

## EFFECT OF SEVERE CORROSION ON LATERAL STRENGTH OF RC BRIDGE COLUMNS

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### ABSTRACT

Corrosion of reinforcing steel bars is the primary durability problem that causes degradation of reinforced concrete structures located in aggressive environments. Severe corrosion of steel bars decreases the load-carrying capacity of reinforced concrete members, causes bond deterioration, reduces anchorage of steel bars, and decreases the confinement by transverse reinforcement. Consequently, corrosion results in drop in the lateral strength of columns. Therefore, studying response of corroded reinforced concrete columns subjected to lateral loads is necessary.

This study investigates response of corroded steel reinforced concrete columns subjected to lateral loading and axial compressive load using a finite element model which was developed on ABAQUS and calibrated against existing experimental tests data, by others. Lateral capacity of RC columns are influenced by corroded longitudinal and transverse reinforcing bars. Effects of parameters such as steel bar area loss percentage, and axial load ratio on lateral strength of columns are discussed. The results of this investigation suggest that corrosion of steel bars has significant impact on load carrying capacity of corroded concrete columns.

**Keywords:** severe corrosion, reinforced concrete, corroded columns, lateral strength, FEM.

### 1. INTRODUCTION

Corrosion of reinforcing steel bars is the primary durability problem that causes degradation of reinforced concrete structures located in aggressive environments. Severe corrosion of steel bars decreases the lateral load-carrying capacity of reinforced concrete members, causes loss in the mechanical properties of reinforcement and cross-sectional area of steel bars and concrete cover, bond deterioration, reduces anchorage of steel bars, and decreases the confinement by transverse reinforcement. Consequently, corrosion results in drop in the lateral strength of columns. Therefore, studying response of corroded reinforced concrete columns subjected to lateral loads is necessary.

According to the Federal Highway Administration (FHWA) report in 2013, 25.9 percent of the total

inventory of highway bridges are deficient or functionally obsolete. Corrosion damage caused by deicing salts is considered one of the main problems that cause a bridge structure to be structurally deficient (FHWA, 2004). Therefore, there is an urgent need for proper guide for evaluation of deteriorated reinforced concrete bridge components that could assist structural engineers estimate the reserved strength of deteriorated bridges, and design cost-effective methods for retrofit (Aboutaha et al., (2013)).

## 2. BACKGROUND

The effect of corrosion on structural behavior of RC columns subjected to seismic loading has been studied by a few researchers as described in the following.

Lee et al. (2003) experimentally investigated structural behavior of rectangular RC columns, which were subjected to constant axial load and cyclic loading. Applying electrochemical corrosion method to produce different levels of corrosion in rebars, it was found that corrosion caused decrease in mechanical properties of rebars and spalling of concrete cover which results in reduction in confining effect of reinforcement. Mode of failure for corroded specimens was shear failing, which was caused by buckling of longitudinal reinforcement and failure of hoops. Aquino et al. (2007) tested circular RC columns with inadequate lap splices and subjected to external current to induce corrosion in the specimens. Due to applying reversed cyclic load, ductility and load bearing capacity of columns are reduced due to bond deterioration caused by corrosion. Observed failure mechanism was rupture of deteriorated hoops and buckling of longitudinal bars. Li et al. (2009) conducted combined lateral cyclic and constant axial loading test on rectangular RC columns. Applying lateral cyclic load at mid-span of corroded columns, they found that by increasing the lateral load, longitudinal cracks due to corrosion developed and followed by flexural cracks. Finally, complete spalling of concrete cover due to de-bonding between concrete cover and core caused the failure of corroded columns. Ma et al. (2012) carried out cyclic loading tests on circular RC columns subjected to different rates of corrosion and axial compressive loads. They found that high corrosion levels and high axial loads led the column to fail in brittle way and cause reduction in stiffness, ductility, energy dissipation as well as poor hysteretic response. Meda et al. (2014) conducted combined lateral cyclic and constant axial loading test on RC columns to investigate the effect of corrosion on corroded RC columns. They found that by increasing the lateral load, flexural cracks were developing. After complete yielding of longitudinal bars and large deformation of compression bars due to buckling, the column experienced the maximum lateral load and then due to concrete crushing and cover spalling the test had been stopped. Same loading on corroded columns showed that by increasing the lateral load, longitudinal cracks due to corrosion developed and followed by flexural cracks. Finally, complete spalling of concrete cover due to de-bonding between concrete cover and core, crushing of concrete and buckling of corroded bars caused the failure of corroded columns.

### 3. METHODOLOGY

Corroded columns have three main losses:

- Losses in the mechanical performance of reinforcing bars due to the losses in their cross-sectional area and ductility,
- Losses in the effective cross-sectional area of concrete due to cracking in the cover concrete,
- Losses in the bond performance of concrete with reinforcements.

When corrosion occurs uniformly, considering area loss percentage of corroded bars is preferred instead of weight loss percentage. Obviously, for corroded columns, de-bonding is inevitable in high corrosion levels. For severely corroded RC members, concrete cover is totally spalled off.

Table 1 shows the relation between corrosion rate of longitudinal and transverse reinforcement according to data provided by Ou et al. (2012). When the corrosion rate in longitudinal bars is more than 10%, practically there is no transverse bar and the contribution of stirrups can be ignored.

Considering all the above-mentioned facts, there is no concrete cover and transverse bars at the corroded side of a severely uniform corroded RC column. There is no bond between the corroded bar and surrounded concrete; therefore, the corroded bar in compression acts as a bare bar at which the compression stress is limited by buckling force.

**Table 1: Relation between corrosion rate of longitudinal and transverse bars**

Bar Type	Corrosion Rate (%)					
Longitudinal Bars	1.38	1.8	2.19	3.37	....	9
Transverse Bars	1.7	3.08	4.08	8.03	....	Fracture

### 4. FINITE ELEMENT MODELING

A finite element model has been developed using ABAQUS (ver. 6.14) to simulate response of corroded reinforced concrete columns. To model concrete elements in ABAQUS, Continuum (Solid) Element, with the ability of cracking under tension and crushing in compression, has employed. Beam Element is the 3D uniaxial tension-compression element type which can model reinforcing steel members. A contact element has been defined around the corroded bars to represent the connection between corroded steel bars and surrounded concrete. The first step of analysis is applying axial load to the rigid plate at top of the column. Next step is applying monotonic lateral load; at which lateral displacement is applied to the rigid plate.

#### 4.1. Materials

The concrete damage plasticity model in ABAQUS with abilities of cracking and crushing gives the capability of acting like a nonlinear material. For multi-linear isotropic properties, stress-strain relation of concrete was defined based on modified Hognestad model for unconfined concrete. The

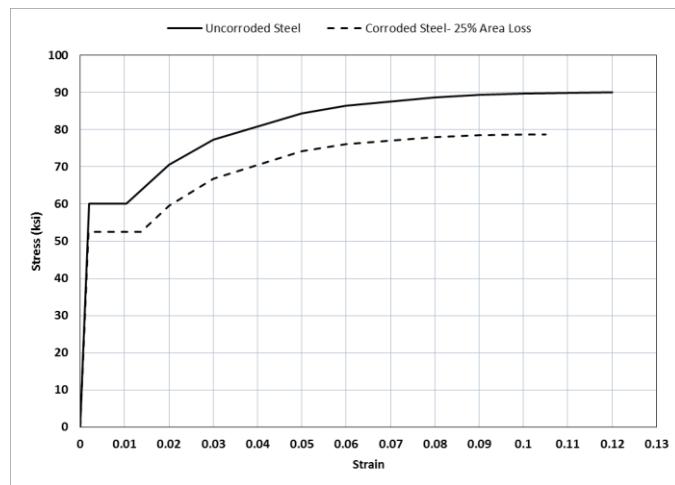
model developed by Saatcioglu and Razvi (1992) was used for confined concrete. To model un-corroded reinforcing steel members, the stress-strain relation with strain hardening (Akkari and Duan (2000), Chai et al. (1990)) is defined. For corroded reinforcing steel bars, cross sectional area ( $A_{corr}$ ), yielding stress ( $f_{y_{corr}}$ ) and ultimate strain ( $\varepsilon_{su_{corr}}$ ) of corroded reinforcing steel bar are calculated based on the initial cross sectional area ( $A_0$ ), yielding stress ( $f_{y0}$ ) and ultimate strain ( $\varepsilon_{su0}$ ) of un-corroded bar considering the area loss (corrosion level) of corroded bars ( $CR$ ) (Du et al., 2005):

$$A_{corr} = A_0(1 - 0.01CR) \quad (1)$$

$$f_{y_{corr}} = f_{y0}(1 - 0.005CR) \quad (2)$$

$$\varepsilon_{su_{corr}} = \varepsilon_{su0}(1 - 0.005CR) \quad (3)$$

Figure 1 shows the tensile stress-strain relation with strain hardening for Grade60 sound steel bar and a corroded Grade60 bar with 25% corrosion level. As there is no interaction between corroded bars and concrete, the equations of the Structural Stability Research Council (SSRC) in its third edition of the Guide (Chen and Lui 1987), has been used in order to compute the buckling stress of steel reinforcement bars in the compression zone. Severely corroded bars are assumed to act as pinned ends single bars with effective length factor of 1. All material properties of corroded bars have been adjusted based on corrosion level.

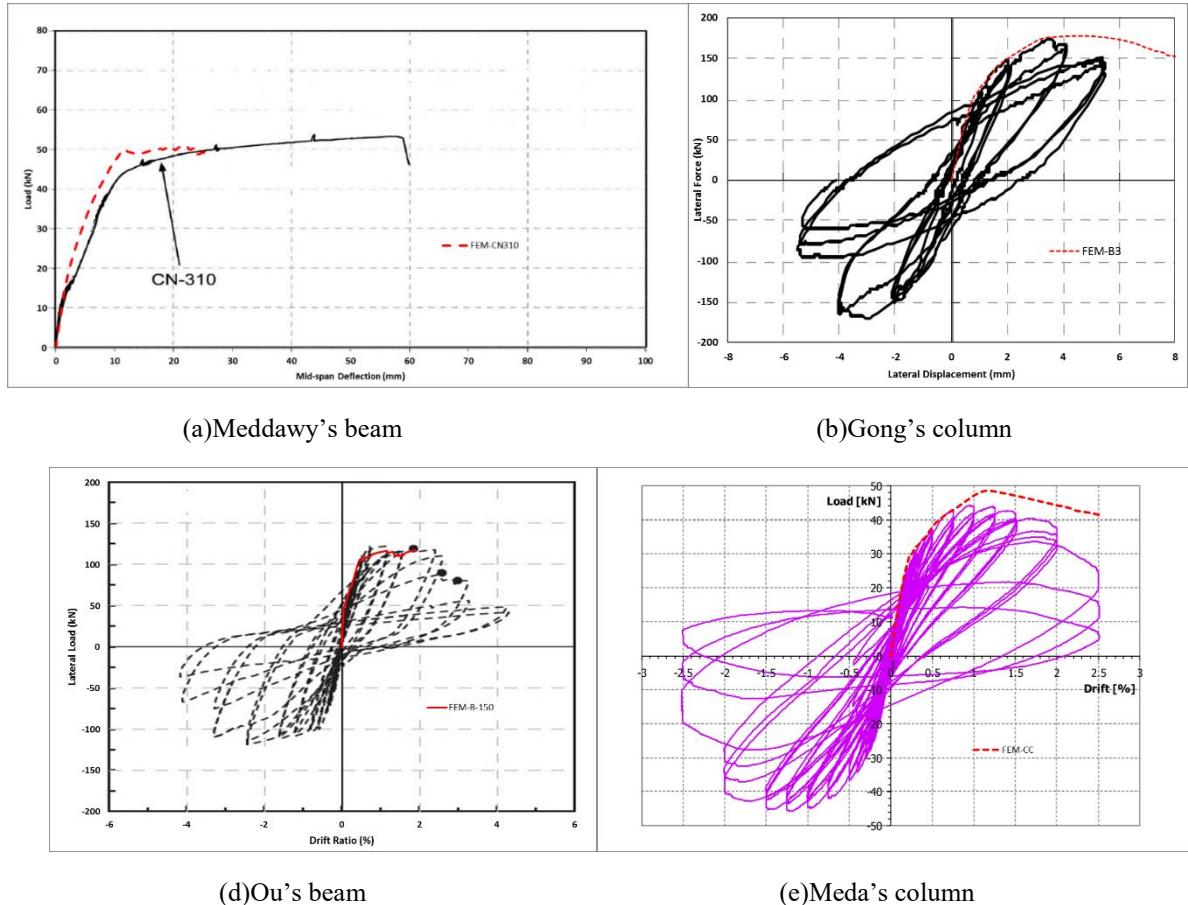


**Figure 1: Tensile stress-strain diagram of un-corroded and corroded steel (Grade 60)**

#### 4.2. Validation of Experimental Data

In order to investigate the response of corroded RC columns subjected to lateral loads, it is necessary to validate the FE model against existing experimental test data. Existing experimental data includes the un-corroded and corroded columns subjected to axial and lateral loads, and corroded beams (representing columns without axial load) subjected to shear forces. All the specimens were modeled according to data provided on related papers. Tested beams of Maaddawy et al. (2005) and Ou et al. (2012) and columns of Gong (2009) and Meda et al. (2014) were modeled and verified. Although FE

model does not provide any rough estimation of ductility, it can show the load carrying capacity of RC columns very well (Figure 2).



**Figure 2: Lateral force- lateral displacement curves of corroded elements; experimental vs. FEM model**

## 5. ANALYTICAL INVESTIGATION

In the study by Sotoud (2016), reinforced concrete columns are modeled as a cantilever. Axial and lateral loads are applied to the free end of the column as shown in Figure 3. All sections are  $24\text{ in} \times 24\text{ in}$  with 12#9 longitudinal reinforcement and 3#4@12 in transverse reinforcement. Two corrosion levels of 25% and 50% for main bars are studied. Length of corroded bars is 24 in. It is important to mention that corrosion level in this study indicates steel bar area loss. Shear span to height ratio of 5 is considered for columns.

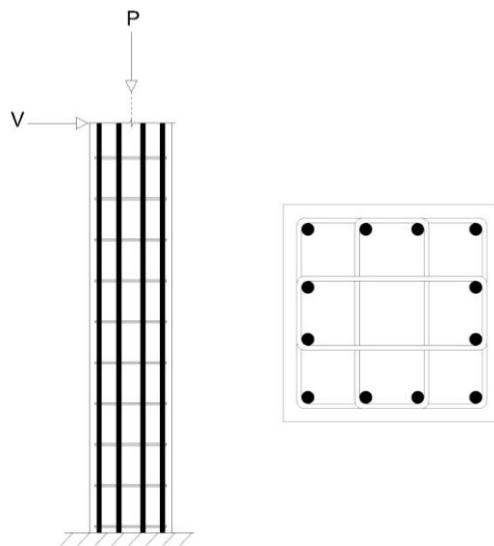
The following parameters are the primary variables in this study:

-Corrosion level (CR=25%, 50%)

-Axial load ratio ( $NR = \frac{P}{f'cA_g} = 0\%, 5\%, 15\%, 25\%$ )

When corrosion occurs at all sides of the column, concrete cover at all sides of the section is removed.

So there is a significant decrease in concrete cross-sectional area of column. Concrete cover has almost 25% area of the whole section. Therefore, compressive strength of column decreases drastically. There is no bond between corroded reinforcing bars and concrete. Although tensile strain is lower for un-bonded bars than bonded reinforcing bars, tensile bars could yield and even enter strain hardening zone because of smaller cross-sectional area and lower yielding stress of corroded bars. Therefore, the tensile force carried by corroded tension bars reduces. On the other side, compressive corroded bars are subjected to buckle. The ultimate force in compression bars is controlled by buckling force. Concrete core is considered unconfined because of existence of no external stirrups and no concrete cover. Less compressive strength due to cover loss, reduced ultimate forces tensile bars could carry due to steel area loss, and de-bonding and limited force carried by compression bars due to area loss and buckling result in significant decrease in load carrying capacity of corroded bars. Failure mode for all corroded columns was flexural-failure as un-corroded specimens.

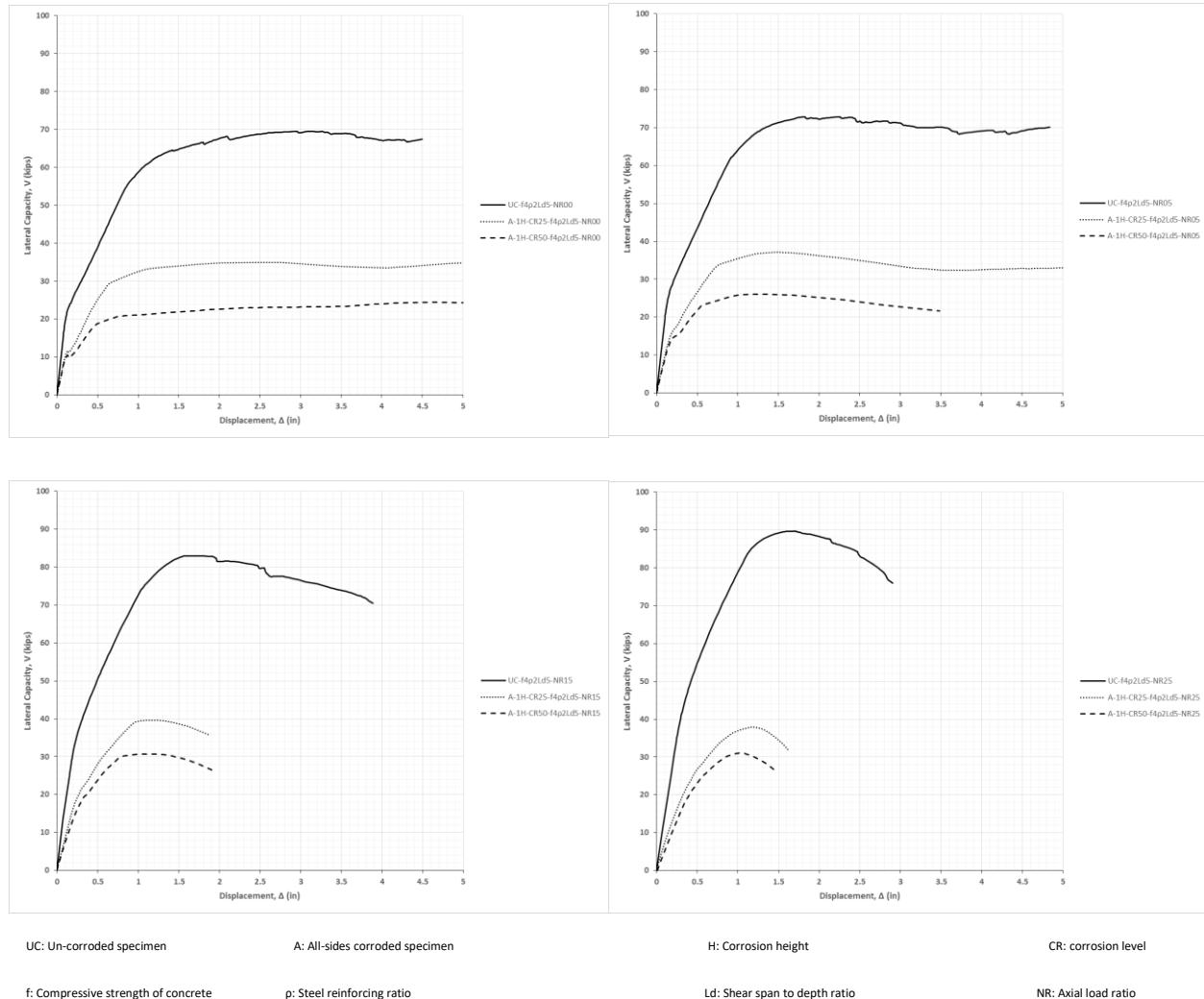


**Figure 3: Side View and cross-section of the column**

Figure 5-1 shows the lateral capacity- displacement diagram of corroded column compared to un-corroded column. Applying lateral load, the first layer of corroded bars in compression side starts to buckle. Based on axial load ratio, the second layer of compression bars could buckle as well. In lower axial load, tension bars start to yield and finally crushing of compressive concrete happens. When the axial load is higher, crushing may occur before yielding of tension bars. In some cases, buckling of corroded bars occurs under axial load. As the buckling is elastic, applying higher lateral load makes the buckled bars in tension side become straight and then corroded bars start to participate in load carrying capacity of column.

Response of corroded columns regarding ductility is different in various axial load ratios. When corroded column is subjected to lower axial load, there is a premature yielding of corroded tension bars and delay in crushing of compressive concrete and therefore, the ductility increases relatively.

When corroded columns are subjected to high axial load, delay in yielding of tension bars and premature crushing of compressive concrete causes the corroded columns to have less ductility.



**Figure 5-1 Lateral capacity- displacement diagram of corroded column compared to un-corroded column**

The initial stiffness of corroded columns decreases in comparison with un-corroded columns, primarily because of loss of concrete cover at all sides of the section and secondly, because of lower cross-sectional area of all corroded bars. The high corrosion level, initial stiffness of corroded columns decreases.

## 6. CONCLUSIONS

Response of corroded steel reinforced concrete columns subjected to lateral loading and axial compressive load. using a finite element model was investigated in this study. The followings are the main results obtained:

- Lateral capacity reduction of corroded columns is 35% to 80%. This reduction is mainly because of loss of concrete cover on all sides, buckling of corroded bars, un-confined concrete core, area loss

of corroded bars, reduced yielding stress and de-bonding of corroded tensile bars.

- In corroded columns, ductility depends on axial load. Corroded columns with low axial load experience more ductility and corroded columns with high axial load have less ductility in comparison with un-corroded columns.
- Corrosion reduces the initial stiffness of corroded columns. High corrosion levels cause less initial stiffness in corroded columns.
- Lateral capacity reduction due to different axial load ratios is almost the same.

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