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-RESEARCH ARTICLE-

Analytical Study on the Effect of Corrosion to the Construction Performance

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Abstract

Corrosion is one of the most important factor to achieve in completing the service life of reinforced concrete structures also cause significant losses in energy damping capacities of structures. In this study, the reinforced concrete column designed in ½ geometrical scale was subjected to accelerated corrosion test for 26.5 days under 1 ampere constant current. As a result of the experiment, weight loss and strength reductions was obtained. Loss of strength in reinforcement due to corrosion damage was obtained with experimental procedure. Loss of cross section and reduction of compressive strength of concrete were obtained with empirical formulas in the literature. Thanks to this data, 3 different scenarios applied on a sample building in Hatay province. Static pushover analyzes of the sample building designed in accordance with the regulations were carried out with Sap 2000 program under the specified corrosion scenarios. The load-displacement curves obtained by the scenarios are compared with the curves of the reference building. As a result of the comparisons, it was observed that corrosion damage caused significant loss in horizontal load carrying capacity of the building. The corrosion scenarios show that corrosion in columns or beams changes collapse modes of the structure.

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Introduction

Structures are exposed to various environmental influences throughout their service life. Concrete, which is a composite material due to its structure, is formed as a result of chemical reactions. Due to the environmental factors, the chemical influences taken from outside cause significant changes in the structure of the concrete. Although the compressive strength of concrete is emphasized in our country, it is a fact that the durability and usability of the concrete is more important as it decreases the service life (Baradan et al., 2013).

When the existing building stock in our country is examined, it is seen that a large part of it consists of reinforced concrete buildings. Therefore, corrosion is one of the biggest problems facing existing structures. In reinforced concrete structures, the moisture that forms in the concrete, CO_2, salt from the use of sea sand, sulfur in the air, disrupts the passive structure of the concrete (changing the pH) and leads to the corrosion of the reinforcing iron. Field investigations after the devastating earthquakes that occurred in the past years indicate that reinforcement corrosion is one of the most important factors in the loss of structural integrity (Ma et al., 2012). Considering the structural performance of an existing structure exposed to corrosion damage; Taking into account the mechanical properties of concrete and reinforcement, the adherence between the concrete and the reinforcement, the cross section area of the reinforcement and the confinement effect on the projected stage, it does not give very realistic results (Yang et al., 2016). When the current construction regulations are examined, the designer does not have a directional reduction in the degree of corrosion damage. Therefore, the main subject of this study is to examine the losses in the horizontal load bearing and ductility capacities during the earthquake due to corrosion damage. For this reason, one ½-sized reinforced concrete column specimen was subjected to accelerated corrosion damage. After the experiment, mass and strength losses occurred in reinforcement of the concrete column specimen were investigated. Then, various scenarios were produced on the example of reinforced concrete building constructed in Hatay province and the strength losses of horizontal load bearing capacities were investigated. Three scenarios were produced and empirical formulas in the literature were used for the strength loss of concrete.

Materials and Methods

Material and Specimen Properties

A specimen of ½-scale reinforced concrete columns was produced to expose the accelerated corrosion test. In order to determine the physical and mechanical properties of the produced concrete, 3 samples were collected from the cube samples with dimensions of 150x150x150 mm during the concrete casting process. The produced concrete samples were kept in their molds for 48 hours and then removed from their molds. Concrete pressure tests were carried out by applying standard curing in lime-saturated water pools with a temperature of 20 ± 2 ºC until the day of 180th. At the end of the 180th day, the cube strength of the samples was obtained as 18.87 MPa (15.09 MPa equivalent cylinder strength).

The details of the column specimen produced are shown in Figure 1. The column has a rectangular cross section and the cross-sectional dimensions are 20cm × 25cm. The height of the column is 80 cm and is supported by a foundation pier with dimensions of 60cm × 45cm × 30cm. 4Φ16 longitudinal reinforcement and Φ8/10cm transverse reinforcement are used in the column.

In contrast to the widespread use of stirrups, it has been no densification. The footing is reinforced with Φ8/10cm stirrups as shear reinforcement and the upper and lower bending reinforcement 3Φ16. The concrete cover of the column is 2 cm and the concrete cover of the foundation foot is 5 cm. The sample produced in Figure 2a is shown before concrete casting. Figure 2b shows the application to prevent the effects to the footing reinforcement of the electrical current. The parts of the column longitudinal reinforcements within the foundation were insulated with epoxy resin and the base surface was bitumen to prevent the penetration of NaCl ions into the base (Figure 2c).

Figure 1. Specimen Detail

| a) | b) | c) |

Figure 2. a) Sample mold plan, b) Insulation of sample, c) Insulation of anchor rods with epoxy resin.

The produced sample was kept in the column mold and removed from the mold after 48 hours. Then, water cure was applied to the column sample for 7 days and kept in laboratory for 28 days.

Accelerated Corrosion Test

In accelerated corrosion testing, the voltage may be constant. Also it can be studied to as a constant current. In this study, the accelerated corrosion test was carried out under constant current. When it is worked in constant voltage on accelerated corrosion tests, the current passing through the circuit must be recorded with a data logger. If it is worked in constant current, the duration of the test can be determined by the Faraday Equation (Equation 1), since the current is constant. However, if the current is constant on corrosion test, it is not possible to know the effect of concrete quality, concrete cover, and chloride ion concentration on corrosion resistance.

$$Weight\ loss(g) = \frac{t(s) \times 0.434 \times 55,847\left(\frac{g}{mol}\right)}{2 \times 96487(coulomb)} \tag{1}$$

Electrochemical method (external current) was applied to corrode the test specimen. For this purpose, a PVC pipe with a diameter of 36 cm was fixed on the column specimens as shown in Figure 2a and a water tank was formed. This water tank was fixed on the foundation with special waterproof products. The inside of this tank was filled with a 5% NaCl solution up to 70 cm in height and an electrolysis medium was occurred (Figure 2b). The electrolysis cell diagram of the specimen subjected to accelerated corrosion testing under constant current was shown in Figure 2c. Accelerated corrosion testing was carried out for 26.5 days under constant 1 ampere current. Firstly, the weights of the reinforcements within the column specimen were weighed and their initial weights were determined before they were corroded. Then, taking into account the weights of both the longitudinal reinforcement and the stirrups in the 70 cm NaCl solution, the test time was determined before starting the corrosion test with the help of the Faraday equation. During this time, the column specimens were subjected to accelerated corrosion tests.

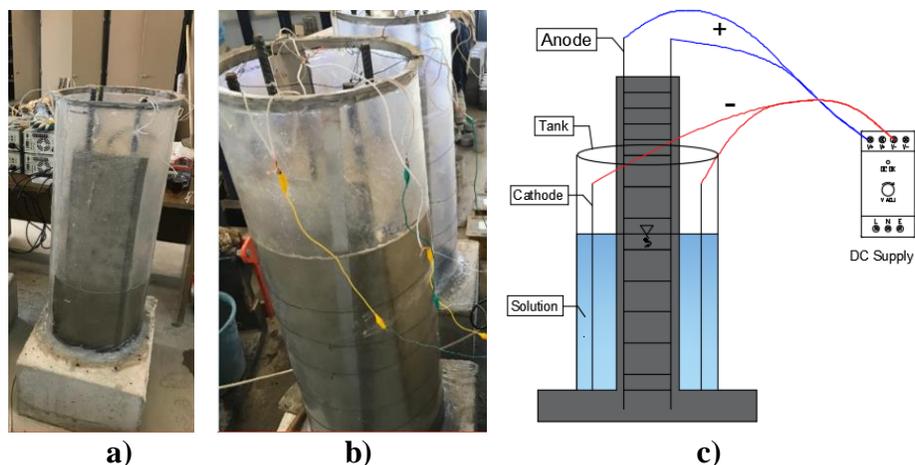**a)**   **b)**   **c)**

Figure 2. a) Preparing the tank and fixing it on the foundation, b) Filling with NaCl solution,   c) Electrolysis cell diagram of specimen.

The rust formation in the column specimen and the corrosion in the reinforcements are shown in Figure 3a. In Figure 3b, column samples were broken and the distribution of corrosion on reinforcements was examined.

a)   **b)**
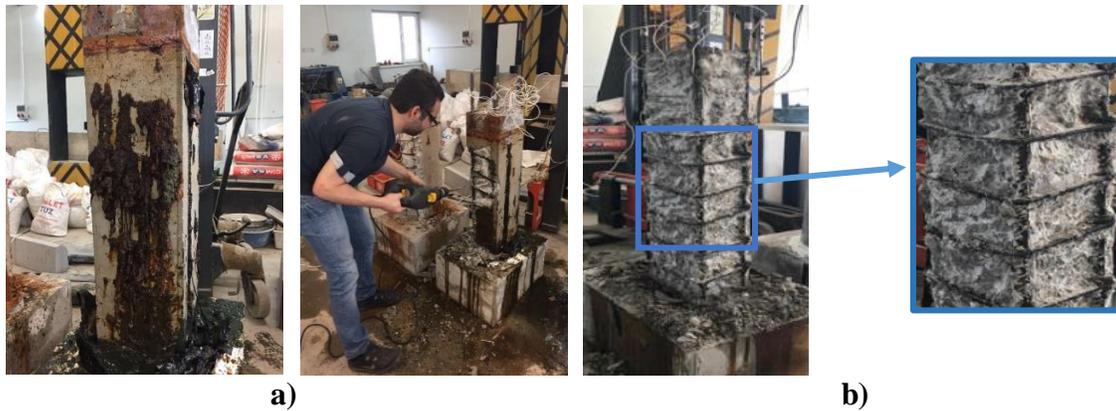
Figure 3. a) View of samples after the experiment, b) Peeling of concrete covers and corrosion distribution of specimen.

The longitudinal reinforcements and stirrups from the column specimen were first examined visually and then the rust and concrete residues on the reinforcements were cleaned with HCL acid solution. Figure 4 shows both the appearance of the reinforcements after corrosion tests and the appearance of the reinforcements cleaned with HCl acid solution.
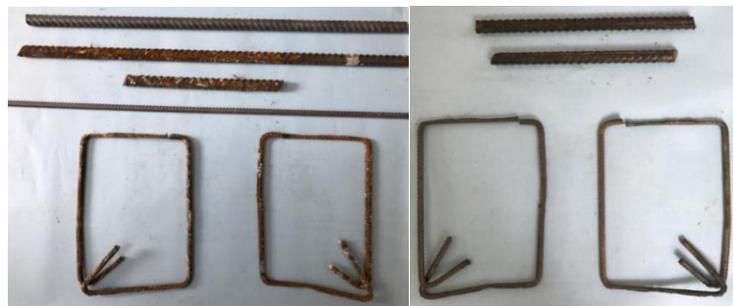
Figure 4. View of reinforcements after accelerated corrosion test.

After 26.5 days, 663.61 gr of theoretical weight loss was expected in the reinforcements. However, after cleaning with the acid solution, a weight loss of 774.44 gr was observed. According to the results, both theoretical and actual weight losses were very close to each other. Tensile tests were performed on column longitudinal reinforcement and stirrup. The yield strength of the longitudinal reinforcement was 441 MPa and the yield strength value was obtained as 386.2 MPa after the corrosion process. Yield strength value of stirrup was obtained as 426 and 345 MPa respectively before and after corrosion.

Modifications of material strengths

In the study, depending on the level of corrosion, the decrease in the mechanical properties of the concrete and reinforcement diameter and the loss of adherence were considered (Berto et al., 2008). The decrease in the mechanical properties of concrete was calculated according to the following equation (Hakan et al., 2012).

$$f_c^* = \frac{f_c'}{1 + K\epsilon_1/\epsilon_{co}} \tag{2}$$

Here, f_c^* reduced strength, f_c' characteristic compressive strength of concrete, K surface roughness and diameter-dependent coefficient (It is recommended by Cape (Cape, 2018), for normal reinforcements as K = 0.1), ϵ_{co} deformation at maximum compressive strength, ϵ_1 is the average deformation value perpendicular to the direction of compressive in cracked concrete. According to equation 3, the value of ϵ_1 is calculated depending on the crack width in the concrete:

$$\epsilon_1 = \frac{n_{bars}*w_{cr}}{b_o} \tag{3}$$

Here, n_{bars} refers to the number of longitudinal reinforcements, w_{cr} is the crack width occurring in the concrete (Equ. 4) (Hakan et al., 2012):

$$w_{cr} = 2\pi(v_{rs} - 1)0.0116I_{corr}t \tag{4}$$

Here v_{rs}, is the ratio of volumetric increase in the volume of pure material due to the oxide, I, current density ($\mu A/cm^2$), 0.0116, conversion coefficient from $\mu A / cm^2$ to mm / year and t is the time, year. As a result of corrosion, the existing reinforcement diameter is calculated according to mass loss and compared with Equ. 5 (Yuksel & Seda, 2013).

$$\Phi(t) = \Phi_o - 2P_x = \Phi_o - 2i_{corr}\,k\,(t - t_{in}) \tag{5}$$

Here; $\Phi_{(t)}$, the diameter of the reinforcement on t time (mm), Φ_0 is the nominal reinforcement diameter (mm), i_{corr} corrosion rate, t_{in} refers to the time elapsed from the start of corrosion on the reinforcement surface (year), P_x shows the average processing value (mm) of the attack. P_x, processing value is defined by the loss in the diameter of the reinforcement (Rodriguez et al., 2001, Bentur et al., 1997).

Static Pushover Analysis

Static pushover analysis has been implemented with the help of SAP 2000 program for a sample building in Hatay province (CSI Sap, 2000). The corrosion resistance of this building is taken as reference and three different corrosion scenarios are selected in this building. These; 3 different ways of corrosion damage occurred in columns, beams and both columns and beams. For this, building modeling was done in SAP 2000 program. The example building is shown in Figure 5 and the geometric dimensions and other features of the building are summarized in Table 1.
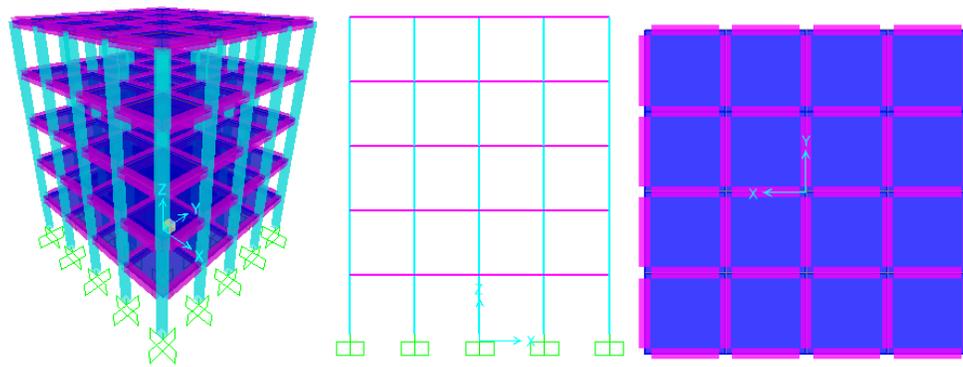

Figure 5. Plan view of the sample building.

Table 1. Summary of the geometric dimensions and other features of the building.

No	Description	Information
1	Number of floors	5 (Basement + floor + 3 normal floors)
2	Plan dimensions	12m*12m
3	Flooring thickness	15cm
4	Beam sizes	40cm * 60cm
5	Column sizes	40cm * 60cm
6	Concrete and Steel grade	15.09 MPa/ S420
7	Material mechanical properties for scenarios	8,55 MPa (Concrete) 386.2 MPa (Longitudinal reinforcement) 345 MPa (Transverse reinforcement)
8	Flooring loads	Dead load 0,15t/m^2, Live load 0,2 t/m^2
9	Wall load	0,15 t/m^2
10	Earthquake Zone	1
11	Building Importance Factor	1
12	Ground class	Z2
13	Structural behavior coefficient	8

Plastic hinges are defined according to Fema-356 rules to take into account the non-linear behavior of the columns and beams, which are defined as rod elements in the SAP 2000 program (Fema-356, 2000). The effective bending stiffness of the sections were determined according to TEC-2007 and the plastic hinge lengths were entered as L = 0.5h (TEC, 2007). Also, considering the confinement effects of the sections, moment-curvature relations were determined by Sap 2000 program. Figure 6 shows the properties of the sections and the relations of moment curvature.
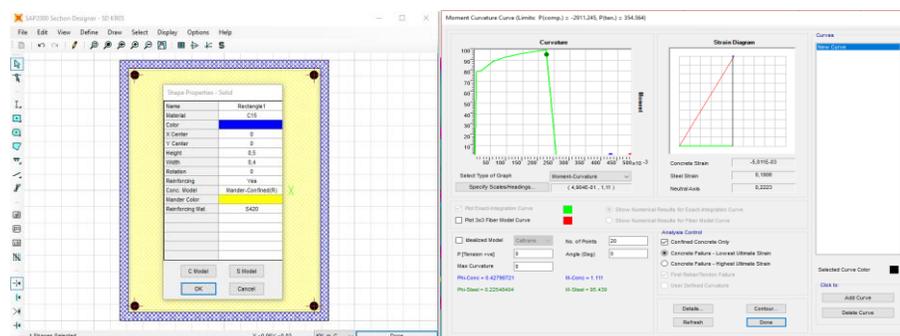

Figure 6. Column and beam cross-sectional area and moment curvature relations of elements

Results

The base shear force-top displacement curves obtained as a result of the static pushover analysis performed under different corrosion scenarios in the X direction of the building are shown in Figure 7 collectively.
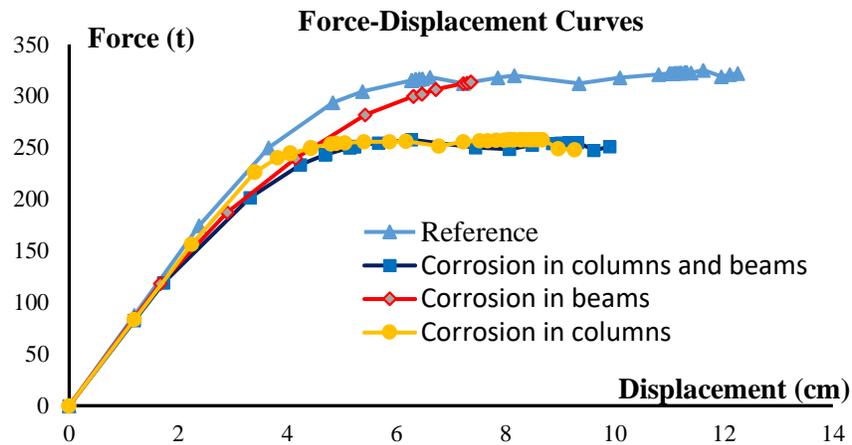
Figure 7. Load-displacement curves of all scenarios

When the load-displacement curves were examined, the largest base shear force was obtained from the reference scenario as 325.36t. The smallest base shear force was obtained from the column-beam corrosion damaged scenario as 255.48t with a decrease of 21.4%. When a comparison was made in terms of displacements, the maximum peak displacement was obtained as 12.26 cm in the reference building, while the smallest displacement occurred in the corrosion damaged scenario in beams of 7.36cm with a 40% decrease. Table 2 summarizes the maximum load and displacement values of the scenarios.

Table 2. Static pushover results of scenarios.

Scenarios	Top Displacement (cm)	Force (t)
Reference	12,26	325,36
Corrosion in Columns and Beams	9,92	255,48
Corrosion in Beams	7,36	313,7
Corrosion in Columns	9,28	257,93

When the scenarios were examined, the corrosion damage occurred in the columns or beams changed the collapse mode of the structure. As a result of corrosion damage to the beams, the ductility of the structure decreased significantly (40%). If the damage occurred in the columns, the horizontal load bearing capacity of the structure decreased by 21%. As a result of the analyzes, it was seen that the corrosion damage occurred in the columns, the damage levels were increased by using the plastic hinges in the beams at full capacity and then the damage levels of the plastic hinges in the columns increased and the building reached its collapse position (Figure 8a). On the other hand, the consist of corrosion damage in the beams, not to the progress of the damage level of the hinges in the beams, the hinge formation jumped to the columns, and therefore the upper floor beams remained in the elastic region of the structure reached the collapse position. (Figure 8b). In the reference building, the plastic hinges were formed on the lower floors and the columns and beams on the upper floors exhibited an elastic behavior (Figure 8c).
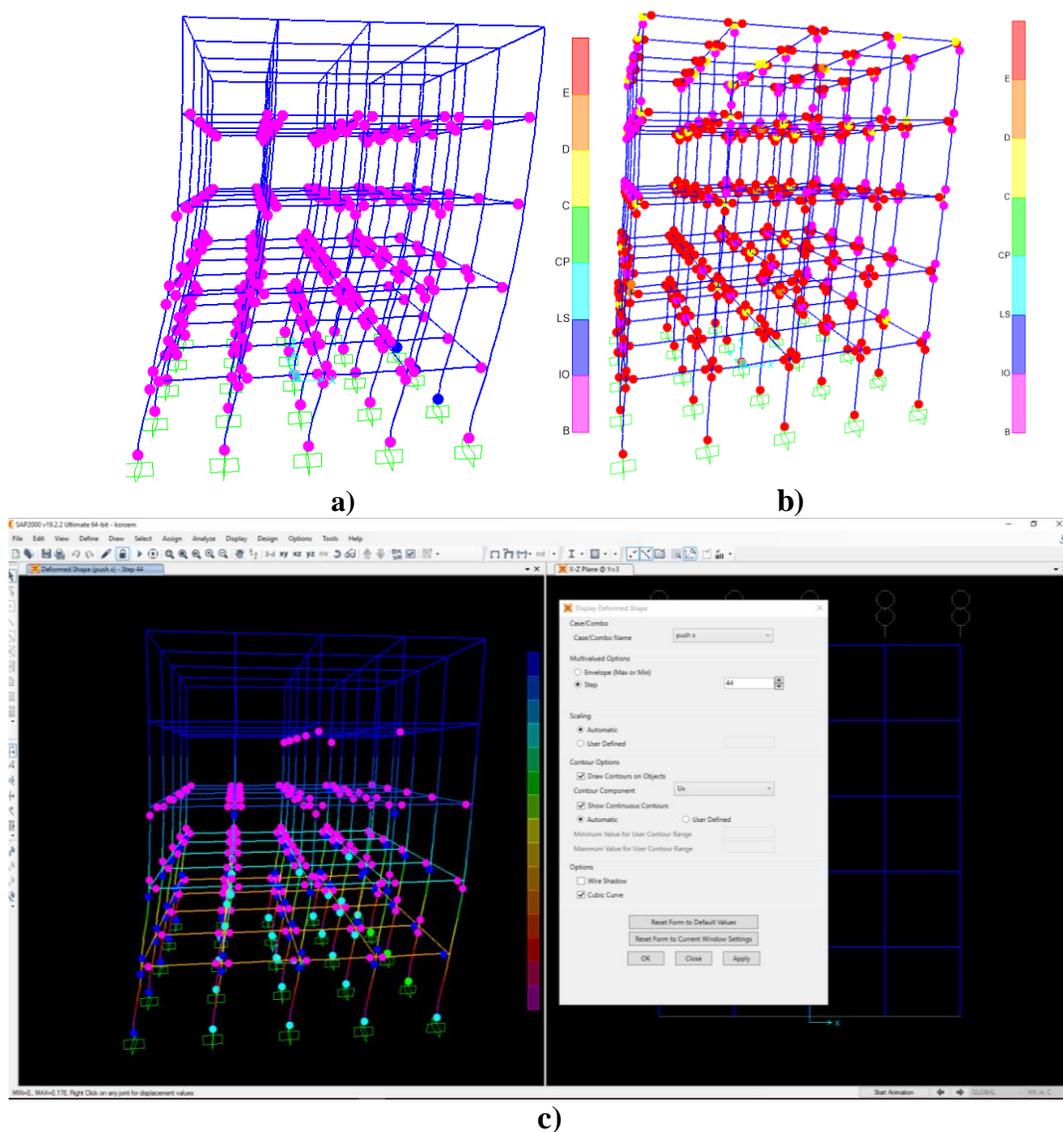
a)   **b)**

c)

Figure 8. a) Development of plastic hinges in beams, b) Development plastic hinge in columns, c) Hinge status in reference building.

Discussion

In this study, the concrete column sample which was produced to expose to accelerated corrosion test was subjected to corrosion damage in laboratory conditions. In this regard, the specimen prepared at ½ scale to represent the existing structures was subjected to accelerated corrosion test to achieve the desired corrosion level. As a result of the accelerated corrosion test, the actual corrosion levels of the reinforcements were calculated from the coupons from the column reinforcement. As a result of the visual inspection, the distribution of corrosion on the column transverse and longitudinal reinforcement was investigated in terms of the type of corrosion. The results were analyzed by applying various scenarios on a sample building in Hatay. As a result of the static pushover analysis applied to the scenarios, the base shear forces and structural displacements in the structure were interpreted according to the condition of the corrosion damage occurred in the column and/or beam elements. In the study results; Corrosion damage in the

columns caused significant losses in the carrying capacity of the structure, whereas corrosion damage occurred in the beams decreased the structural ductility to a great extent. In the light of this information, it is recommended to take into account in the calculations to be carried out at the planning stage if there is corrosion damage in the evaluation of the earthquake performance of the existing structures or if the development of corrosion in the new buildings will be possible.

Acknowledgements

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