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Prediction of strength and drift capacity of corroded reinforced concrete columns

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HIGHLIGHTS

- A 3D non-linear finite element model for corroded RC columns was developed.
- The effects of key parameters on lateral load resistance and ultimate drift ratio of corroded RC columns was investigated.
- Prediction equations for lateral load resistance and ultimate drift ratio capacity of corroded RC columns were proposed.

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ABSTRACT

Steel reinforcement corrosion has been recognized as a major deterioration issue for the performance and safety of reinforced concrete (RC) structures. In this paper, the behavior of corroded RC columns under the seismic loading was studied using a three-dimensional (3D) non-linear Finite Element (FE) analysis, considering the material properties deterioration of reinforcement and concrete induced by corrosion. The experimental results of nine reinforced concrete (RC) columns in three experimental studies in literature were selected to verify the accuracy of the proposed 3D non-linear FE model. Thereafter, an extensive parametric investigation, including the FE models of 240 RC columns subjected to the simulated seismic loading was performed to study the influence of various crucial parameters on the seismic performance of corroded RC columns, particularly their lateral load resistance and ultimate drift capacity deterioration. Finally, these key parameters were incorporated into two prediction equations of the lateral load resistance and ultimate drift capacity for corroded RC columns.

1. Introduction

Steel reinforcement corrosion has been considered as a main cause of deterioration for reinforced concrete (RC) structures in the corrosive environments. At the material level, the tensile stresses will develop at the interface between reinforcing bars and concrete because of the volumetric expansion of corrosion product induced by reinforcement corrosion, causing the cover concrete of RC structures to crack and eventually spall off as well as reducing the bond strength of reinforcement at these interfacial regions. In addition, the confinement effect of core concrete will be also decreased due to corrosion of transverse reinforcement, particularly its maximum compressive strength and ultimate strain [1]. With regard to the corroded reinforcement, some experimental studies in literature revealed that the cross-sectional area, strength and ultimate strain of steel reinforcement are significantly decreased due to corrosion [2–4]. As a result, these mechanical properties deteriorations of reinforcement and concrete adversely affect the long-term performance and safety of RC structures, especially these structures under severely corrosive environments and subjected to the seismic loading.

Previous research mainly focuses on the causes and mechanism of reinforcement corrosion and its influences on the deteriorations of reinforcement and concrete [5–8]. On the other hand, the corrosion effect on the performance of RC structures subjected to the seismic loading has relatively little concern. Recently, several experimental investigations on the seismic behavior of corroded RC columns have been carried out in literature [9–13], which revealed that the corrosion phenomenon strongly affects the global performance of these structures, particularly their strength and ultimate drift capacity. For instance, in the experimental program carried out by Meda et al. [13], comparing to the uncorroded column with the same specifications and loading conditions, the corroded column with the corrosion level of approximately 20%

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Notation

a	shear span defined as distance from maximum moment section to point of inflection
A_g	gross cross-sectional area of the RC column
A_{pit}	cross-sectional area of corroded reinforcement at the pitting location
$A_s(X_{corr})$	average corroded cross-sectional area of reinforcement
A_{stnom}	original cross-sectional area of reinforcement
A_v	cross-sectional area of transverse reinforcement
b_0	circumference of the RC column section
c_c	smaller of concrete cover and one-half spacing between reinforcing bars
D_0	diameter of uncorroded reinforcement
D_c	diameter of corroded reinforcement
DR_{ultC}	ultimate drift ratio capacity of corroded RC column
d	effective depth of RC column section
d_b	diameter of reinforcing bar
E_{force}	normalized hysteretic force error
E_{energy}	normalized hysteretic energy error
f'_c	compressive strength of concrete
f'_{cC}	compressive strength of corroded cover concrete
f'_t	tensile strength of uncorroded concrete
f'_{tC}	tensile strength of corroded concrete
f_{yh}	yield strength of stirrup
F_{cal}	calculated lateral force at corresponding displacements
F_{mea}	measured lateral force at corresponding displacements
F_i	lateral force corresponding to the i^{th} step
k	coefficient regarding to the diameter and roughness of reinforcement
K	confined strength coefficient
N	axial compression force
R	factor that predicts the change of bond strength due to the corroded reinforcement

s	bond slip
s_1, s_2, s_3	value of slip related to various bond conditions
S	spacing between stirrups
T_{corr}	corrosion initiation time
t	corrosion time
X_{corr}	corrosion level in terms of mass loss (%)
x	depth of corrosion attack
V_{nC}	lateral load resistance of corroded RC column
W_0	reinforcement weight before corrosion
W_1	corroded reinforcement weight after corrosion
w/c	water to cement ratio
w_{cr}	crack width due to corrosion penetration
Δ_i	lateral displacement corresponding to the i^{th} step
Ω_{mea}	measured area within the hysteresis loops
Ω_{cal}	calculated area within the hysteresis loops
α	yield and ultimate strength factor of reinforcement induced by pitting corrosion
β	ultimate strain factor of reinforcement induced by pitting corrosion
ε_1	average tensile strain in cracked concrete
ε_{co}	concrete strain at maximum concrete stress
ε_{cu}	ultimate strain of confined concrete
ε_{uo}	ultimate strain of uncorroded reinforcement
ε_{uc}	ultimate strain of corroded reinforcement
τ_{fC}	bond stress of corroded reinforcement
τ_{f0}	bond stress of uncorroded reinforcement
$\tau_{\max C}$	maximum bond stress of corroded reinforcement
$\tau_{\max 0}$	maximum bond stress of uncorroded reinforcement
υ_{cr}	ratio of the volumetric expansion of the corroded steel to the virgin steel
ρ_v	volumetric transverse reinforcement ratio

showed a decrease of 30% of the lateral load and 50% of the maximum displacement. Similarly, the experimental study conducted by Ma et al. [11] also indicated that the reduction of 50% ultimate displacement capacity and 20% of yield as well as ultimate forces can be found in the corroded RC column subjected to the corrosion level of 15% when comparing to the uncorroded column. Therefore, it is vital to quantify the corrosion effect and its interaction among the other important factors on the lateral load resistance and ductility deterioration of corroded RC columns, specifically column aspect ratio, axial force ratio, concrete strength, and reinforcement ratio.

This study aims to develop a 3D non-linear FE analysis to study the seismic performance of corroded RC columns that deliberates the influences of corrosion level and various key parameters. The effects of corrosion damage on RC columns can be modeled by adapting the material properties of corroded reinforcement, unconfined cover and confined core concrete, modifying the bond behavior between corroded reinforcement and concrete. The experimental results reported in literature are employed to validate the accuracy of the proposed 3D non-linear FE model. Thereafter, this proposed FE model is adopted to study the behavior of corroded RC columns in an extensive parametric investigation. Finally, based on the multivariable regression analysis, two prediction equations of the lateral load resistance and ultimate drift capacity are developed for corroded RC columns.

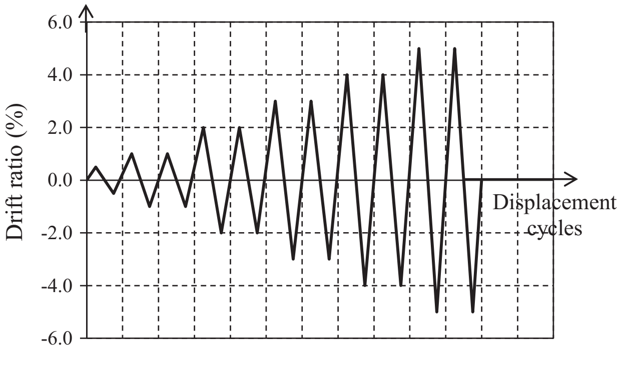

Fig. 1. Quasi-static cyclic loading history for FE model columns.

2. 3D non-linear finite element model of corroded RC column

2.1. General

In this paper, a 3D non-linear FE analysis was carried out to simulate the seismic behavior of RC columns with corroded reinforcement using DIANA [14] – a commercial non-linear FE software package. The validity and reliability of this FE software to model the behavior of corroded RC structures have been confirmed in literature [15–17].

In this proposed 3D non-linear FE model, concrete is modeled by adopting the twenty-node isoparametric solid brick element while the separate truss element which is connected to the concrete element using interface element is utilized to model the reinforcement. The local bond stress-slip law proposed in the CEB-FIP [18] is employed and modified to incorporate the corrosion effect in this study. A combination of a horizontal cyclic displacement and a vertical axial force is applied to simulate the