ACI ITG-4.3R-07

Report on Structural Design and Detailing for High-Strength Concrete in Moderate to High Seismic Applications

Reported by ACI Innovation Task Group 4
and Other Contributors

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ACI ITG-4.3R presents a literature review on seismic design using high-strength concrete. The document is organized in chapters addressing the structural design of columns, beams, beam-column joints, and structural walls made with high-strength concrete, and focuses on aspects most relevant for seismic design. Each chapter concludes with a series of recommended modifications to ACI 318-05 based on the findings of the literature review.

The recommendations include proposals for the modification of the equivalent rectangular stress block, equations to calculate the axial strength of columns subjected to concentric loading, column confinement requirements, limits on the specified yield strength of confinement reinforcement, strut factors, and provisions for the development of straight bars and hooks.

An accompanying standard, ITG-4.1, is written in mandatory language in a format that can be adopted by local jurisdictions, and will allow building officials to approve the use of high-strength concrete on projects that are being constructed under the provisions of ACI 301, "Specifications for Structural Concrete," and ACI 318, "Building Code Requirements for Structural Concrete."

ITG 4 has also developed another nonmandatory language document: ITG-4.2R. It addresses materials and quality considerations and is the supporting document for ITG-4.1.

Keywords: bond; confinement; drift; flexure; high-strength concrete; high-yield-strength reinforcement; seismic application; shear; stress block; strut-and-tie.

CONTENTS

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CHAPTER 1—INTRODUCTION

1.1—Background

The origin of ACI Innovation Task Group (ITG) 4, High-Strength Concrete for Seismic Applications, can be traced back to the International Conference of Building Officials (ICBO) (now International Code Council [ICC]) *Evaluation Report* ER-5536, "Seismic Design Utilizing High-Strength Concrete" (ICBO 2001). Evaluation Reports (ER) are issued by Evaluation Service subsidiaries of model code groups. An ER essentially states that although a particular method, process, or product is not specifically addressed by a particular edition of a certain model code, it is in compliance with the requirements of that particular edition of that model code.

ER-5536 (ICBO 2001), first issued in April 2001, was generated by Englekirk Systems Development Inc. for the seismic design of moment-resisting frame elements using high-strength concrete. High-strength concrete was defined as "normalweight concrete with a design compressive strength greater than 6000 psi (41 MPa) and up to a maximum of 12,000 psi (83 MPa)." It was based on research carried out at the University of Southern California and the University of California at San Diego to support building construction in Southern California using concrete with compressive strengths greater than 6000 psi (41 MPa).

The Portland Cement Association performed a review* of ER-5536 and brought up several concerns that focused on inconsistencies between the evaluation report and existing industry documents in two primary areas: material and structural. Despite those concerns, it was evident that the evaluation report had been created because quality assurance and design provisions were needed by local jurisdictions, such as the City of Los Angeles, to allow the use of high-strength concrete without undue restrictions. ACI has assumed a proactive role in the development of such provisions with the goal of creating a document that can be adopted nationwide.

ACI considered its own Committee 363, High Strength Concrete, to be the best choice to address the materials and quality aspects of the document, while ACI Subcommittee 318-H, Structural Concrete Building Code—Seismic Provisions, was considered the best choice to address the seismic detailing aspects. Because 318-H is a subcommittee of a code-writing body, the development of a technical document of this kind is not part of its intended mission. In addition, producing a document through a technical committee can be a lengthy process. Based on these limitations, a request was made to form an ITG that would have the advantage of following a shorter timeline to completion. In

*Unpublished report available from PCA, Skokie, Ill., Aug. 2001.

response to the request, the Technical Activities Committee (TAC) of ACI approved the formation of ITG 4 and established its mission. The mission was to develop an ACI document that addressed the application of high-strength concrete in structures located in areas of moderate and high seismicity. The document was intended to cover structural design, material properties, construction procedures, and quality-control measures. It was to contain language in a format that allowed building officials to approve the use of high-strength concrete in projects being constructed under the provisions of ACI 301-05, "Specifications for Structural Concrete," and ACI 318, "Building Code Requirements for Structural Concrete."

The concept of "moderate to high seismic applications," stated in the mission of the document, dates back to when U.S. seismic codes divided the country into seismic zones. These seismic zones were defined as regions in which seismic ground motion on rock, corresponding to a certain probability of occurrence, remained within certain ranges. Present-day seismic codes (ASCE/SEI 2006) follow a different approach to characterizing a seismic hazard. Given that public safety is a primary code objective, and that not all buildings in a given seismic zone are equally crucial to public safety, a new mechanism for triggering seismic design requirements and restrictions, called the seismic performance category (SPC), was developed. The SPC classification includes not only the seismicity at the site, but also the occupancy of the structure.

Recognizing that building performance during a seismic event depends not only on the severity of bedrock acceleration, but also on the type of soil that a structure is founded on, seismic design criteria in more recent seismic codes are based on seismic design categories (SDC). The SDC is a function of location, building occupancy, and soil type. The TAC Technology Transfer Committee (TTTC)-established mission of ITG 4 was interpreted to mean that the Task Group was to address the application of high-strength concrete in structures that are:

- Located in Seismic Zones 2, 3, or 4 of the "Uniform Building Code" (ICBO 1997); or
- Assigned to SDC C, D, or E of "The BOCA National Building Code" (BOCA 1993 and subsequent editions) or the "Standard Building Code" (SBCCI 1994); or
- SDC C, D, E, or F of the "International Building Code" (IBC 2003) or the National Fire Protection Association (NFPA) NFPA 5000 "Building Construction and Safety Code" (2003).

SPC or SDC C is also referred to as the "intermediate" category. Similarly, SPC D and E or SDC D, E, and F are referred to as "high" categories. The terminology "moderate to high seismic applications," however, is used throughout this document.

1.2—Scope

This document addresses the material and design considerations when using normalweight concretes having specified compressive strengths of 6000 psi (41 MPa) or greater in structures designed for moderate to high seismic applications. Irrespective of seismic zone, SPC, or SDC, this document is also applicable to normalweight high-strength concrete in intermediate or special moment frames and intermediate or special structural walls as defined in ACI 318-05 (ACI Committee 318 2005).

The term "high-strength concrete," as defined by ACI 363R-92 (ACI Committee 363 1992), refers to concrete having a specified compressive strength for design of 6000 psi (41 MPa) or greater. The 6000 psi (41 MPa) threshold that was chosen for this document is similar to that adopted by ACI Committee 363.

Even though high-strength concrete is defined based on a threshold compressive strength, the concept of high strength is relative. The limit at which concrete is considered to be high strength depends largely on the location in which it is being used. In some regions, structures are routinely designed with concrete having specified compressive strengths of 12,000 psi (83 MPa) or higher, whereas in other regions, concrete with a much lower specified compressive strength is considered high strength. Essentially, the strength threshold at which concrete is considered high strength depends on regional factors, such as the characteristics and availability of raw materials, production capabilities, testing capabilities, and experience of the ready mixed concrete supplier.

ITG-4 produced three documents: ITG-4.1 is a reference specification that can be cited in the project specifications; ITG-4.2R addresses materials and quality considerations that are the basis for the ITG-4.1 specification; and ITG-4.3R, this document, addresses structural design and detailing. Certain modifications of ACI 318 requirements are proposed in Chapter 10 of ITG-4.3R.

From a materials perspective, there are few differences between the properties of high-strength concrete used in seismic applications and those of high-strength concrete used in nonseismic applications; therefore, the information presented in ITG-4.1 and ITG-4.2R is generally applicable to all high-strength concrete. When special considerations are warranted due to seismic applications, they are addressed specifically. Unlike ITG-4.1 and ITG-4.2R, most of the material contained in ITG-4.3R is specific to seismic applications of high-strength concrete structural members.

The information in Chapters 4 through 9 of this document is presented in a report format. Chapter 10 contains suggested modifications to design and detailing requirements in ACI 318-05.

Some topics, such as compressive stress block and confinement of beam-columns, are more developed than others because there is significantly more literature available on these topics. For all topics, an attempt was made to be as thorough as possible in summarizing the most relevant information pertaining to the design of members with high-strength concrete. For topics with limited information in the literature, however, recommendations were made with the intent of preventing potentially unsafe design.

CHAPTER 2—NOTATION

$A_{b,max}$ = cross-sectional area of largest bar being developed or spliced, in.^{2} (mm^2)
A_{cc} = cross-sectional area of structural member measured center-to-center of transverse reinforcement, in.^{2} (mm^2)
A_{ch} = cross-sectional area of structural member measured out-to-out of transverse reinforcement, in.^{2} (mm^2)
A_{cv} = gross area of concrete section bounded by web thickness and length of section in direction of shear force considered, in.^{2} (mm^2)
A_g = gross area of concrete section, in.^{2} (mm^2). For hollow section, A_g is area of concrete only and does not include area of void(s)
A_{sh} = total cross-sectional area of transverse reinforcement (including crossties) within spacing s and perpendicular to dimension b_c, in.^{2} (mm^2)
A_{sp} = cross-sectional area of transverse reinforcement crossing potential plane of splitting of bars being developed or spliced, in.^{2} (mm^2)
A_{st} = total area of nonprestressed longitudinal reinforcement (bars or steel shapes), in.^{2} (mm^2)
A_{sv} = total area of vertical reinforcement in structural wall, in.^{2} (mm^2)
A_{swb} = total area of vertical reinforcement in boundary element of structural wall, in.^{2} (mm^2)
A_{sww} = total area of vertical reinforcement in web of structural wall, excluding the boundary elements, in.^{2} (mm^2)
A_{te} = sum of areas of tie legs used to provide lateral support against buckling for longitudinal bars of column, in.^{2} (mm^2)
A_{tr} = total cross-sectional area of all transverse reinforcement within spacing s that crosses potential plane of splitting through reinforcement being developed, in.^{2} (mm^2)
A_v = area of shear reinforcement with spacing s, in.^{2} (mm^2)
A_w = gross cross-sectional area of structural wall, in.^{2} (mm^2)
a_v = shear span, equal to distance from center of concentrated load to either: a) face of support for continuous or cantilever members; or b) center of support for simply supported members, in. (mm)
b = width of compression face of member, in. (mm)
b_c = cross-sectional dimension of column core measured center-to-center of outer legs of transverse reinforcement comprising area A_{sh}, in. (mm)
b_w = web width or diameter of circular section, in. (mm)
c = distance from extreme compression fiber to neutral axis, in. (mm)
c' = $c_{min} + d_b/2$ = spacing or cover dimension, in. (mm)
c_1 = dimension of rectangular or equivalent rectangular column, capital, or bracket measured in direction of span for which moments are being determined, in. (mm)
c_2 = dimension of rectangular or equivalent rectangular column, capital, or bracket measured in direction perpendicular to c_1, in. (mm)
c_b = smaller of: a) distance from center of bar or wire to nearest concrete surface; or b) one-half center-to-center spacing of bars or wires being developed, in. (mm)
c_c = clear cover of reinforcement, in. (mm)
c_{cb} = least distance from surface or reinforcement to tension face, in. (mm)
c_{max} = maximum of c_{cb} and c_s, in. (mm)
c_{min} = minimum cover used in expressions for bond strength of bars not confined by transverse reinforcement. Smaller of c_{cb} and c_s, in. (mm)
c_p = $\rho_{vr} \cdot f_{yt}/f'_c$ = volumetric confinement index
c_s = minimum of c_{so} and $(c_{si} + 0.25)$ in. [$(c_{si} + 6.35)$ mm], in. (mm)
c_{sfw} = flexural stress index for structural wall that represents measure of ratio of neutral axis depth to length of wall, in. (mm)
c_{si} = one-half of clear spacing between bars, in. (mm)
c_{so} = clear side concrete cover for reinforcing bar, in. (mm)
DR_{lim} = (Δ_{lim}/h_{col}) = limiting drift ratio
d = distance from extreme compression fiber to centroid of longitudinal tension reinforcement, in. (mm)
d_b = nominal diameter of bar, wire, or prestressing strand, in. (mm)
d_s = nominal diameter of bar used as transverse reinforcement, in. (mm)
E = load effects of earthquake or related internal moments and forces
EE_p = $[(M_{calc} - M_{exp})/M_{exp}] \times 100$ = parameter used to characterize accuracy of nominal moment strength of column
E_s = modulus of elasticity of reinforcement and structural steel, psi (MPa)
f'_c = specified compressive strength of concrete, psi (MPa)
f'_{co} = in-place strength of unconfined concrete in columns, psi (MPa) (often assumed as $0.85f'_c$)
f_p = $P/A_g f'_c$ = axial load ratio
f_{pc} = $P/A_{ch} f'_c$ = axial load ratio based on area of confined core
f_s = calculated tensile stress in reinforcement at service loads, psi (MPa)
$f_{t,l}$ = stress imposed on concrete by compression field associated with reinforcement oriented in direction parallel to flexural reinforcement located at edge of compression field, psi (MPa)
$f_{t,t}$ = stress imposed on concrete by compression field associated with reinforcement oriented in

direction perpendicular to flexural reinforcement located at edge of compression field, psi (MPa)

f_u = maximum tensile stress that can be developed in bar with 90-degree hook, psi (MPa)

f_{yl} = specified yield strength of longitudinal reinforcement, psi (MPa)

f_{yt} = specified yield strength of transverse reinforcement, psi (MPa)

$f_{yt,l}$ = specified yield strength of transverse reinforcement oriented parallel to flexural reinforcement located at edge of uniform compression field, psi (MPa)

$f_{yt,t}$ = specified yield strength of transverse reinforcement oriented perpendicular to flexural reinforcement located at edge of uniform compression field, psi (MPa)

h'' = core dimension perpendicular to transverse reinforcement providing confinement measured to outside of hoops, in. (mm)

h_a = tie depth, in. (mm)

h_{col} = clear column height, in. (mm)

h_w = height of entire wall from base to top or height of segment of wall considered, in. (mm)

h_x = maximum center-to-center horizontal spacing of crossties or hoop legs on all faces of column, in. (mm)

j = ratio of internal lever arm to effective depth of beam

K_{tr} = $(A_{tr}f_{yt}/1500sn)$ = transverse reinforcement index (refer to ACI 318-05, Section 12.2.3)

K'_{tr} = $(0.5t_dA_{tr}/sn)f_c'^{\,1/2}$ = transverse reinforcement index for Committee 408 development length expression, in. (mm)

k_1 = ratio of average to maximum stress in compression zone of flexural member

k_2 = ratio of distance from extreme compression fiber to location of compression reaction to distance from extreme compression fiber to location of neutral axis in flexural member

k_3 = ratio of maximum stress in compression zone of flexural member to cylinder strength

k_{cc} = cover factor in calculation of development length of hooked bars

k_d = development length factor in calculation of development length of hooked bars

k_j = development length and lever arm factor in calculation of development length of hooked bars

k_s = transverse reinforcement bar diameter factor for calculation of development length of hooked bars

l_b = dimension of loading plate or support in axial direction of member, in. (mm)

l_d = development length in tension of deformed bar, deformed wire, plain or deformed welded wire reinforcement, or pretensioned strand, in. (mm)

l_{dh} = development length in tension of deformed bar or deformed wire with standard hook, measured from critical section to outside end of hook, in. (mm)

l_o = length, measured from joint face along axis of structural member, over which special transverse reinforcement must be provided, in. (mm)

l_w = length of entire wall or length of segment of wall considered in direction of shear force, in. (mm)

M = maximum unfactored moment due to service loads, including P-Δ effects, in.-lb (N-mm)

M_{exp} = measured flexural strength of column, in.-lb (N-mm)

M_{ncol} = nominal flexural strength of column, in.-lb (N-mm)

m = $f_{yl}/0.85f_c'$ = ratio of nominal yield strength of longitudinal reinforcement to nominal strength of concrete in column

n = number of bars being spliced or developed in plane of splitting

n_L = number of legs of reinforcement in hoops and ties

P = unfactored axial load, lb (N)

P_o = nominal axial strength at zero eccentricity, lb (N)

s = center-to-center spacing of items, such as longitudinal reinforcement, transverse reinforcement, prestressing tendons, wires, or anchors, in. (mm)

s_o = center-to-center spacing of transverse reinforcement within length l_o, in. (mm)

T_b = total bond force of developed or spliced bar, lb (N)

T_s = steel contribution to total bond force, additional bond strength provided by transverse steel, lb (N)

t_d = term representing effect of bar size on T_s

V = maximum unfactored shear force at service loads, including P-Δ effects, lb (N)

V_a = nominal shear strength provided by strut spanning between load point and support in reinforced concrete members with shear span-depth ratios below 2.5, lb (N)

V_{all} = allowable shear force under service loads, lb (N)

V_c = nominal shear strength provided by the concrete, lb (N)

V_n = nominal shear strength, lb (N)

V_s = nominal shear strength provided by shear reinforcement, lb (N)

$V_{t,l}$ = nominal shear strength provided by uniform compression field associated with transverse reinforcement oriented parallel to flexural reinforcement located at edge of compression field, lb (N)

$V_{t,t}$ = nominal shear strength provided by uniform compression field associated with transverse reinforcement oriented perpendicular to flexural reinforcement located at edge of compression field, lb (N)

$v_{c,all}$ = allowable shear stress in concrete

w_{st} = strut width, in. (mm)

α_1 = factor relating magnitude of uniform stress in equivalent rectangular compressive stress