# ANALYSIS OF RC STRUCTURES CONSIDERING REBARS CORROSION

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## ABSTRACT

One of the most detrimental processes which adversely affects the life of a reinforced concrete structure is the corrosion of the reinforcement. This concerning process whose long-term indications are revealed in the forms of durability and serviceability degradation, weakens the structural performance widely, specially in the structures which are exposed to a chloride bearing environment.

The major aim of this research is to investigate the effects of corrosion as one of the most important causes of degradation on the seismic response of RC frames. Here numerical studying has been conducted using a finite element program named COM3. The results were verified using experimental data obtained previously. Cracking, loss of cross sectional area and change in bond strength are some items which have been taken into account. For evaluating the seismic performance of the structures, incremental dynamic analysis is done.

## INTRODUCTION

Corrosion of the reinforcement is one of the major sources of degradation in RC structures. This issue has recently turned into a matter of growing concern since it adversely affects the performance of the structure. Reinforcement corrosion leads to a reduction in load carrying capacity of the structural element and also deterioration in bond between concrete and steel bars. The cost of maintenance and also repair of damaged structures is another problematic aspect of the issue.

In recent years, a number of researches have been conducted in order to clarify the performance of structures subjected to corrosion. Bazant was the first to propose an analytical model of the corrosion-induced cracking. Liu and Weyers tried to improve his models. El Maaddawy and Soudki, Malumbela et al., Wang and Liu  and Bhargava et al. were some other researchers who have studied corrosion analytically. Coronelli and Gambarova and Toongoenthong and Maekawa have also presented numerical models using Finite Element method.

A substantial number of the RC structures prone to corrosion, are actually located in regions with high risk of earthquake. The seismic requirements which the codes oblige the buildings to meet, are indeed established for the structure in the normal situation. Cracks formed in an affected structure and also the lack of confinement may threaten the durability of the damaged element.

In this paper, three principal effects of corrosion are considered including section loss of the steel bars, concrete strength degradation and bond change. Numerical modeling is conducted with finite element program called COM3 which has been developed in university of Tokyo. Here, the corrosion phenomenon is numerically modelled on a six storey frame in different conditions. First the results of static analyses are presented and then the ones gained by dynamic analyses are provided.

## MODELING CORROSION

In this study, fiber elements are implemented for modeling. In order to simulate the corrosion phenomenon on the structural elements, its effects should be appropriately defined. Formation of the expansive corrosion products, causes some cracks in the concrete surrounding the corroded steel bars. Therefore the compressive strength of concrete decreases as a function of the corrosion amount. In this study, the equation suggested by Safaeian (Safaeian and Soltani, 2008) is implemented so as to modify the initial compressive strength of concrete. Eq. (1) is as follows.

$$\begin{cases} f'_{c,cor} = f'_{co} & ; \quad \gamma \le \gamma_{cr} \\ f'_{c,cor} = \dfrac{f'_{co}}{0.8 + 170 k_{sh}\sqrt{\rho}\left(1 - \sqrt{1-\gamma}\right)} & ; \quad \gamma > \gamma_{cr} \end{cases}$$

$$\gamma_{cr} = 1 - \left(1 - \frac{0.001}{k_{sh}\sqrt{\rho}}\right)^2 \qquad (1)$$

In which $f'_{co}$ and $f'_{c,cor}$ are primary and secondary compressive strengths respectively. $k_{sh}$ is shape factor which is equal to 3.14 for circular section and 4 for rectangular section. $\gamma$ and $\rho$ are corrosion amount (ratio of section loss to primary section) and reinforcement ratio respectively. Stiffness is also diminished in proportion to the strength decrease.

So as to modify the tensile model of behaviour in corroded element, a parameter named critical steel ratio is defined and then if the steel ratio in a corroded specimen exceeds the aforementioned value, tension stiffening models can be considered in the RC member analysis and if the section steel ratio is lower than this value, concrete behaviour is regarded as tension softening. The equation suggested by Safaeian is used for calculating critical steel ratio (Eq. (2)).

$$\rho_{cro} = \frac{f_t}{f_y} \quad , \quad k_{\left(\gamma, c/d_b\right)} = 200\gamma + (4 - 1.4\frac{c}{d_b}) \qquad (2)$$

In which $c$ is the cover depth (distance from center of steel bar to concrete surface) and $d_b$ is the steel bar diameter. $f_t$ and $f_y$ are tensile strength of concrete and yield strength of steel respectively.

The reduction in steel bar diameter which is the most conspicuous effect of corrosion is simply computed using steel section loss.

Considering the mentioned items, corrosion is simulated in RC structures.

## VERIFICATION OF CORROSION MODELING

With the purpose of investigating the program performance in corrosion modeling, experimental studies which have been conducted by Lee et al. (Lee et al., 2002) is used. Columns with different corrosion levels were first under gravity loads and then cyclic lateral displacement was applied to them. First the column is modeled in the state of no corrosion and then considering two different corrosion levels, modeling is fulfilled and the results are compared with the experimental ones. Each column is modeled with five fiber elements and one interface element. The details of the columns section are shown in figure 1.

Since the published paper has only given some information on the volume of integrated electric current in each case of experiment, and not the section loss of the member, using the crack pattern figure presented in the paper itself, minimum and maximum values of corrosion-induced crack widths are obtained. Tensile strain in cracked section is estimated by having values of crack widths and knowing the section where $f_c$ and $\varepsilon_t$ are the peak compressive stress of concrete and the average (smeared) tensile strain in the cracked concrete at right angles to the direction of the applied compression (Coronelli and Gambarova, 2004).

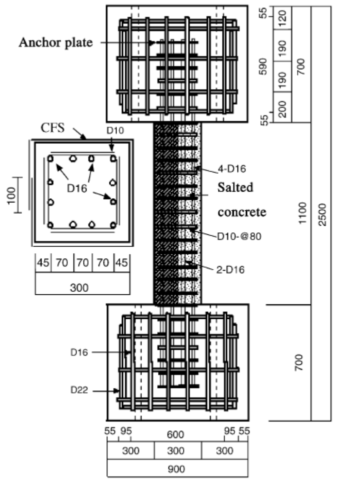


Figure 1. geometry and reinforcement of the specimen (unit:mm) (Lee et al., 2002)

width. Ultimately, compressive strength of cracked concrete is calculated using the equation suggested by Coronelli and Gambarova. Eq. (3) will result:

$$= \frac{f_c}{1 + 100\varepsilon_t} \tag{3}$$

Finally upper and lower limits for compressive strength of concrete in the second analysis are gained as 34.6 and 30.9 MPa respectively. For the third analysis these values are calculated as 32.7 and 27.3 MPa. Reduced concrete modulus of elasticity is also achieved for each case. Analyzing the column with each compressive strength, lateral load-displacement diagram is obtained. In Figure 2 and Figure 3, experimental results gained by Lee et al. are compared with the analytical ones for the two sets of analyses.

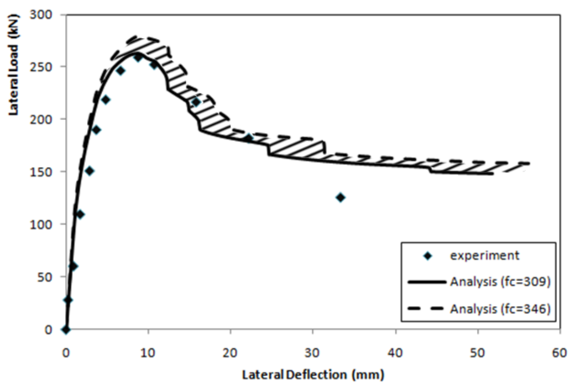


Figure 2. verification for column in state one

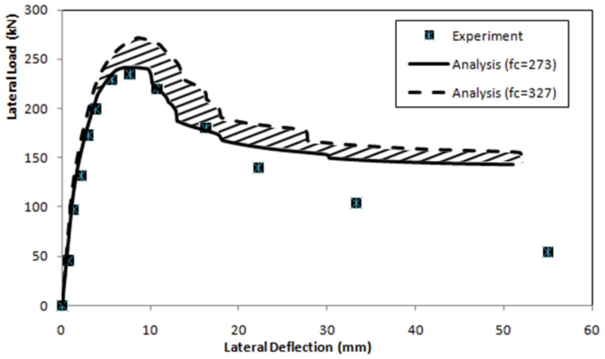


Figure 3. verification for column in state two

As can be seen in the above diagrams, there is an acceptable agreement between the analytical results and the ones achieved by the experiments.
In the following some investigations are carried out on a six storey frame.

## SIX STOREY FRAME CASE STUDY

In this section, a reinforced concrete frame which has three spans is used for studying. The length of each span and also the height of each storey equals to three meters. Some of the parameters in the design of the frame are provided in table 1.

Table 1. design parameters of the frame (Atefi and Soltani, 2013)

| | | | |
|---|---|---|---|
| compressive strength of concrete | 210 kg/cm$^2$ | importance factor | 1 |
| yield stress of the reinforcement | 4000 kg/cm$^2$ | R | 10 |
| steel modulus of elasticity | $2*10^6$ kg/cm$^2$ | storey live load | 200 kg/m$^2$ |
| A (g) | 0.35 | roof live load | 150 kg/m$^2$ |
| storey dead load | 530 kg/m$^2$ | roof dead load | 500 kg/m$^2$ |

The details of the frame sections and reinforcement are shown in figure 4.

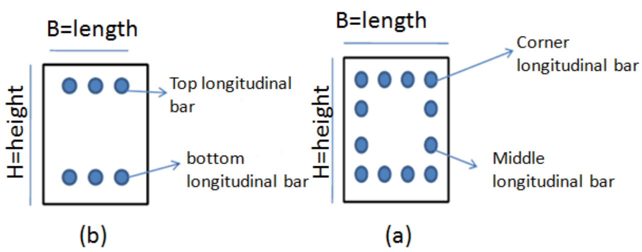


Figure 4. Simplified cross sections for a) columns b) beams (Atefi and Soltani, 2013)

Characteristics of the designed frame are declared in table 2.

Table 2. characteristics of the designed six storey frame (Atefi and Soltani, 2013)

| stories | | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|---|
| Column section | Length (cm) | 40 | 40 | 40 | 35 | 35 | 35 |
| | Height (cm) | 40 | 40 | 40 | 35 | 35 | 35 |
| | Corner bar | φ14 | φ14 | φ14 | φ14 | φ14 | φ14 |
| | Middle bar | φ14 | φ14 | φ14 | φ12 | φ12 | φ12 |
| Beam section | Length (cm) | 30 | 30 | 30 | 30 | 30 | 30 |
| | Height (cm) | 30 | 30 | 30 | 30 | 30 | 30 |
| | Top bar | φ18 | φ18 | φ18 | φ16 | φ14 | φ12 |
| | Bottom bar | φ16 | φ16 | φ16 | φ14 | φ12 | φ12 |

Fiber element is used for frame modeling in COM3 program. Geometric nonlinearity is also considered.

## INVESTIGATING GENERAL AND LOCAL CORROSION EFFECT

A number of different cases of corrosion are assumed here and the structure is analyzed in each condition and at last, the structural responses are compared. Since the rebars of the ground floor of the buildings is the most exposed ones to corrosion, the following situations are considered for studying.

- Corrosion in one corner column in the ground floor
- Corrosion in all columns of the ground floor
- Corrosion in beams and columns of the ground floor
- Corrosion in columns of ground and first floor
- Corrosion in columns and beams of ground and first floor
- Corrosion of all structural members
- No corrosion

At first the results of static analyses are presented and then the ones achieved by dynamic analysis will be shown.

### Static Analysis

In this section each of the cases mentioned in the above, is modelled in the frame according to the previous explanations. The ratio of section loss in the rebars is assumed 0.026. Lateral loading is in the form of triangular distribution along the frame height which is applied at each storey level. Finally the diagram of lateral force versus lateral displacement is gained as can be seen in figure 5.

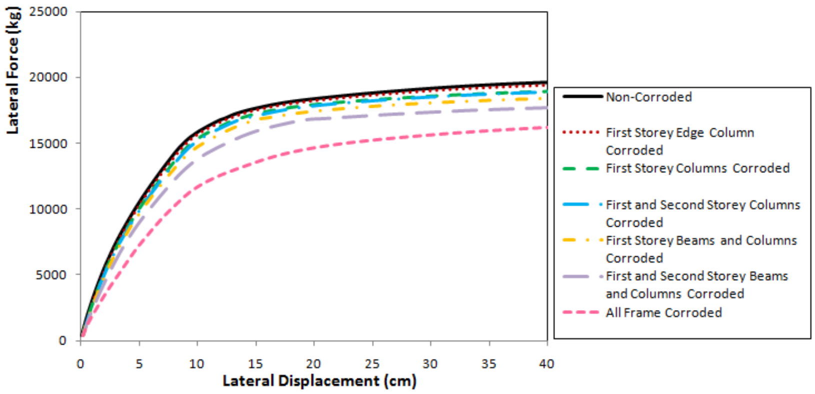


Figure 5. effect of corrosion on the frame performance in the static analysis

As it is clear in this diagram, the condition in which all the structural elements of the building are exposed to rebar corrosion, the greatest stiffness and capacity reduction happens. Among the other cases, corrosion of beams and columns of ground and first floor causes the largest effect on performance degradation of the frame. The other corrosion cases affect the primary diagram, insignificantly.

## DYNAMIC ANALYSES

IDA involves performing a series of nonlinear dynamic analyses in which the intensity of the ground motion selected for the collapse investigation is incrementally increased until the global collapse capacity of the structure is reached. It also involves plotting an intensity measure (i.e., the peak ground acceleration (PGA) and Sa at the fundamental natural period of the structure) against a damage measure (i.e., the maximum inter-story (MIDR) drift or roof drift).

In this section the incremental dynamic analyses are conducted via three ground motion records chosen from the Long Magnitude Small distance (LMSR) records suggested by Shome and Cornell. The properties of these intended records are provided in table 3.

Table 3. Properties of the records (Atefi and Soltani, 2013)

| Record ID | Event | Year | M | R (km) | Station | Soil Type | PGA (g) Component X | PGA (g) Component Y | Selected Component |
|---|---|---|---|---|---|---|---|---|---|
| BLD | Northridge | 1994 | 6.7 | 31.3 | LA - Baldwin Hills | C | 0.168 | 0.239 | Y |
| GLE | Northridge | 1994 | 6.7 | 17.7 | Sunland - Mt Gleason Ave | C | 0.157 | 0.127 | X |
| HOW | Northridge | 1994 | 6.7 | 20 | Burbank - Howard Rd | C | 0.163 | 0.12 | Y |

The analyses are done till the structural failure. The following diagrams in Figures 6, 7 and 8 illustrate the IDA results for the intended records.

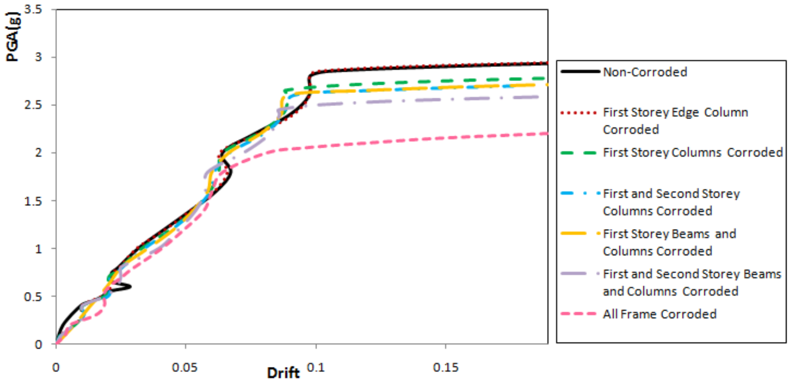


Figure 6. different corrosion effects when analyzing by BLD record

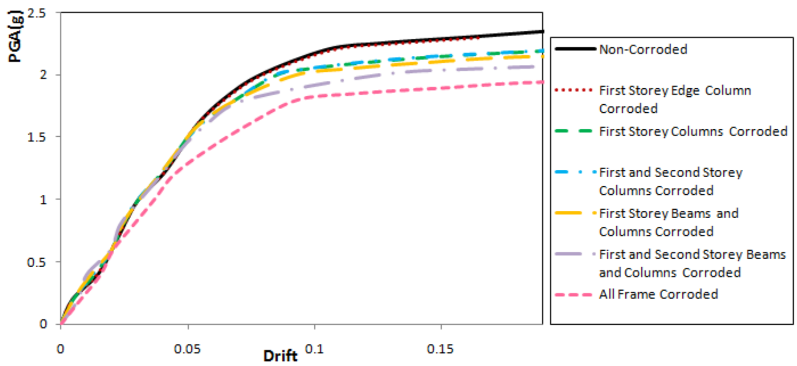


Figure 7. different corrosion effects when analyzing by HOW record

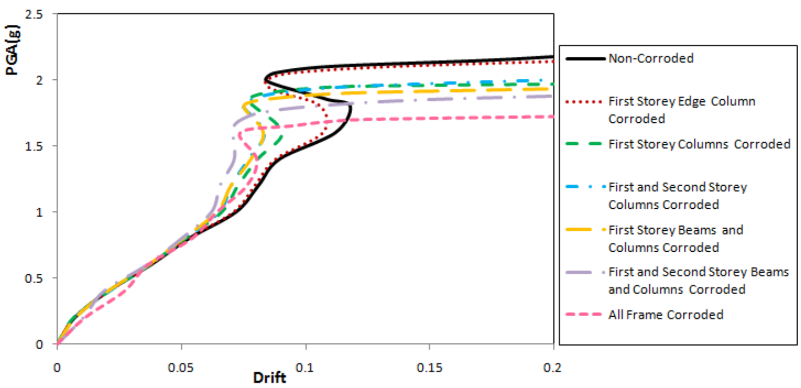


Figure 8. different corrosion effects when analyzing by GLE record

As depicted in these diagrams, the condition in which the whole structure is corroded, begets the most tremendous reduction in the failure acceleration of the structure. Generally, the amount of corrosion effect on the frame performance depends on the ductility demand of the corroded members. The case in which only one corner column is corroded, has the least impact on the response of the structure which is actually due to the fact that this column has little ductility demand that even at the accelerations near the failure one, corrosion affected the sound frame diagram inconsiderably.

In figures 9 and 10, time histories of interstory drift for each case of corrosion condition are displayed for one of the intended earthquake records at the peak ground accelerations of 0.4g and 1g, respectively.

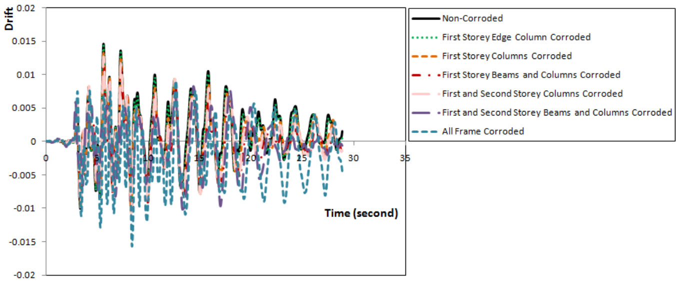


Figure 9. drift-time diagram at the acceleration of 0.4 g when analyzed by HOW record

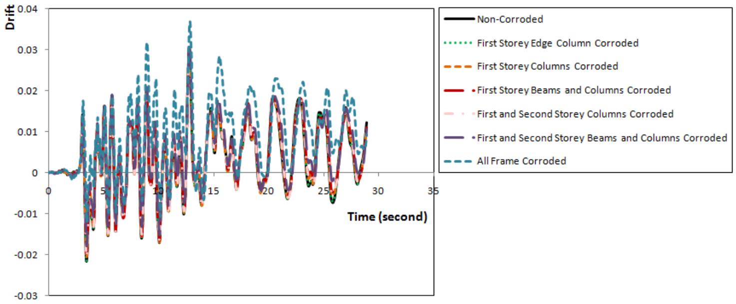


Figure 10. drift-time diagram at the acceleration of 1.0 g when analyzed by HOW record

As can be seen, the time history diagrams of drift are almost close to each other except for the condition of whole corrosion. The results of these diagrams are consistent with the ones obtained from the IDA curves.

## CONCLUSIONS

In this study, corrosion effect was numerically simulated by modifying some parameters in the frame modeling. According to the higher possibility of some elements to be corroded in a frame, different cases of corrosion have been investigated in a six storey frame. The results achieved by dynamic analyses were in agreement with the ones gained by static analyses.

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