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 basically 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

ACI ITG-4.3R-07 was published and became effective August 2007.

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.