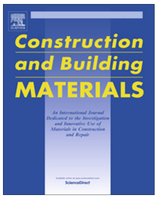
Construction and Building Materials 54 (2014) 572–583

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat



Degradation of flexural strength in reinforced concrete members caused by steel corrosion

Sun-Jin Han [a,1], Deuck Hang Lee [a,1], Kang Su Kim [a,*], Soo-Yeon Seo [b,2], Juhyuk Moon [c,3], Paulo J.M. Monteiro [d,4]

[a] *Department of Architectural Engineering, University of Seoul, 90 Jeonnong-dong, Dongdaemun-gu, Seoul 130-743, Republic of Korea*
[b] *Department of Architectural Engineering, Korea National University of Transportation, 50 Daehakno, Chungjusi, Chungbuk 380-702, Republic of Korea*
[c] *Civil Engineering Program, Department of Mechanical Engineering, State University of New York at Stony Brook, NY 11794, USA*
[d] *Roy W. Carlson Distinguished Professor, Department of Civil & Environmental Engineering, University of California, 115 Davis Hall, Berkeley, CA 94720, USA*

HIGHLIGHTS

- Strength degradation model in RC members with corroded steel bars was proposed.
- The proposed model reflects the bond performance degradation due to corrosion.
- The area loss of steel bars was also considered in the analysis model.
- The concept of average expansion pressure was introduced into the analysis model.
- The proposed non-linear analysis model was validated by various test results.

ARTICLE INFO

Article history:
Received 28 October 2013
Received in revised form 27 December 2013
Accepted 30 December 2013
Available online 28 January 2014

Keywords:
Corrosion
Bond strength
Cracking
Expansion pressure
Development length
Flexural strength

ABSTRACT

The volume expansion of reinforcements due to corrosion produces tensile stresses on the surrounding concrete, leading to radial cracks in the concrete cover and to significant reduction in the serviceability performance and durability of reinforced concrete members. In this study, a flexural strength assessment model of reinforced concrete (RC) members with corroded bars has been developed, which is an extension of the steel–concrete bond strength models based on the thick-walled cylinder theory. This model simulates the degradation of flexural strength in RC members according to the corrosion rate and flexural cracks, and is in good agreement with available experimental data.

1. Introduction

The high pH in the pore solution of concrete protects the embedded steel in reinforced concrete structures against corrosion in moderate environments [1–3]. However, once the thin passive film protecting the steel against corrosion is damaged by concrete carbonation or chlorides, the corrosion mechanism is initiated [1–3]. Corrosion products generated on the periphery of reinforcing bars cause two to six times the volume expansion compared to the amount of steel consumed by corrosion [1–5]. This results in radial cracks in the concrete around the reinforcing bars or the delamination of the cover concrete [3–7]. Furthermore, the loss of the effective cross-sectional area of reinforcing bars due to corrosion and the reduction of the bond strength due to the damage to the rebar ribs directly degrade the flexural strength of reinforced concrete members [2,3,8–25]. Previous studies have proposed various analysis models for the relationship between the corrosion rate and the bond strength [8,9,22,24,25]. Most of the existing models are based on the two-dimensional thick-walled cylinder model (TWCM). Although this approach can easily model the splitting cracking on concrete along the longitudinal direction over the reinforcing bars due to their volume expansion, the effect of cracking perpendicular to the member axis caused by the service

---

* Corresponding author. Tel.: +82 2 2210 5707; fax: +82 2 2248 0382.
E-mail addresses: sjhan@uos.ac.kr (S.-J. Han), dklee@uos.ac.kr (D.H. Lee), kangkim@uos.ac.kr (K.S. Kim), syseo@ut.ac.kr (S.-Y. Seo), jmoon3081@gmail.com (J. Moon), monteiro@ce.berkeley.edu (P.J.M. Monteiro).
[1] Tel.: +82 2 2210 5374; fax: +82 2 2248 0382.
[2] Tel.: +82 43 841 5205x5200.
[3] Tel.: +1 510 326 0695.
[4] Tel.: +1 510 643 8251; fax: +1 510 643 5264.

0950-0618/$ - see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.conbuildmat.2013.12.101

Nomenclature

A_{cef}	area of effective embedment zone of the concrete
A_s	sectional area of non-corroded tensile reinforcement
A'_s	sectional area of compressive reinforcement
A_v	sectional area of transverse reinforcement
A_x	sectional area of corroded tensile reinforcement
b	beam width
C	clear cover thickness
c	neutral axis depth
C_c	compressive force in concrete
c_e	effective depth of concrete cover
C_s	compressive force in reinforcing bars
d	depth to the tensile reinforcement
d'	depth to the compressive reinforcement
d_0	core diameter of deformed bar
d_b	diameter of non-corroded bar
d_x	diameter of corroded bar
E_c	elastic modulus of concrete
E_s	elastic modulus of steel
f	friction coefficient of crushed concrete
f_c	compressive stress of concrete
f_{ck}	compressive strength of concrete
f_r	modulus of rupture
f_s	tensile stress in reinforcement
f_t	concrete tensile strength
f_y	yield strength of steel bar
fp_x	friction force on the bearing face
h_x	rib height of corroded steel bar
I_1	invariants of the stress tensor
J_2	invariants of the deviatoric stress tensor
J_3	invariants of the deviatoric stress tensor
K_1	coefficient that characterizes bond properties of steel bar
K_2	coefficient to account for strain gradient
K_{sv}	coefficient to account for stirrup confinement
l_d	development length of tensile reinforcement
l_r	rib spacing
M_n	flexural strength
P_{avg}	average corrosion pressure over the length of crack element
P_c	confining stress in uncracked concrete
P_{corr}	corrosion pressure due to expansion of corrosion products
P_{crx}	average radial force
p_x	pressure in front of the bar rib
r	radius from the center of steel bar
R_c	radius at the crack tip
R_i	initial radius of steel bar
R_o	radius at the surface of concrete
R_u	radial distance at which the hoop strains reach ε_u
s	maximum spacing between longitudinal reinforcing bars
s_m	average spacing of flexural cracks
s_v	stirrup spacing
T_c	tensile force in concrete
T_s	tensile force in reinforcement
t_r	thickness of rust layer
u	radial displacement
x	corrosion penetration depth
x_{cr}	corrosion penetration depth at cover cracking
α	volume ratio of corrosion products to initial steel
α_1	stress-block factor
α_c	face angle of concrete crushing plane
β	angle of inclined cracking
β_1	stress-block factor
γ	angle between the direction of P_x and the inclined cracking
ε_1	concrete strain corresponding to the tensile stress $0.15f_t$
ε_c	compressive strain in concrete
ε_{co}	concrete strain corresponding to concrete compressive strength
ε_{cr}	cracking strain corresponding to concrete tensile strength (f_t/E_c)
ε_r	flexural cracking strain corresponding to modulus of rupture
ε_s	tensile strain in reinforcing bar
ε'_s	compressive strain in reinforcing bar
ε_u	concrete strain corresponding to zero tensile stress in concrete
ε_y	yield strain of steel bar
ε_α	largest tensile strain in the effective embedment zone
ε_β	smallest tensile strain in the effective embedment zone
ε_θ	tangential tensile strain
$\varepsilon_{\theta c}$	tangential tensile strain at $r = R_o$ (surface cracking)
θ	angle of octahedral shear stress (angle of similarity)
λ	parameter to calculate the failure condition of concrete under multiaxial stress state
μ	friction coefficient between steel and concrete
ρ_{ef}	tensile reinforcement ratio in the effective embedment zone
ρ_v	stirrup ratio in splitting plane ($A_v/c_e s_v$)
Σ_0	perimeter of the corroded rebar (πd_x)
σ_1	principal stress in the direction 1
σ_2	principal stress in the direction 2
σ_3	principal stress in the direction 3
σ_c	average radial compressive stress
σ_m	octahedral stress
σ_θ	tangential tensile stress
τ	average shear stress
τ_{avg}	average bond strength over the length of crack element
τ_{bu}	bond strength of corroded reinforcing bar considering corrosion pressure effect
τ_{crx}	bond strength of corroded reinforcing bar without corrosion pressure effect
τ_{total}	bond strength of corroded reinforcing bar considering stirrup confining effect
φ	rib face angle of deformed bar

loads, such as the flexural cracking, is not taken into account. Therefore, this study incorporates, the concept of average corrosion pressure into the bond strength analysis model so that it is possible to include the effect of flexural cracking on the concrete volume pressure in a simple but reasonable way. This modified bond strength model was implemented into a non-linear flexural strength analysis of the reinforced concrete members with corroded bars.

2. Estimation of raidal pressure due to corrosion

2.1. Compatibility and constitutive relationships

Fig. 1(a) shows an idealized TWCM consisted of a reinforcing bar embedded in concrete. According to the theory of elasticity [26], the deformation-strain relationship [$u(r)–\varepsilon_\theta(r)$] can be expressed in the polar coordinate system as follows: