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Report on Equivalent Rectangular Concrete Stress Block and Transverse Reinforcement for High-Strength Concrete Columns

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Reported by Joint ACI-ASCE Committee 441

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This report provides a research summary of equivalent rectangular concrete compressive stress blocks and transverse reinforcement design requirements for high-strength concrete (HSC) columns. Because ACI 318 code provisions for column design are mostly based on concrete strengths less than 10,000 psi (70 MPa), the use of equivalent rectangular concrete stress block factors given in the code has been questioned. As a result, many alternative expressions have been developed. This report provides a summary of various suggestions of equivalent rectangular concrete stress block and design guidelines for HSC columns.

The report also provides highlights of the research on the performance of HSC columns under various loading conditions, including monotonically increasing concentric or eccentric compression, and load reversals with increasing deformation and constant axial compression. The behavior of HSC columns subjected to combined axial load and bending moment is discussed. Various proposals for determining the amount and details of transverse reinforcement for seismic design are also reviewed.

Keywords: axial load; bending moment; columns; concrete stress block; ductility; flexural strength; high-strength concrete; longitudinal reinforcement; seismic design; transverse reinforcement.

CONTENTS

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CHAPTER 1—INTRODUCTION

High-strength concrete (HSC) has advantages over normal-strength concrete (NSC), especially for columns of high-rise buildings, as it reduces column sizes and increases the durability of concrete (Smith and Rad 1989). Moreover, HSC can be advantageous with regard to lateral stiffness and axial shortening (Colaco 1985). Another advantage cited by Colaco in the use of HSC columns is the cost reduction of formwork stemming from reduced cross-sectional dimensions. This economic advantage is achieved by using HSC in lower-story columns and reducing concrete strength over the height of the building while keeping the same column size over the building height.

Increased use of HSC has caused concerns over the applicability of the current building code requirements (ACI 318) for the design and detailing of HSC columns. Those concerns are mainly related to: 1) equivalent rectangular concrete stress distribution; and 2) transverse reinforcement requirements for seismic design. Chapter 22 of ACI 318-14 provides a concept of equivalent rectangular concrete stress distribution (ACI concrete stress block) for design of reinforced concrete columns. In the equivalent rectangular concrete stress block, an average stress of $0.85f_c'$ is used with a rectangle of depth $a = \beta_1 c$. The 1976 supplement to the 1971 code adopted a lower limit of β_1 equal to 0.65 based on research data from tests with concrete strengths exceeding 8000 psi (55 MPa). Several research studies reported that the use of current rectangular concrete stress block expressions of ACI 318 could produce overestimated flexural and axial strengths of HSC columns (Wahidi 1995; Ibrahim and MacGregor 1996; Lloyd and Rangan 1996). As a result, alternative concrete stress block expressions have been proposed (Ibrahim and MacGregor 1997; Bae and Bayrak 2003; Ozbakkaloglu and Saatcioglu 2004; Azizinamini et al. 1994).

Numerous research studies (Sakai and Sheikh 1989; Elwood et al. 2009a,b; Paultre and Légeron 2008) have been conducted in several countries to investigate the behavior of HSC columns, to evaluate similarities or differences between HSC and NSC columns, and to identify important parameters affecting performance of HSC columns designed for seismic, as well as nonseismic, areas. As a result, Chapter 18 of ACI 318-14 has updated the transverse reinforcement requirement to address the concern on the use of HSC columns for seismic design.

This document reports the results of recent studies on the equivalent rectangular concrete stress distribution, or concrete stress block, and transverse reinforcement requirements of HSC columns for seismic design.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

A_b = area of an individual longitudinal reinforcing bar, in.^{2} (mm^2)
A_c = area of core concrete measured out-to-out of transverse reinforcement, in.^{2} (mm^2)
A_{ch} = cross-sectional area of a member measured to the outside edges of transverse reinforcement, in.^{2} (mm^2)
A_g = gross area of concrete section, in.^{2} (mm^2). For a hollow section, A_g is the area of concrete only and does not include the area of void(s)
A_{sh} = total cross-sectional area of transverse reinforcement, including crossties, within spacing s (or s_h) and perpendicular to dimension b_c, in.^{2} (mm^2)
A_{st} = total area of nonprestressed longitudinal reinforcement including bars or steel shapes, and excluding prestressing reinforcement, in.^{2} (mm^2)
A_{te} = sum of the areas of tie legs used to provide lateral support against buckling for longitudinal reinforcement of column, in.^{2} (mm^2)
b = width of compression face of member, in. (mm)
b_c = cross-sectional dimension of member core measured to the outside edges of the transverse reinforcement composing area A_{sh}, in. (mm)
c = distance from extreme compression fiber to neutral axis, in. (mm)
d = distance from extreme compression fiber to centroid of longitudinal tension reinforcement, in. (mm)
d'' = depth of concrete core of column measured from center-to-center of peripheral rectangular hoop, circular hoop, or spiral in. (mm)
d_b = nominal diameter of bar, wire, or prestressing strand, in. (mm)
E_s = modulus of elasticity of reinforcement and structural steel, excluding prestressing reinforcement, psi (MPa)
f_c' = specified compressive strength of concrete, psi (MPa)
f_{cm} = measured compressive strength of concrete, psi (MPa)
f_s = transverse steel stress at or shortly after the attainment of maximum strength under concentric compression, psi (Eq. (4.5))
f_y = specified yield strength for nonprestressed reinforcement, psi (MPa)
f_{yh} (or f_{yt}) = specified yield strength of transverse reinforcement, psi (MPa)
h = overall height or depth of member, in. (mm)
h'' = dimension of concrete core of rectangular section, measured perpendicular to the direction of the hoop legs, measured to the outside of the peripheral hoop, in. (mm)
h_c = cross-sectional dimension of member core measured to outside edges of transverse reinforcement composing area A_{sh}, in. (mm), parallel to shear force in the member