building and Industrial Construction, Hanoi University of Civil Engineering, 55 Giai Phong road, Hai Ba Trung district, Hanoi, Vietnam*
[b]*Faculty of Building Materials, Hanoi University of Civil Engineering, 55 Giai Phong road, Hai Ba Trung district, Hanoi, Vietnam*

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Abstract

This paper presents an experimental study of corrosion-damaged reinforced concrete (RC) columns under eccentric compression. Three RC concrete column specimens, identical in geometry, reinforcing steel bars, and concrete mix, were fabricated. One undamaged control specimen served as the control group, while the other two column specimens underwent corrosion due to chloride ion exposure. All specimens were subjected to a minor eccentric compressive load. The test results have revealed the behavior of RC columns damaged by steel corrosion. Additionally, a comparison of the load-bearing capacity of corrosion-damaged RC columns was conducted between calculation and experiment. The results indicate a close alignment between calculated and experimental outcomes. Furthermore, the degree of decrease in the load-bearing capacity of corrosion-damaged RC columns over time was evaluated based on the axial load-moment interaction diagram. This evaluation considered the influence of the reduction in concrete strength and the cross-sectional area of the reinforcement.

Keywords: corrosion; RC column; eccentric load; load-moment interaction diagram; experimental study.

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1. Introduction

The corrosion of reinforcement is one of the major causes of deterioration in reinforced concrete (RC) structures. It primarily affects structures exposed to aggressive environments, such as coastal areas with chloride contamination, or industrial facilities like paper mills and fertilizer factories. Additionally, urban areas can also be impacted by the carbonation phenomenon. Research institutions worldwide have provided statistics showing that reinforcement corrosion is the leading cause of structural damage and premature degradation in RC concrete [1–3]. Numerous investigations have reported rapid deterioration of RC structures in coastal areas, even within 10 years of construction [4, 5]. This deterioration is often attributed to the low quality and inadequate thickness of the concrete cover.

Corrosion of reinforcement leads to an increase in volume, resulting in cracking and detachment of both the protective concrete layer and the steel bar. This corrosion can occur in specific cross-sectional areas (such as the side of a column) or across the entire cross-section of the structure [6, 7]. One common phenomenon observed in damaged RC structures due to reinforcement corrosion is the reduction of the concrete cross-section and the cross-sectional area of the reinforcement. This reduction leads to a decrease in the bonding between the reinforcement and the concrete, ultimately resulting in a reduction of the bearing capacity of the structure [7–11].

*Corresponding author. *E-mail address:* hieunt@huce.edu.vn (Hieu, N. T.)

Eccentric compression of RC columns is a common phenomenon in construction practice. The load acting on the center creates an uneven stress distribution over the cross-section and the bearing state of the section will be different depending on large or small eccentricity conditions. Especially, as the eccentricity is large, the tension zone is mainly ensured through the work of the tensile reinforcement. Therefore, it will significantly affect the bearing capacity of the column as corrosion of reinforcement occurs in this area [12–15]. Indeed, studies on corroded RC columns, particularly those subjected to eccentric compression, are relatively limited. Rodiguez et al. [10] conducted an experimental study involving 24 RC column specimens that were subjected to monotonic axial compressive loads. The results of the study indicated a decrease in the compressive bearing capacity of the corroded columns over time. Revathy et al. [14] conducted an experimental study to investigate the behavior of corroded RC columns. Small-sized RC columns were prepared and artificially corroded to various corrosion levels, ranging from 10% to 25% loss of steel mass. The study aimed to evaluate the effects of corrosion on the ductility, ultimate strength, and final strain of the RC columns. Xia et al. [15] conducted a test involving 24 RC columns, out of which 20 were subjected to corrosion and 4 remained uncorroded. The study revealed that the corrosion of reinforcing steel bars in RC columns led to various types of concrete damage, including cracking, spalling, and delamination of the concrete cover. This deterioration not only resulted in a reduction of the mechanical properties of the columns but also increased the loading eccentricity. The increased eccentricity further accelerated the failure of the columns.

This study aims to investigate the behavior of corrosion-damaged RC columns under eccentric compressive loads. The obtained results will provide valuable insights into the performance and durability of RC columns exposed to aggressive environments. The experimental study was carried out at the Laboratory of Testing and Construction Inspection, Ha Noi University of Civil Engineering.

2. Experimental research

2.1. Specimen and material properties

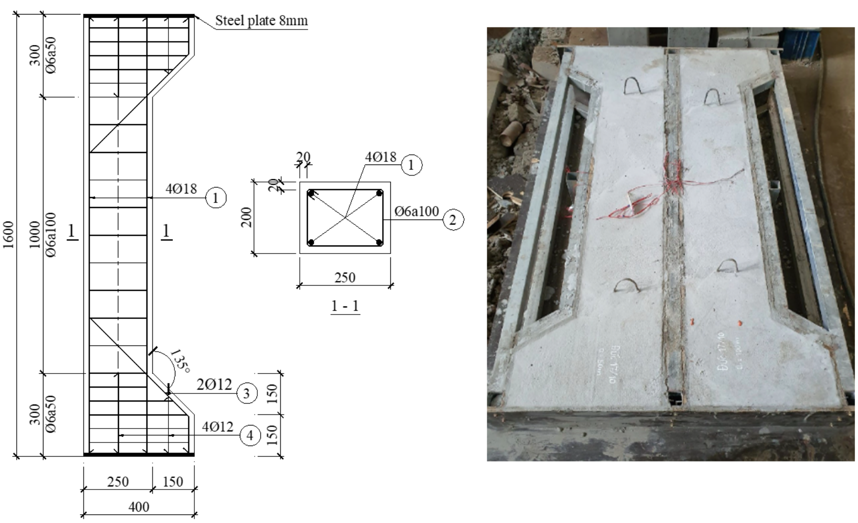


Figure 1. Details of test specimens

A total of three specimens were fabricated and subjected to a combination of axial load and flexural moment. The test specimens consisted of one control specimen, named C-0, and two corrosion-damaged specimens, named C-C-1 and C-C-2. All columns were comprised of a test zone in the center of the specimens with a rectangular cross-section of 200 × 250 mm and a corbel with a cross-section of 200 × 400 mm at each end of the columns, resulting in a total height of 1600 mm. Each column specimen was longitudinally reinforced in the test region with four deformed rebars with an 18 mm diameter, corresponding to a steel reinforcement ratio of 2.0%. The transverse reinforcement was made of 6 mm diameter ties with a spacing of 100 mm in the test zone, and a reduced spacing of 50 mm was adopted in the corbel end to avoid localized damage. The concrete cover was 20 mm. Details of the test specimens are provided in Fig. 1.

Table 1 presents concrete mix proportioning with an achieved 28-day compressive strength of 31.5 MPa. This strength was determined by three cuber samples with a size of 150 × 150 × 150 mm. The longitudinal bars ∅18 and stirrups ∅6 had yield strengths of 410 and 330 MPa, respectively.

Table 1. Concrete mix proportioning (kg/m^3)

Cement (kg)	Sand (kg)	Crushed stone (10-20mm) (kg)	Water (kg)	Water/Cement (W/C) ratio	The 28-day compressive strength (MPa)
390	680	1210	178	0.45	31.5

2.2. *Accelerated corrosion test by electrochemical method*

Fig. 2 shows a schematic description of the accelerated corrosion test by the electrochemical corrosion method. After the age of 28 days, two test specimens C-C-1 and C-C-2 were placed in a storage tank and immersed in a 5% NaCl solution. In the accelerated corrosion test, the direct current (D.C) was employed to simulate the corrosion of reinforcing bars that occur under actual environmental conditions for RC structures The DC density of 25 μA/mm^2 was chosen based on the cross-sectional area of the reinforcement and previous studies conducted by [16–19]. This current density was maintained continuously throughout the experiment to minimize the test duration.

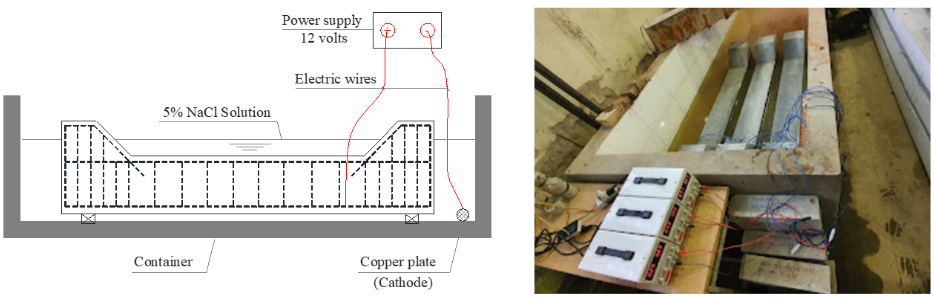


Figure 2. Setup for accelerated corrosion test by electrochemical method

The test was continued until two stopping conditions were met: (1) cracks appeared along the longitudinal reinforcement length and (2) cracks consistent with actual corrosion damage to RC structures became discernible to the naked eye. Taking into account the factors mentioned above and the experimental conditions, an experimental duration of approximately 60 days was selected.

After conducting the accelerated corrosion test, two specimens were retrieved from the tank and left to air-dry. Following this, the distribution of cracks that had arisen due to the corroded reinforcement on the column surface was measured and depicted (Fig. 3). More details about the crack results can be found in Fig 6. Following the finishing of the compressive test, the corroded longitudinal bars were extracted from the test columns, cleaned of rust, and weighed to determine the weight loss resulting from corrosion.

(a) C-C-1 specimen (b) C-C-2 specimen

Figure 3. Illustration of surface crack on the test specimens C-C-1 and C-C-2

2.3. *Testing column specimens under eccentric compressive load*

Fig. 4 illustrates the eccentric compression test setup, while Fig. 5 shows a test in progress. Each specimen was tested under monotonically increasing eccentric load. A hydraulic actuator was employed to apply axial load to the test specimens. The upper ends of the test specimens were connected to the actuator, while the lower ends were supported by a steel reaction frame. Both of the end supports were designed as hinged connections, initially set with an eccentricity e_0 of 30 mm, simulating columns experiencing minor eccentric compression. This eccentricity equals the distance between the applied load and the centroid of the column's cross-section in the test region. To ensure the lateral stability of each specimen, both in-plane and out-of-plane, suitable steel supports were used, as illustrated in Fig. 5.

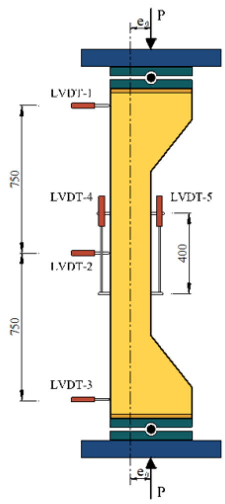


Figure 4. Test setup

Figure 5. Image of a test in progress

To determine the horizontal displacement of the column due to the applied load and monitor the functionality of the joints at both ends, three electronic horizontal displacement transducers (Linear Variable Differential Transducers - LVDTs) are installed. These LVDTs are positioned at the two ends of the column and the cross-section located within the column height is designated as LVDT-1, LVDT-2, and LVDT-3.

The lateral displacement at the midpoint of the column, f, will be determined using the following formula (1):

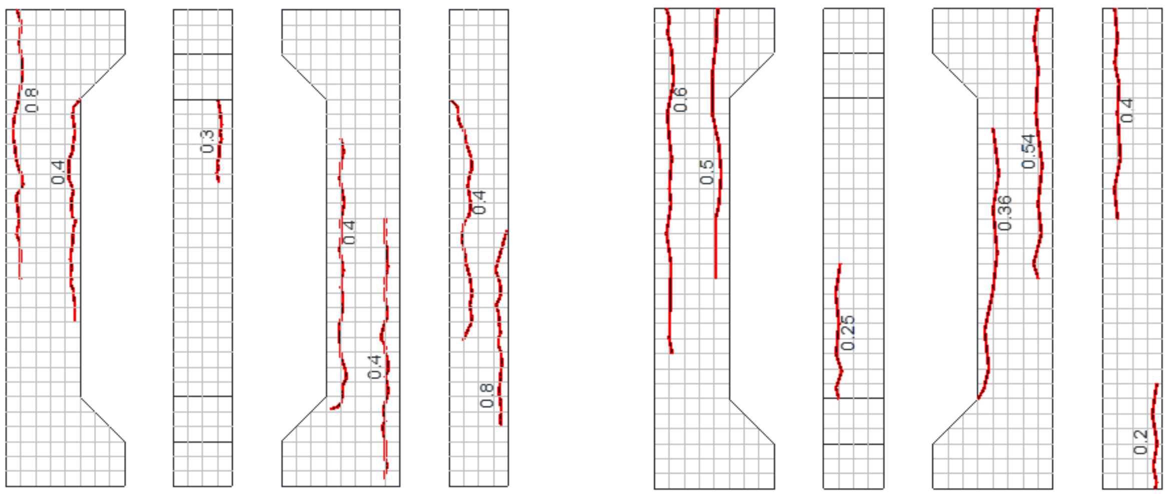
$$f = f_2 - 0.5\,(f_1 + f_3) \tag{1}$$

where f_1, f_2 and f_3 is the reading on the corresponding measuring instruments of LVDT-1, LVDT-2 and LVDT-3.

3. Results and discussions

3.1. Crack status and corrosion degree of longitudinal steel bars

Fig 6 presents the crack patterns observed on all four sides of the two test specimens, namely C-C-1 and C-C-2, following the completion of the accelerated corrosion test. Over the course of 60 days, cracks became visible on the surface of the column specimens, primarily running along the length of the longitudinal steel bars within the columns. These cracks exhibited widths ranging from 0.3 mm to 0.9 mm. The observed crack patterns confirm that the accelerated corrosion test effectively replicates the corrosion of steel bars, closely resembling real-world environmental conditions.



(a) C-C-1 specimen (b) C-C-2 specimen

Figure 6. Crack maps attributable to steel corrosion on the four sides of test columns

Fig. 7 depicts the rust condition observed on the longitudinal reinforcement steel bars, while Table 2 provides information on the weight loss resulting from corrosion. The values presented in Table 2 represent the averages of results obtained from two longitudinal reinforcement samples, each measuring 500 mm in length and extracted from the middle of the test specimen. With regard to stirrups, the measurement results indicate that stirrup corrosion averaged around 6.5% in the two test specimens C-C-1 and C-C-2.

(a) The longitudinal steel bar (∅18)

(b) The stirrup (∅6)

Figure 7. Images of rust condition on the longitudinal steel bar

Table 2. Degree of corrosion of reinforcement ∅18

Specimen	Initial mass (g)	Mass of specimens after corrosion (g)	The mass loss (%)
C-C-1	976	904	72
C-C-2	976	921	56

3.2. Behavior of test specimens under eccentric compressive load

a. Failure mode

Fig. 8 illustrates the photos of the control and corroded specimens at failure, along with the corresponding failure regions. The failure mode for both the control and corroded specimens was typical. Cracks were observed in the compression zone, leading to a reduction in the bearing capacity of the test specimens. This mode of failure is suitable for cases with small eccentric effects.

(a) C-0 specimen

(b) C-C-1 specimen

Figure 8. Failure of tested specimens

b. Load-lateral displacement relationship

The compressive load versus lateral mid-height displacement curves for both the control and damaged columns are depicted in Fig. 9. The summary of the ultimate load and the corresponding lateral mid-height displacement is provided in Table 3.

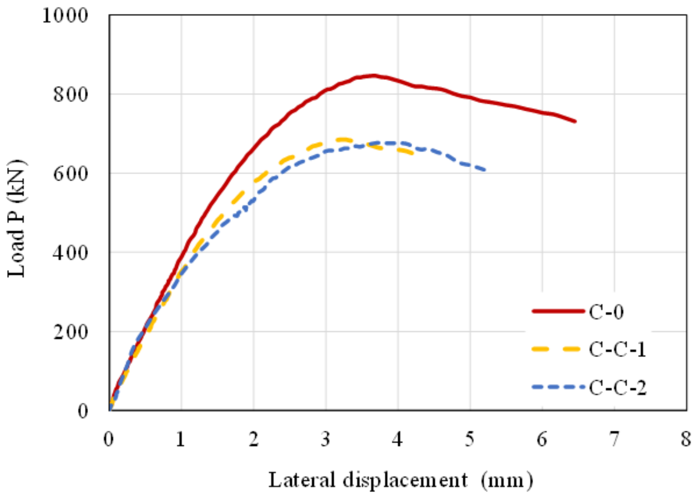


Figure 9. Load-lateral displacement at the mid-height of test specimens relationship

The results presented in Fig. 9 indicate that the stiffness of the two tested columns, which were damaged by reinforcement corrosion, has been reduced. When compared to the control specimen (C-0) subjected to the same applied load, the damaged columns exhibit larger lateral displacements. However, the degree of stiffness reduction is relatively small and becomes noticeable only when the applied load exceeds 400 kN.

Regarding the ultimate load experienced by the test columns, the findings shown in Fig. 9 and Table 3 demonstrate a significant decrease in the bearing capacity of the columns affected by corrosion. The corrosion of reinforcement leads to the formation of cracks in the protective concrete layer, while the reduction in reinforcement diameter is the primary cause of this capacity reduction.

Table 3. Ultimate axial load and corresponding lateral displacement

Specimens	Ultimate axial load P_{ul} (kN)	Corresponding lateral displacement (mm)	% decrease in P_{ul}
C-0	856	3.8	-
C-C-1	734	3.1	-14.2 %
C-C-2	719	3.5	-16.0%

3.3. Comparison of the loadbearing capacity of corrosiondamaged RC columns according to calculation and experiment

After 60 days of accelerated corrosion testing, the extent of deterioration in concrete compressive strength was assessed for the C-C-1 and C-C-2 specimens. Following the completion of the compressive tests on the corroded column samples, crack-free concrete sections from each column were selected for drilling concrete samples. In the case of each tested column, three cylindrical samples measuring D × H = 70 × 140 mm were extracted to determine compressive strength. The average compressive strength of the concrete beams was calculated and then normalized to a standard cylinder sample size of 150 × 300 mm, with a value of 30.2 MPa. The average reduction in compressive strength between the pre- and post-corrosion test measurements was found to be 4.1%, indicating that the decline in concrete compressive strength over the 60-day accelerated corrosion test period was negligible

For the longitudinal reinforcement bar, after the column compressive test, two corroded longitudinal steel bars were extracted from the area close to the corbel for use in the tensile strength test. The test results revealed an average tensile strength value of 402 MPa, indicating a decrease of 1.95% from the tensile strength of uncorroded steel

Fig. 10 shows the axial load-moment (P-M) interaction diagrams for the control and corrosion-damaged column specimens according to TCVN 5574:2018 [20]. The experimental results of the ultimate axial load and corresponding flexural moment are represented as data points. It is evident from the figure that the predicted results closely align with the experimental results.

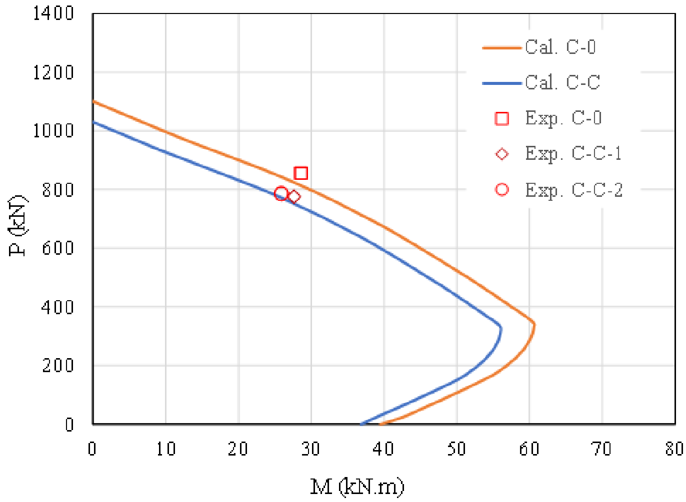


Figure 10. Comparison of predicted and experimental results

4. Assessment of decrease in load-bearing capacity of corrosion-damaged RC columns over time

When the reinforcement is corroded, not only does the cross-sectional area decrease, but the mechanical properties of the reinforcement, such as tensile strength and maximum relative deformation, are also reduced. In this experiment, the reduction of strength and cross-sectional area of the reinforcement is determined using experimental formulas suggested by Du et al. [6] as follows:

$$f_{y,corr} = (1 - 0.005Q_{corr})\, f_y \tag{2}$$

$$A_{s,corr} = A_{s0}\,(1 - 0.01Q_{corr}) \tag{3}$$

$$Q_{corr} = 1 - \left(\frac{d_{corr}}{d_0}\right)^2 \tag{4}$$

where f_y and f_{corr} represent the tensile strength of the reinforcement in the initial and corroded situations, respectively. $A_{s,0}$ and $A_{s,corr}$ indicate the initial cross-sectional area and corroded cross-sectional area, respectively. Q_{corr} denotes the level of corroded reinforcement as a percentage. d and d_{corr} represent the initial and corroded diameters of the reinforcement, respectively.

According to [21], the reduction in the diameter of the reinforcement due to steel corrosion is determined as follows:

$$d_{corr} = d_0 - 0.0232 I_{corr}(t)\, t_p \tag{5}$$

In formula (5), I_{corr} represents the velocity of steel corrosion (μA/cm^2), and t_p is the time in years referring to the period from the point of corroded reinforcement to the point of calculating the reduction in the diameter of the reinforcement. According to [6], the value of I_{corr} depends on two parameters: the water-to-cement (W/C) ratio and the thickness of the concrete cover, c. It is determined as follows:

$$I_{corr}(t) = 32.1 \frac{\left(1 - \frac{W}{C}\right)^{-1.64}}{c} t_p^{-0.29} \tag{6}$$

Based on the formula provided earlier and the experimental data presented in Table 2, it is possible to predict the reduction in the diameter of the reinforcement over time for an RC column located in a coastal area, where steel corrosion occurred 10 years after the initial use. By applying the appropriate values to the formula, the predicted reduction of the reinforcement's diameter over time can be calculated. The resulting predictions are illustrated in Fig. 11.

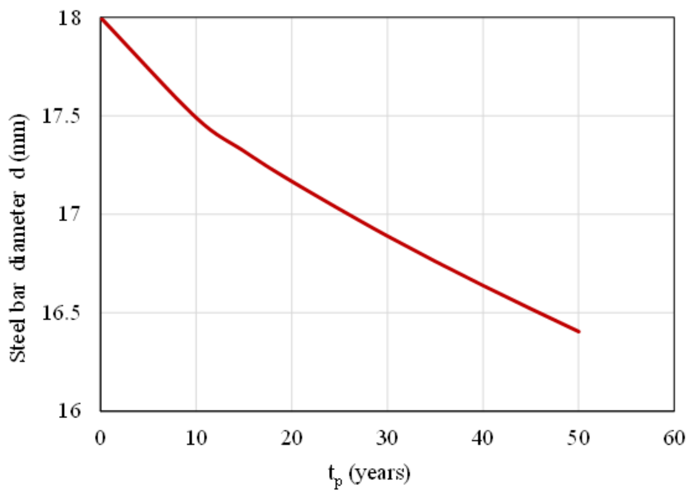


Figure 11. Reduction of steel diameter over time due to corrosion

Regarding the decrease in concrete compressive strength due to steel corrosion, Mohsen et al. [22] conducted several electrochemical corrosion experiments in an environment containing chloride ions. The results indicate that the reduction in concrete strength depends on the corrosion rate of the reinforcement. The researchers have proposed an experimental formula to determine the concrete strength when steel corrosion occurs, as follows:

$$f'_{c,corr} = (1 - \lambda) f'_c \tag{7}$$

where f'_c and $f'_{c,corr}$ represent the concrete strength in the initial and corroded reinforcement situations, respectively. λ represents the percentage of decreased compressive strength of concrete, which is determined by the corrosion level of the reinforcement and the water-to-cement (W/C) ratio. Specifically, when W/C is equal to 0.45, the values for λ are determined as follows:

$$\lambda = 2.29 Q_{corr} - 1.73 \tag{8}$$

Based on the predicted results of the reduction in concrete compressive strength, the diameter of steel reinforcement, the interaction diagrams P-M of the RC column are established and presented in Fig. 12 for the 30-year, 40-year, and 50-year time points from the date of use. These diagrams clearly illustrate the level of reduction in the load-bearing capacity of the RC column over time. This information is crucial for the repair and strengthening of RC columns during their service life to ensure the required longevity and structural integrity.

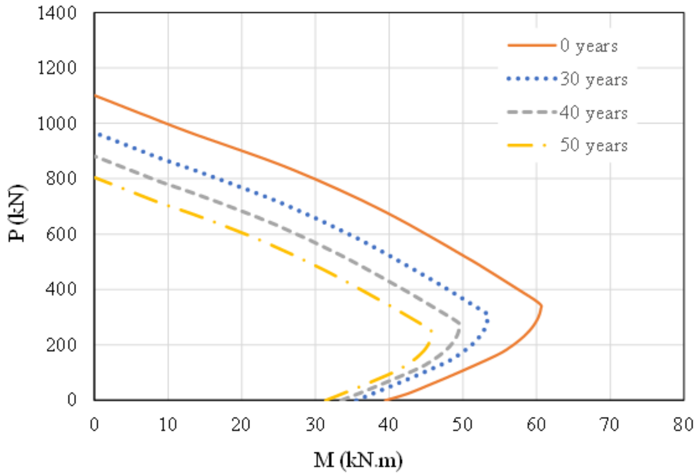


Figure 12. Interactive diagram P-M over time

5. Conclusions

This paper presents an experimental investigation of corrosion-damaged and eccentrically compressed RC columns with a rectangular section. Three specimens were tested to failure, with one serving as a control specimen and the other two intentionally damaged by steel corrosion. Based on the obtained results, several conclusions can be drawn:

- The accelerated corrosion test proved to be a suitable method for rapidly inducing the corrosion of reinforcement steel bars in RC columns. The selection of the appropriate DC played a crucial role in simulating the corrosion that occurs in actual environmental conditions for RC structures.

- Corrosion-damaged RC columns exhibited a decrease in stiffness and load-bearing capacity. The results showed that with an average corrosion rate of 7.0%, the load-bearing capacity of the RC column decreased by 18%.

- The degree of reduction in the load-bearing capacity of the corrosion-damaged RC column over time was evaluated based on the predicted results of the reduction in concrete compressive strength and the diameter of steel reinforcement. This result serves as the foundation for the strengthening of corrosion-damaged RC columns, ensuring their longevity and structural integrity.

It is essential to further study the effect of steel reinforcement in RC columns subjected to large eccentric compressive loads. This aspect is crucial for understanding the behavior and performance of RC columns under such loading conditions.

These conclusions highlight the importance of considering corrosion effects in the design, maintenance, and evaluation of RC structures. Understanding the impact of corrosion on the structural performance of RC columns is vital for ensuring their long-term durability and safety. Further research in this area can contribute to the development of more effective corrosion prevention and mitigation strategies in RC structures.

Acknowledgements

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