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# Stress-strain model for confined concrete with corroded transverse reinforcement

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ABSTRACT

This paper presents an experimental study on the stress-strain relation of confined concrete that considers the corrosion effects of transverse reinforcement. The main variables are the corrosion level of transverse reinforcement, cross sectional shape of confined concrete, as well as arrangement and configuration of confining transverse reinforcing bars. The test results revealed that four key parameters of the complete stress-strain relation are significantly affected due to the corrosion of transverse reinforcement, including the maximum concrete strength and corresponding axial concrete strain, maximum concrete strain at the fracture of the first hoops, and descending branch of the stress-strain curve after exceeding the maximum strength. Based on the test data and regression analysis, the empirical equations to estimate these key parameters are proposed, and a complete stress-strain model for confined concrete with corroded transverse reinforcement is developed. The proposed model showed good correlation with the test data of both circular and square specimens with various corrosion levels and subjected to compression axial loading.



## 1. Introduction

Corrosion of steel reinforcement has been found to be one of the most significant causes of deteriorations for reinforced concrete (RC) structures subjected to various corrosive environmental actions. The corrosion products expand the volume of corroded steel reinforcement that develops the tensile stresses at the interfacial regions between reinforcement and concrete, causing the cover concrete of these RC structures to crack and spall off [1]. Additionally, the deterioration of strength and ductility of reinforcement due to corrosion also results in the significant reduction of the confinement effectiveness for confined concrete and buckling resistance of longitudinal reinforcement. As a result, the durability and safety performance of RC structures will be adversely affected especially important since these structures usually exist in the severely corrosive environments and earthquake prone regions [2,3].

Past earthquakes have proved that inadequate confinement of core concrete results in brittle characteristics under severe earthquake which should be avoided in design. The amount and arrangement of confining transverse reinforcement play a significant role in enhancing the performance of RC structures, especially in their inelastic ranges. During the service life of RC structures, their strength and ductility often deteriorate due to reinforcement corrosion, hence these deteriorations should be accurately predicted and taken into account from the outset of the design process, even more so for structures built in corrosive environments and subjected to seismic loading. In literature, the behavior of reinforced concrete beams with corroded reinforcement has been well investigated, particularly their flexural and shear strength deteriorations due to corrosion of reinforcement [4–7]. In addition, there are also several experimental studies about the effects of corrosion on the performance of RC columns subjected to seismic loading. Particularly, studies conducted by Meda et al. [8], Yang et al. [9], and Goksu and Ilki [10] were devoted to investigate the effects of corrosion on the seismic behavior of RC columns which failed in flexural manners while the other studies carried out by Bousias et al. [11], Li et al. [12], and Meda et al. [13] have focused on the effectiveness of strengthening methods on corroded RC columns subjected to cyclic loading. It is also clearly recognized that the stress-strain relations of reinforcement and confined concrete material are important input parameters to predict the performance of RC members, particularly their flexural and shear

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**Nomenclature**

| | |
|---|---|
| $D_0$ | original diameter of reinforcement |
| $D_{min}$ | minimum residual diameter of corroded reinforcement |
| $D_{re}$ | average residual diameter of corroded reinforcement |
| $E_c$ | elasticity modulus of concrete |
| $E_{sec}$ | secant modulus of confined concrete at maximum stress |
| $E_{stress}$ | normalized corroded concrete stress error |
| $f_c$ | longitudinal concrete stress |
| $f'_c$ | compressive strength of standard concrete cylinder specimens |
| $f'_{cc}$ | compressive strength of corroded confined concrete |
| $f'^{exp}_{cc}$ | measured compressive strength of corroded confined concrete |
| $f'^{pro}_{cc}$ | calculated compressive strength of corroded confined concrete using Eq. (15) |
| $f'_{co}$ | compressive strength of unconfined concrete |
| $f'_l$ | effective lateral confining stress |
| $f_y$ | yield strength of longitudinal reinforcement |
| $f_{yh}$ | yield strength of transverse reinforcement |
| $f^c_{yh}$ | yield strength of corroded transverse reinforcement |
| $F_{mea}$ | measured corroded concrete stress |
| $F_{cal}$ | calculated corroded concrete stress |
| $k_e$ | confinement effectiveness coefficient |
| $l_i$ | length of the crack $i$ |
| $L$ | clear height of column |
| $p_0$ | perimeter of specimen cross section |
| $X_{corr}$ | corrosion level in terms of mass loss |
| $X^{(1)}_{corr}$ | corrosion level in terms of average residual cross sectional area |
| $X^{(2)}_{corr}$ | corrosion level in terms of minimum residual cross sectional area |
| $w_{cri}$ | width of crack $i$ |
| $W_{cr}$ | total crack width of the specimen |
| $W_0$ | original weight of reinforcement before corrosion |
| $W_1$ | residual weight of reinforcement after corrosion |
| $\alpha$ | stress correction coefficient |
| $\alpha_s$ | yield strength reduction factor for corroded transverse reinforcement |
| $\beta$ | strain correction coefficient |
| $\beta_s$ | ultimate strain reduction factor for corroded transverse reinforcement |
| $\varepsilon_c$ | longitudinal concrete strain |
| $\varepsilon_{cc}$ | corroded concrete strain at maximum concrete stress |
| $\varepsilon^{exp}_{cc}$ | measured corroded concrete strain at maximum concrete stress |
| $\varepsilon^{pro}_{cc}$ | calculated corroded concrete strain at maximum concrete stress using Eq. (16) |
| $\varepsilon_{cu}$ | ultimate strain of corroded confined concrete |
| $\varepsilon^{exp}_{cu}$ | measured ultimate strain of corroded confined concrete |
| $\varepsilon^{pro}_{cu}$ | calculated ultimate strain of corroded confined concrete using Eq. (17) |
| $\varepsilon_{sm}$ | steel strain at maximum tensile stress of transverse reinforcement |
| $\varepsilon^c_{sm}$ | steel strain at maximum tensile stress of corroded transverse reinforcement |
| $\rho_s$ | volumetric ratio of transverse reinforcement of uncorroded confined concrete |
| $\rho_{sc}$ | volumetric ratio of transverse reinforcement of corroded confined concrete |

behavior. While the stress-strain relations for corroded reinforcement have been well studied in literature [14–20], to the authors' knowledge, so far there is no analytical stress-strain model for confined concrete with corroded transverse reinforcement. In this study, the stress-strain relation of confined concrete with various corrosion levels of transverse reinforcement has been experimentally investigated. Meanwhile, the influences of corrosion level of transverse reinforcement on the characteristic parameters of the stress-strain relation are investigated. Finally, an analytical stress-strain model for confined concrete with corroded transverse reinforcement is proposed based on the experimental data by incorporating the corrosion effects into the model for uncorroded confined concrete suggested by Mander et al. [21].

## 2. Experimental program

### 2.1. Test specimens

This experimental study included 36 reinforced concrete columns with 600 mm in height which were either 200 mm square or 200 mm diameter circular sections, with cover concrete thickness of 10 mm. Fig. 1 shows the arrangements of longitudinal reinforcing bars, transverse hoops, square helices, and spiral reinforcement of the specimens. As indicated, the test specimens were divided into three series: Series A (AS, AM, AL), Series B (BS, BM, BL), and Series C (CS, CM, CL) that represent different cross sectional shapes, various arrangements of longitudinal and transverse reinforcing bars. Following which the specimens in each series were corroded with different corrosion levels by controlling the accelerated corrosion time and the applied current intensity. The reinforcement details of the square and circular test specimens are summarized in Table 1.

In order to make sure that test specimens fail in the middle regions, the spacing of transverse reinforcement was decreased to 25 mm within the regions of 100 mm from both ends of the specimens to provide more confinement effect in these regions. To prevent the spalling of cover concrete at both ends of the specimens because of the stress concentration and corrosion attacks, the external confinement using the steel frames was also installed in two end regions of the specimens, as demonstrated in Figs. 1 and 3.

### 2.2. Material properties

The target concrete strength of 30 MPa for test specimens was supplied by a local ready-mix plant and casted in five batches. Three 150 × 300 mm cylinder specimens and an unconfined concrete specimen were made for each batch. The unconfined concrete specimens have the same dimension as the other specimens, however, without transverse reinforcement, that is 600 mm in height and either 200 mm square or 200 mm circular sections, which were tested to estimate the maximum strength and the corresponding axial strain for unconfined concrete. The average compressive strengths of the cylinders at testing days, above 28 days, for the five batches of specimens were 30.5, 29.3, 25.9, 25.3, and 31.9 MPa while the corresponding strengths of the unconfined concrete specimens were 25.4, 24.9, 21.7, 18.0, and 24.4 MPa, respectively. The axial concrete strain of unconfined concrete at maximum stress for each batch of specimens was also recorded, as indicated in Table 1. As a result of the size effect and less effective consolidation, the maximum strength of unconfined concrete