

Building Code Provisions for Precast/Prestressed Concrete: A Brief History

Thomas J. D'Arcy, P.E., FPCI

Consulting Engineer
The Consulting Engineers Group, Inc.
San Antonio, Texas



This article traces the evolution of building code provisions for precast/prestressed concrete in the United States. The first part presents the influence of European practices, then discusses American developments, PCI initiatives in writing code provisions and the role of the ACI Building Code. The latter part discusses the emergence of the model building code provisions with particular emphasis on seismic design issues.



George D. Nasser, P.E.

Editor Emeritus
Precast/Prestressed Concrete Institute
Chicago, Illinois

Back in 1949-1950, when the Walnut Lane Memorial Bridge was being constructed in Philadelphia, Pennsylvania, prestressed concrete was not recognized by the ACI Building Code nor by any other official jurisdiction in the United States. (It is generally recognized that it was the excitement and publicity generated by the Walnut Lane Bridge, the first major prestressed concrete structure in North America, that gave birth to the precast/prestressed concrete industry in the United States.) But before we digress any further, let's go back to the origins of prestressed concrete.

European Influence

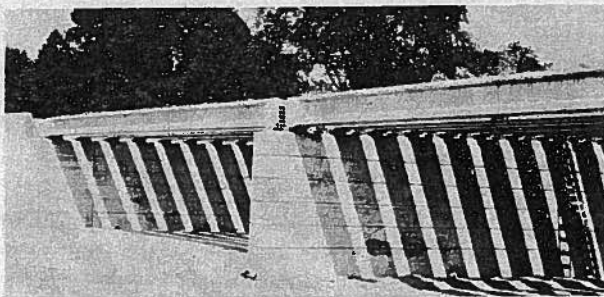
In 1936, the French pioneer Eugene Freyssinet, generally regarded as the "father" of prestressed concrete, announced at a special meeting before the British Institution of Structural Engineers in London that by combining concrete with high strength prestressing steel he had discovered a completely new material possessing properties very different from those of ordinary reinforced concrete.^{1,2} This new "revolutionary" material would always be in compression

S.K. Ghosh, Ph.D., FPCI

President
S.K. Ghosh Associates, Inc.
Northbrook, Illinois



Criteria for Prestressed Concrete Bridges



U. S. DEPARTMENT OF COMMERCE
BUREAU OF PUBLIC ROADS
WASHINGTON: 1954

Criteria for Prestressed Concrete Bridges

DESIGN

Temporary stresses

Temporary stresses before creep and shrinkage shall not exceed the following:¹

Concrete:	
Compression in extreme fiber	$\left\{ \begin{array}{l} \text{pretensioned} \dots\dots\dots 0.60f_{ci} \\ \text{post-tensioned} \dots\dots\dots 0.55f_{ci} \end{array} \right.$
Tension	$\dots\dots\dots 0.05f_{ci}$
Prestressing steel: Tension	$\dots\dots\dots 0.80f_s$

Stress under dead, live, or impact load

Stress after creep and shrinkage under dead, live, or impact load, or any combination of these forces, shall not exceed the following:

Concrete:	
Compression in extreme fiber	$\dots\dots\dots 0.4f_c$
Tension in extreme fiber	$\dots\dots\dots 0$

Where the computations show tension in the extreme fiber, unprestressed reinforcement may be used, and designed to take the total tensile stresses, provided that the computed tension in the concrete before the unprestressed steel is added does not exceed $0.08f_c$.

Prestressing steel: $\dots\dots\dots 0.6f_s$, or $0.8f_{sy}$, whichever is less.

Creep, shrinkage, and elastic deformation

Decrease in prestress in steel due to creep, shrinkage, and elastic deformation shall be assumed to be as follows:

Pretensioned concrete	$\dots\dots\dots 6,000 + 18f_{se} + 0.04f_{se}$
Post-tensioned concrete	$\dots\dots\dots 3,000 + 11f_{se} + 0.04f_{se}$

In these criteria the efficiency of the anchorage has been assumed to be 100 percent. The designer should add to the figure given for creep and shrinkage an amount sufficient to allow for the anchorage efficiency, as determined by test.

Light-weight aggregate: An amount to be determined by tests.

Decrease in prestress due to friction

Where the prestressing steel is "draped" and wherever minor irregularities occur in the alignment of the ducts, the stress in the interior of the beam will be somewhat less than that at the jack, due to friction. This loss shall be estimated and verified in the field as given in the section on construction under the heading "Post-tensioning method (p. 5). A guide to the estimation of the loss will be found in the discussion.

¹ A notation appears on page vi.

Fig 1. U.S. Bureau of Public Roads Criteria for Prestressed Concrete Bridges (1954).

and thus would not allow tensile stresses or cracking under any service loads. [It should be appreciated that Freyssinet's concept (including some applications) of prestressed concrete occurred much earlier than 1936, which was inspired in connection with his work on time-dependent deformations of reinforced concrete arch bridges. However, his London lecture was the first time that the English-speaking world became fully aware of the significance of his work on the potential of prestressed concrete.]

Word of Freyssinet's concept of prestressed concrete, together with its applications, gradually reached the outside world, but its full implementation was, unfortunately, interrupted by the onset of World War II. However, interest in prestressed concrete took on a new dimension after the war, especially because of the pressing need to build new bridges and buildings due to the wartime destruction of the European infrastructure. At the same time, there was a worldwide shortage of structural steel. Thus, prestressed concrete provided an efficient and economical solution to Europe's rebuilding program.

In the post-war years, several European researchers and practitioners questioned whether prestressed concrete members needed to be in total compression during their service life. A change in concept was particularly advocated by Paul Abeles in England. Based on research and his work with British Railways, he showed that partially prestressed con-

crete, i.e., members reinforced by a combination of prestressing steel and mild steel reinforcement, that allowed some tension under service load, could perform very well even in a cracked state.³⁻⁵ His tests showed that partially prestressed concrete beams could withstand tensile stresses as high as 750 psi (5 MPa) under service loads.

This concept was further reinforced when a partially prestressed concrete beam was built on the roof of a London train station. This beam was purposely allowed to develop cracks during service loads. These cracks were held open with stainless steel razor blades. The beam was exposed to acidic smoke from coal-fueled locomotive trains for several years. The end result was that the beam performed very well, showing no major signs of distress.

Practitioners also discovered that prestressed concrete beams, designed for compression only, were vulnerable to excessive camber as well as long-term creep and shrinkage. Thus, the concept of allowable tension was born, which prevails in today's concrete codes.

American Developments

Returning now to the Walnut Lane Bridge, this structure was designed by Professor Gustave Magnel of Belgium. The design specifications were basically European. The anchorage hardware used was the Magnel system, a patented sys-

Standard SPECIFICATIONS

For Pre-Tensioned Bonded Prestressed Concrete— Adopted by the PRESTRESSED CONCRETE INSTITUTE, October 7th, 1954, effective November 7, 1954. Amended March 7, 1955.

Section 1. SCOPE

(A) These specifications cover the design and use of Pre-tensioned Bonded Prestressed Concrete, in any structure to be erected under the provisions of these specifications.

Section 2. DEFINITIONS

(A) The term 'Pre-tensioned Bonded Prestressed Concrete' refers to the concrete in which the prestressing strands and/or wire are tensioned, before the hardening of concrete, between fixed abutments in a prestressing bed, or against strong moulds. When the concrete has hardened, the connection between the strands (and/or wire), and the abutments are released and the pre-tensioned strands (and/or wires) will contract and thus to create mainly internal compressive stress in concrete through bond between the strands and the concrete.

(B) The definitions of all other terms pertaining to prestressed concrete shall conform to the latest report of Joint ACI-ASCE Committee 323.

Fig. 2. PCI's first Specifications for Pretensioned Bonded Prestressed Concrete (1954).

PCI STANDARD BUILDING CODE FOR PRESTRESSED CONCRETE PRESENTED FOR REVIEW

Copies of our tentative Building Code have been distributed to our membership and to registrants at the PCI Fifth Annual Convention. Constructive criticism is now invited. It is suggested that all discussion and criticism be made clear and concise and referred to the respective sections of the Code. They should be sent to the Committee Chairman, Professor T. Y. Lin, with minimum of two duplicates, to his address listed below. Seven copies are preferred if convenient. Closing date for their acceptance is March 1, 1960. Copies have also been sent to members of the Federation Internationale de la Precontrainte for their review and comment.

The committee intends to revise and publish the Code in its final form, based on constructive criticism received.

Correspondence should be addressed to Professor T. Y. Lin, Chairman PCI Standard Building Code Committee, Engineering Materials Library, University of California, Berkeley 4, California.

Fig. 3. PCI Standard Building Code for Prestressed Concrete (1959).

tem developed by the professor himself, while the prestressing steel used was 0.276 in. (7 mm) diameter, stress-relieved wire furnished by Roebling, a Swiss-American company famous for supplying the steel cables for the Brooklyn Bridge in New York City and other suspension bridges.

Note that seven-wire strand was still in the experimental stage and in limited use. The bridge was essentially a post-tensioned concrete girder structure cast on site.⁶ The girder spans were 160 ft (49 m) long, which are fairly large even by today's standards.

With the successful completion of the Walnut Lane Bridge, interest in prestressed concrete began to spread across the United States. Within the next decade, nearly 100 precast/prestressing plants sprouted in North America. And yet, there were still no provisions for prestressed concrete in

Section 4. DESIGN STRESSES

(A) PRESTRESSING STRAND AND WIRE

- (1) Initial stresses shall not exceed 70% of minimum ultimate strength for stress-relieved strand and/or wire.
- (2) Loss in initial prestress due to creep, shrinkage and plastic deformation shall be assumed not less than 16%.

(B) CONCRETE

- (1) Maximum allowable stresses in concrete at the time of transfer of prestressing shall be as follows:

Compression in Bridge Members	0.50 f_c'
Compression in Building Members	0.55 f_c'
Tension	0.06 f_c'

Unless additional is taken by reinforcing steel.

- (2) Maximum allowable stresses under final dead and live load conditions shall be as follows:

Compression in bridge members	0.40 f_c'
Compression in building members	0.44 f_c'
Tension in bottom fiber in bridge members	0
Tension in bottom fiber in building members	0.05 f_c'
Tension in top fiber	0.04 f_c'

Unless the additional is carried by reinforcing steel, but not more than 0.08 f_c'

Diagonal tension 0.04 f_c'

- (C) When concrete of light weight aggregate is used, data on stress losses due to creep, shrinkage, and plastic deformation should be presented and these stress losses used instead of those listed under 4 (A) (2).

the ACI Building Code. Nevertheless, interest in prestressed concrete was evident as early as 1944 by the formation of the ACI-ASCE Joint Committee 323 (later 423) on Prestressed Concrete. This committee was to play an important role in the formulation of provisions for prestressed concrete 14 years later (1958).

Based primarily on the work of Eric L. Erickson, in Louisiana, the U.S. Bureau of Public Roads (the precursor of the Federal Highway Administration) published in 1954 the *Criteria for Prestressed Concrete Bridges* (see Fig. 1).⁷ This document was to have a major impact on the future of prestressed concrete, especially for bridges. One very important outcome of this document was the inclusion of precast, prestressed concrete provisions in the AASHTO Standard Specifications for Highway Bridges⁸ and the more recent LRFD Design Specifications.⁹

With the founding of the Prestressed Concrete Institute in 1954, the early precasters found it necessary to develop their own set of "code provisions" for pretensioned concrete products. This document came in the form of a three-page pamphlet titled "Specifications for Pretensioned Bonded Prestressed Concrete," published on October 7, 1954 (see Fig. 2), and made effective on November 7, 1954.¹⁰ Then, in December 1959, the PCI announced that its Standard Building Code Committee (T.Y. Lin, chairman) had developed a "Standard Building Code for Prestressed Concrete" (see Fig. 3). Prior to official adoption, this document was open to public discussion with a deadline for comments by March 1, 1960.

ACI Code

It is important to mention that in the late 50s, considerable progress was being made in developing the Joint ASCE-ACI Committee 323 report on Prestressed Concrete. This report (see Fig. 4), which had a major impact on the 1963 ACI Code, was published simultaneously in the *ACI Journal* and in the *PCI JOURNAL* in 1958.¹¹

With the proliferation of precast/prestressed concrete in

JOINT ASCE-ACI REPORT ON PRESTRESSED CONCRETE

Prepared by
COMMITTEE 323

This Report is herein published with the approval of the AMERICAN CONCRETE INSTITUTE and the AMERICAN SOCIETY OF CIVIL ENGINEERS.

No reprints or individual copies of the Report can be published by the PRESTRESSED CONCRETE INSTITUTE. Separate reprints are available only from the AMERICAN CONCRETE INSTITUTE.

Discussion of all aspects of this tentative Report should be directed to the AMERICAN CONCRETE INSTITUTE not later than April 1, 1958.

This Report is being published by the PRESTRESSED CONCRETE INSTITUTE in order to acquaint its membership with this tentative Report, which sometime in the future will be adopted and used throughout the United States as a standard for the design and construction with prestressed concrete.

A. M. OZELL,
Editor
PCI JOURNAL

Fig. 4. ASCE-ACI 323 report on Prestressed Concrete (1958).

the 50s and 60s, the American Concrete Institute felt it was desirable to have prestressed concrete covered in the ACI Building Code, which until then had provisions only for reinforced concrete, so that a practitioner would have to deal with one code only. ACI approached the PCI to explore the possibility of PCI refraining from publishing its own "code" on prestressed concrete, provided it received proper representation in the ACI 318 Building Code.

At a meeting in Detroit in 1959, PCI negotiated an agreement with ACI in which ACI agreed to incorporate provisions for prestressed concrete into its code and to have four members from PCI on the ACI Code Committee to draft the code language. (This group comprised Ross Bryan, Armand Gustaferro, T.Y. Lin and Irwin Speyer.) Further, PCI would be allowed to distribute the ACI Code under a PCI cover showing the particular edition or year of the code. The result of this agreement was the inclusion of prestressed concrete code provisions for the first time in the 1963 edition of the ACI Code (see Fig. 5).¹²

Subsequently, two chapters appeared in the ACI 318 Code: Chapter 16 on Precast Concrete and Chapter 18 on Prestressed Concrete.

The trend in recent years has been for both European and American codes of practice to lump reinforced and prestressed concrete into a single entity, namely, structural con-

207—ALLOWABLE STEEL AND CONCRETE STRESSES

207.1—Prestressing steel

207.1.1—Temporary stresses

Under normal design loads stress in prestressing steel will almost always be less than stress at initial prestress. Stress at the anchorage immediately after seating has been effected should not exceed $0.70f_{pu}$ for material having stress-strain properties defined in Chapter 3. Overstressing for a short period of time to $0.80f_{pu}$ may be permitted provided the stress, after seating of anchorage occurs, does not exceed $0.70f_{pu}$.

207.1.2—Stress at design loads

Effective steel stress after losses described in Section 208 should not exceed:

$$0.60f_{pu} \text{ or } 0.80f_{py}$$

whichever is smaller.

207.2—Non-prestressed reinforcement

Non-prestressed reinforcement provided to resist tension in conformance with requirements of Section 207.3.1.b.2 may be assumed stressed to 20,000 psi.

207.3—Concrete

207.3.1—Temporary stresses

Concrete stress in psi before losses due to creep and shrinkage should not exceed the following:

a. Compression

For pretensioned members.....	$0.60f'_{ci}$
For post-tensioned members.....	$0.55f'_{ci}$

b. Tension

1. For members without non-prestressed reinforcement:

Single element.....	$3\sqrt{f'_{ci}}$
Segmental element.....	zero

2. For members with non-prestressed reinforcement provided to resist the tensile force in the concrete, computed on the basis of an uncracked section:

Single element.....	$6\sqrt{f'_{ci}}$
Segmental element.....	$3\sqrt{f'_{ci}}$

207.3.2—Stresses at design loads

After full prestress losses, stresses in psi should not exceed the following:

a. Compression

1. Single element	
a. Bridge members.....	$0.40f'_{ci}$
b. Building members.....	$0.45f'_{ci}$

2. Segmental elements

a. Bridge members.....	$0.40f'_{ci}$
b. Building members.....	$0.45f'_{ci}$

b. Flexural tension in the precompressed tensile zone

1. Single element

a. Bridge members.....	zero
b. Pretensioned building elements not exposed to weather or corrosive atmosphere.....	$6\sqrt{f'_{ci}}$
c. Post-tensioned bonded elements not exposed to weather or corrosive atmosphere.....	$3\sqrt{f'_{ci}}$

2. Segmental elements

a. Bridge members.....	zero
b. Building members.....	zero

Allowable flexural tension of $6\sqrt{f'_{ci}}$ in Section 207.3.2.b.1.b may be exceeded provided it is shown by tests that the structure will behave properly under service conditions and meet any necessary requirement for cracking load or temporary overload.

crete. This is reflected in the current edition of the ACI Code (ACI 318-02).¹³

Over the years, despite PCI involvement in the ACI Code development process, code provisions favorable to precast/prestressed concrete have not always met expectations. The code negotiating process has often been difficult and time consuming. Some design engineers in the precast/prestressed concrete industry have felt at times that the ACI provisions have held back the proper development of prestressed concrete and that, in some cases, the ACI provisions were in error. Pressure began to mount on PCI to again enter the code-writing arena, at least in a limited way.

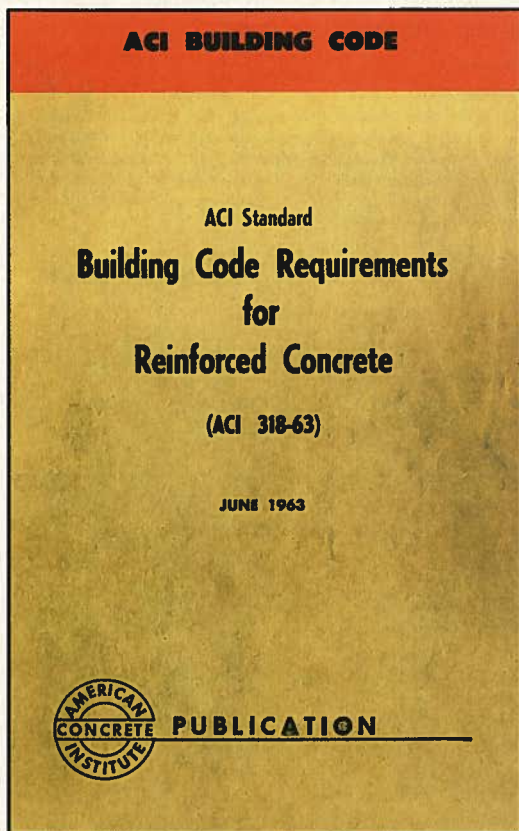


Fig. 5. First inclusion of prestressed concrete provisions in 1963 ACI Code.

PCI Standard Design Practice

Prepared by

PCI Technical Activities Council
and
PCI Committee on Building Code

Technical Activities Council
THOMAS J. D'ARCY
Chairman

ROGER J. BECKER
NED M. CLELAND
GREG FORCE
GERALD E. GOETTSCHIE
RICHARD GOLEC
PHILLIP J. IVERSON
PAUL D. MACK
GUILLERMO MECALCO

DONALD F. MEINHEIT
GEORGE D. NASSER
JAGDISH C. NIJHAWAN
MICHAEL G. OLIVA
A. FATTAH SHAIKH
IRWIN J. SPEYER
C. DOUGLAS SUTTON

Committee on Building Code
LESLIE D. MARTIN
Chairman

ROGER J. BECKER
ANANT Y. DABHOLKAR
GREG FORCE
HARRY A. GLEICH
EDWARD J. GREGORY
PHILLIP J. IVERSON
L. S. (PAUL) JOHAL
PAUL D. MACK
MICHAEL J. MALSOM
W. MICHAEL McCONOCHIE

RITA SERADERIAN
DOUG MOORADIAN
MICHAEL G. OLIVA
WALTER J. PREBIS
JOHN SALMONS
KIM SEEBER
IRWIN J. SPEYER
EDWARD P. TUMULTY
DON WEISS

PCI Initiatives

As chairman of the Technical Activities Council in 1997, Thomas J. D'Arcy worked with the PCI Building Code Committee to develop a PCI Code of Practice which would incorporate proven design practices within the industry, but would not necessarily be in full compliance with the ACI Building Code. In developing this report, more than fifty key design engineers of precast/prestressed concrete structures were surveyed for their expertise, and were asked to cite specific areas which differed from ACI Code practice.

This effort resulted in the first "PCI Standard Design Practice," which was published in the March-April 1997 issue of the PCI JOURNAL (see Fig. 6).¹⁴ A revised edition of this document was published in the January-February 2003 issue of the PCI JOURNAL.¹⁵ Note that the 1997 report also appears as an appendix in the Fifth Edition of the PCI Design Handbook. A slightly revised version of the report will also be included in the upcoming Sixth Edition of the Design Handbook.

The Standard Design Practice not only provides a forum for the design of precast/prestressed concrete members in compliance with current practice, but it also allows designers to review the research or practice upon which the recommendations were based. For each recommendation, an ACI 318 section is quoted, the PCI revisions suggested, and the tech-

ACI CODE	PCI PRACTICE
CHAPTER 18 PRESTRESSED CONCRETE	
18.4.1 Stresses in concrete immediately after prestress transfer (before time-dependent prestress losses) shall not exceed the following:	18.4.1 Recent research (see Strength Design of Prestressed Flexural Concrete Members at Prestress Transfer by Noppakunwijai, Tadros, Ma, and Mast, PCI JOURNAL, January-February 2001, pp. 34-52) has shown that the compression limitations at transfer are more conservative than necessary, and have an effect on economy and safety. It has been common practice to allow compression up to $0.70f'_c$. Other sections of the code define cracking stress as $7.5\sqrt{f'_c}$, so the $6\sqrt{f'_c}$ is not consistent. There also does not seem to be a logical reason for limiting the transfer tension at midspan to less than at the ends, since service load compression in the top is higher at midspan. Thus, at all sections, tension limits of $7.5\sqrt{f'_c}$ are more consistent with Code philosophy. It is recommended that nominal reinforcement (at least 2 No. 4 or nominally tensioned strands) be provided in tops of beams even when tension stress is less than $7.5\sqrt{f'_c}$.
(a) Extreme fiber stress in compression $0.60f'_c$	
(b) Extreme fiber stress in tension except as permitted in (c) $3\sqrt{f'_c}$	
(c) Extreme fiber stress in tension at ends of simply supported members $6\sqrt{f'_c}$	
Where computed tensile stresses exceed these values, bonded additional reinforcement (nonprestressed or prestressed) shall be provided in the tensile zone to resist the total tensile force in concrete computed with the assumption of an uncracked section.	

Fig. 6. PCI Standard Design Practice (1997).

nical work or research supporting the recommendation provided. Where needed, PCI has conducted additional research to support these published design recommendations.

Already, this document and its supporting technical bases have been used successfully to initiate changes in the ACI Code. We are confident that this process will continue. PCI will maintain its involvement in the ACI Code development process, and would like to retain its ability to influence timely changes that will benefit the precast/prestressed concrete industry, the engineering profession, designers and the public.

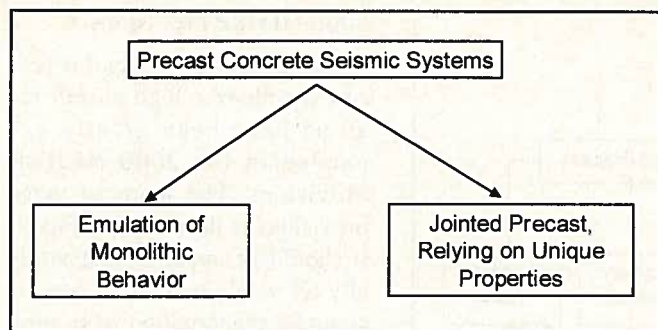


Fig. 7. Options for seismic-force-resisting systems of precast concrete.

SEISMIC DESIGN PROVISIONS

The previous part discussed the role of the ACI Code with regard to code provisions for precast/prestressed concrete. These code provisions pertained mainly to non-seismic design issues. In the case of the model codes, the emphasis will be on seismic issues.

Legality of Codes

It may not be widely understood that the ACI 318 Building Code Requirements for Structural Concrete, despite its title, is a standard and not a code. A standard, unlike a code, is not a legal document. A standard acquires legal authority usually by a two-step adoption process. The first step is adoption of the standard by a model code.¹⁶⁻²⁰ The second step is adoption of that model code by the legal code of a local jurisdiction (city, county, or state).

For instance, ACI 318-95²¹ is currently law within the State of California, because the 2001 California Building Code²² has adopted the 1997 Uniform Building Code,¹⁸ which in turn has adopted ACI 318-95. In some cases, a standard may be directly adopted by the legal code of a local jurisdiction. For instance, ACI 318-89²³ is law within the City of New York today, because the Building Code of the City of New York, 2001 edition,²⁴ has adopted ACI 318-89.

Until relatively recently, precast concrete structures could be built in areas of high seismicity, such as California, only under an enabling provision of ACI 318, which is adopted by all the model codes. The provision allows precast concrete construction in a highly seismic area "if it is demonstrated by experimental evidence and analysis that the proposed system will have a strength and toughness equal to or exceeding those provided by a comparable monolithic reinforced concrete structure...." The enforcement of this vague, qualitative requirement was, for obvious reasons, non-uniform. The need for specific enforceable design requirements for precast structures in regions of high seismicity was apparent for quite some time.

The first set of specific design provisions ever developed in the United States for precast concrete structures in regions of high seismicity appeared in the 1994 edition of the National Earthquake Hazards Reduction Program (NEHRP) Recommended Provisions,²⁵ issued by the Building Seismic

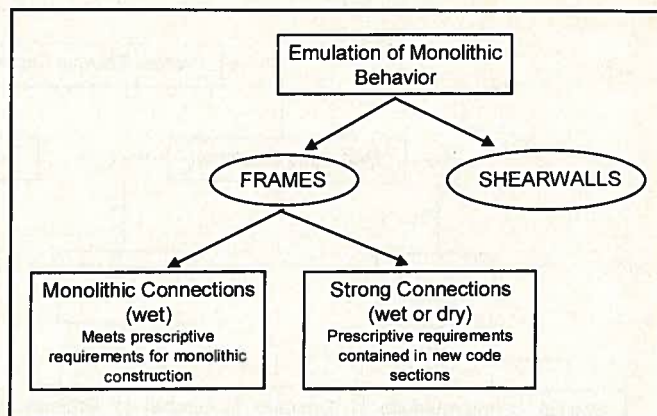


Fig. 8. Options for emulation of monolithic behavior.

Safety Council (BSSC). These provisions have evolved significantly since the publication of that document.

1994 NEHRP Provisions

The 1994 NEHRP Provisions presented two alternatives for the design of precast lateral-force-resisting systems (see Fig. 7). One choice is emulation of monolithic reinforced concrete construction. The other alternative is the use of the unique properties of precast concrete elements interconnected predominantly by dry connections (jointed precast). A "wet" connection uses any of the splicing methods of ACI 318 to connect precast or precast and cast-in-place members, and uses cast-in-place concrete or grout to fill the splicing closure. A "dry" connection is a connection between precast or precast and cast-in-place members that does not qualify as a wet connection.

Design procedures for the second alternative (jointed precast) were included in an appendix to the chapter on concrete in the 1994 NEHRP Provisions. These procedures were intended for information and trial design only because the existing state of knowledge made it premature to propose codifiable provisions based on information available at that time.

1997 Uniform Building Code

The Ad Hoc Committee on Precast Concrete of the Structural Engineers Association of California (SEAOC) Seismology Committee used the 1994 NEHRP requirements for precast concrete lateral-force-resisting systems as a starting point for their work in developing a code change for the 1997 UBC. However, the committee decided to limit their scope to frames only (excluding wall systems) and to the monolithic emulation option only. Jointed precast concrete is allowed only under the "unidentified structural systems" provisions of the 1997 UBC.

For emulation of the behavior of monolithic reinforced concrete construction, two alternatives are provided (see Fig. 8): structural systems with "wet" connections and those with "strong" connections. Precast structural systems with wet connections must comply with all requirements applicable to monolithic reinforced concrete construction. A strong

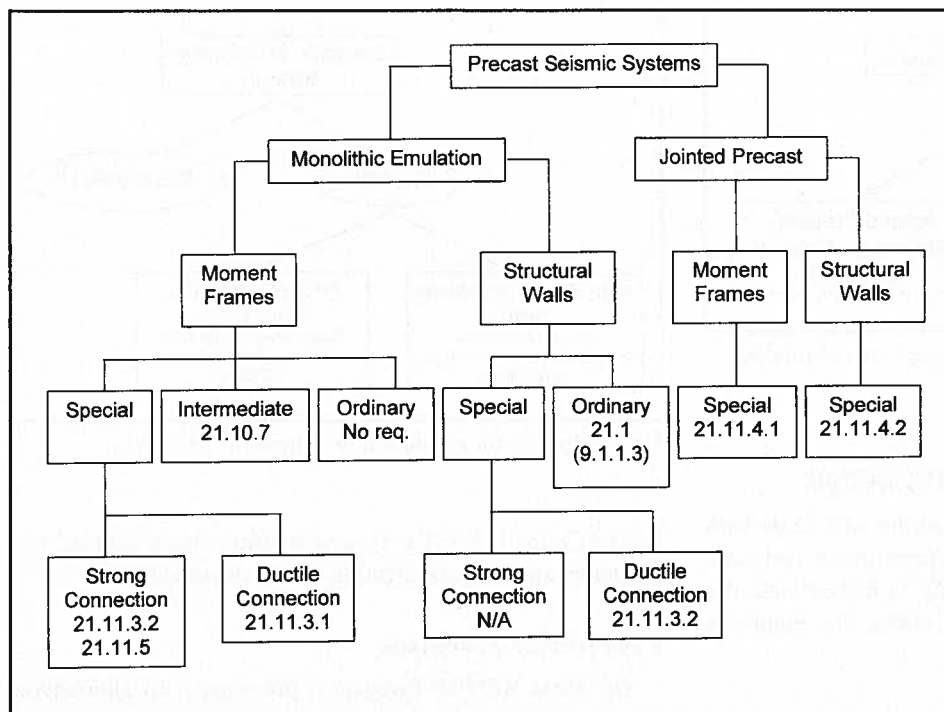


Fig. 9. Seismic design requirements for precast/prestressed concrete structures in 2000 NEHRP Provisions.

connection is a connection that remains elastic while designated portions of structural members (plastic hinges) undergo inelastic deformations (associated with damage) under the design basis ground motion. Prescriptive requirements are given for precast frame systems with strong connections. Such requirements for precast wall systems with strong connections are not included.

The 1994 NEHRP Provisions also addressed emulation of monolithic construction using ductile connections, covering both frame and wall systems, where the connections have adequate nonlinear response characteristics and it is not necessary to ensure plastic hinges remote from the connections. Usually, experimental verification is required to ensure that a connection has the necessary nonlinear response characteristics. The designer is required to consider the likely deformations of any proposed precast structure, compared to those of the same structure in monolithic reinforced concrete, before claiming that the precast form emulates monolithic construction. The 1997 UBC does not directly address emulation of monolithic construction using ductile connections.

1997 NEHRP Provisions and 2000 International Building Code

The 1997 UBC provisions concerning the design of precast concrete structures in regions of high seismicity were adopted into the 1997 edition of the NEHRP Provisions. The first edition of the International Building Code, which is replacing the prior model codes (now called "Legacy Codes") as the basis of the building codes for many legal jurisdictions, has its seismic design provisions based on the 1997 NEHRP Provisions. The design provisions for precast concrete structures exposed to high seismic risk are included.

2000 NEHRP Provisions

The design provisions for precast structures in high seismic regions have been greatly expanded in the 2000 NEHRP Provisions. The scope of these provisions is illustrated in Fig. 9. It should be apparent that virtually all viable options of precast concrete construction have now been considered.

The 2000 NEHRP Provisions adopts ACI 318-99 by reference to regulate concrete design and construction. Amendments are made by inserting additional provisions into, or revising the existing provisions of, ACI 318-99. In ACI 318-99, the seismic risk of a region is described as low, moderate or high. Chapter 21 contains specific requirements for the design of concrete structures in regions of high and moderate seismic risk. Structures in

regions of low seismic risk need only meet the requirements of Chapters 1 through 18 of ACI 318-99.

In the NEHRP Provisions, the applicability of Chapter 21 requirements depends not only on the region in which the structure is located, but also on the occupancy of the structure and the characteristics of the soil on which it is founded. In the 2000 NEHRP Provisions, these three considerations are combined in terms of Seismic Design Categories (SDC) which are assigned letters A through F.

ACI 318-99 recognizes SDCs A and B as being equivalent to regions of low seismic risk and needing only detailing that meets the requirements of Chapters 1 through 18. Structures assigned to SDC C are recognized as requiring detailing mandated for regions of moderate seismic risk, and structures assigned to SDCs D, E and F require detailing prescribed for regions of high seismic risk.

Section numbers in Fig. 9 starting with the number 9 (for ordinary structural walls) identify specific provisions of the NEHRP Provisions. Section numbers starting with the number 21 identify specific provisions inserted into ACI 318-99.

The 2000 NEHRP Provisions requires that seismic-force resisting systems in precast concrete structures assigned to SDCs D, E and F consist of special moment frames, special structural walls, and superior Type Z connections.

For structures assigned to SDC C, moment frames made from precast elements must utilize, as a minimum, Type Y connections. However, they can also have the tougher Type Z connections if the designer so chooses. Structural walls constructed with precast elements can be designed as ordinary structural walls per Chapters 1 through 18 of ACI 318-99, with the requirements of Chapter 16 superseding those of Chapter 14 and with Type Y connections, as a minimum, between elements.

Over the last decade, many advances have been made in our understanding of the seismic behavior of precast concrete frame structures. Those advances have made possible the standardization by ACI of acceptance criteria for concrete special moment frames, based on validation testing, in ACI T1.1-01.²⁶ That provisional standard, together with research advances, has made possible the development of criteria for the design of frames constructed from interconnected precast elements. While criteria for such frames have existed in the NEHRP Provisions since 1994, the previous criteria were in an appendix and contained penalties for the use of precast elements compared to monolithic concrete elements. Those penalties are eliminated in the 2000 NEHRP Provisions and the possible behavioral benefits of using precast construction are recognized.

The studies that led to the development of the acceptance criteria of ACI T1.1-01 for special moment frames also catalyzed studies that have resulted in the development of similar acceptance criteria for special structural walls.

The 2000 NEHRP Provisions requires that the substantiating experimental evidence and analysis for special structural wall systems meet requirements similar to those of ACI T1.1-99 for the design procedure used for the test modules, the scale of the modules, the testing agency, the test method, and the test report.

ACI 318-02

The 2002 edition of the ACI 318 standard, for the first time, includes design provisions for precast concrete structures located in regions of moderate to high seismic risk or assigned to intermediate or high seismic design categories (C, D, E, or F). Fig. 10 illustrates the scope of these provisions. It is evident that the scope is somewhat more limited, when compared to that of the 2000 NEHRP Provisions. Notably, provisions for non-emulative design of precast wall systems are not included in ACI 318-02. When the same item is covered in both documents, the requirements are for the most part similar.

A Progress Report

A Proposed Provisional Standard and Commentary titled "Acceptance Criteria for Special Structural Walls Based on Validation Testing" was developed by Neil Hawkins and S. K. Ghosh in early 2003.²⁷ This document defines the minimum experimental evidence that can be deemed adequate to attempt to validate, in regions of high seismic risk or in structures assigned to high seismic performance or design categories, the use of structural walls (shear walls) for Bearing Wall and Building Frame Systems (Section 9 of ASCE 7-02)²⁸ not satisfying fully the prescriptive requirements of Chapter 21 of ACI 318-02.

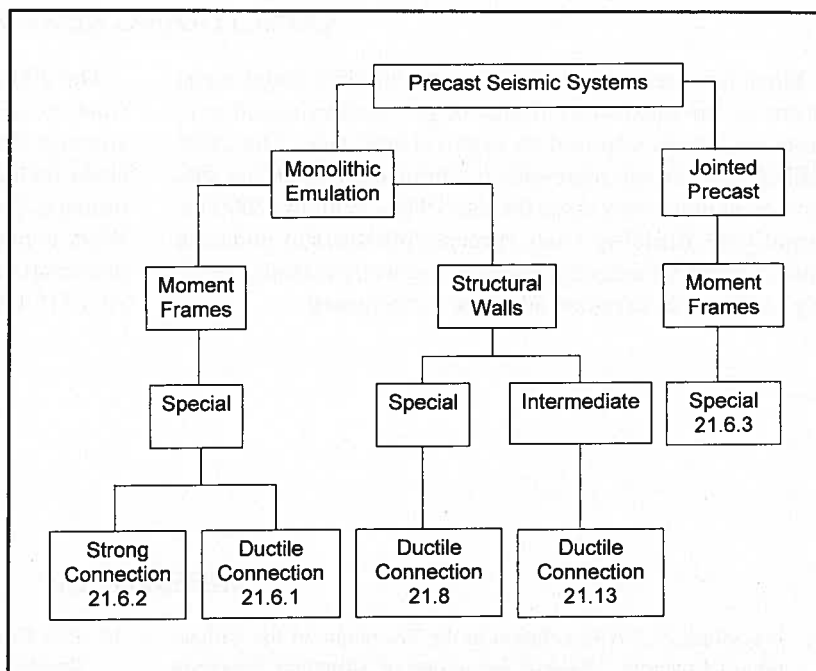


Fig. 10. Seismic design requirements for precast/prestressed concrete structures in ACI 318-02.

The document consists of both a Provisional Standard and a Commentary that is not part of the Provisional Standard. The document has been written in such a form that its various parts can be adopted directly into Sections 21.0, 21.1, and 21.2.1 of ACI 318-02 and the corresponding sections of ACI 318R-02. Among the subjects covered are requirements for: procedures that shall be used to design test modules; configurations for these modules; test methods; test reports; and determination of satisfactory performance.

A PCI-initiated proposal to permit non-emulative design of special precast concrete shear walls, using a modified version of "Acceptance Criteria for Special Structural Walls Based on Validation Testing," has been approved for inclusion in the 2003 edition of the NEHRP Provisions. This is a significant milestone.

Future Course

If one follows the path that led to the inclusion of non-emulative special moment frames in ACI 318-02, an Innovation Task Group (ITG) must be formed within ACI to develop a provisional standard similar to ACI T1.1-01 for precast shear wall systems. Such a group, ITG 5, has in fact been formed and has been charged with standardizing the proposed "Acceptance Criteria for Special Structural Walls Based on Validation Testing" by Hawkins and Ghosh.

If all goes well, a provisional standard may be approved by the Standards Board of ACI by the fall of 2005. If this transpires, it should be possible to have provisions included in ACI 318-08, which would permit non-emulative design of special precast structural walls using the provisional standard. ACI 318-08 will be the reference document for IBC 2009.

CONCLUDING REMARKS

Much has been accomplished in the building codes arena to enable the satisfactory design of precast/prestressed concrete structures exposed to high seismic risk. The 2000 NEHRP Provisions represents a culmination of efforts that have been under way since the late 1980s. With the 2000 International Building Code, precast/prestressed concrete buildings can be designed with the necessary seismic detailing and features to ensure adequate performance.

The 2002 edition of the ACI Building Code, for the first time, contains design provisions for precast/prestressed concrete structures exposed to high seismic risk. The provisions include the non-emulative design of special precast moment frames, but not special precast structural walls. Work is now progressing towards the intended inclusion of non-emulative design of special precast structural walls in ACI 318-08.

REFERENCES

1. Freyssinet, E., "A Revolution in the Technique of the Utilization of Concrete," *Journal*, Institution of Structural Engineers (London), V. 14, No. 5, May 1936, p. 242.
2. Freyssinet, E., "Prestressed Concrete: Principles and Applications," *Journal*, Institution of Civil Engineers (London), V. 33, No. 4, February 1950, p. 331.
3. Abeles, P. W., "Fully and Partially Prestressed Reinforced Concrete," *ACI Journal*, Proceedings V. 41, January 1945, p. 181.
4. Abeles, P. W., "Partial Prestressing and Possibilities for Its Practical Application," *PCI JOURNAL*, V. 4, No. 1, June 1959, pp. 35-51.
5. Abeles, P. W., "Partial Prestressing in England," *PCI JOURNAL*, V. 8, No. 1, February 1963, pp. 51-72.
6. *Reflections on the Beginnings of Prestressed Concrete in America*, Prestressed Concrete Institute, Chicago, IL, 1981, pp. 6-32.
7. *Criteria for Prestressed Concrete Bridges*, U.S. Department of Commerce, Bureau of Public Roads, Washington, DC, 1954.
8. AASHTO, *Standard Specifications for Highway Bridges*, American Association of State Highway and Transportation Officials, Washington, DC, 1960.
9. AASHTO, *LRFD Bridge Design Specifications*, American Association of State Highway and Transportation Officials, Washington, DC, 1995.
10. *Specifications for Pretensioned Bonded Prestressed Concrete*, Prestressed Concrete Institute, Boca Raton, FL, October 1954, 3 pp.
11. ASCE-ACI Committee 323, "Joint ASCE-ACI Report on Prestressed Concrete," *PCI JOURNAL*, V. 2, No. 4, March 1958, pp. 28-62.
12. ACI Committee 318, "Building Code Requirements for Reinforced Concrete (ACI 318-63)," American Concrete Institute, Detroit, MI, 1963.
13. ACI Committee 318, "Building Code Requirements for Structural Concrete (ACI 318-02)," American Concrete Institute, Farmington Hills, MI, 2002.
14. PCI Technical Activities Council and PCI Committee on Building Code, "PCI Standard Design Practice," *PCI JOURNAL*, V. 42, No. 2, March-April 1997, pp. 34-46.
15. PCI Committee on Building Code, "PCI Standard Design Practice," *PCI JOURNAL*, V. 48, No. 1, January-February 2003, pp. 14-30.
16. BOCA, *National Building Code*, Building Officials and Code Administrators International, Country Club Hills, IL, 1999.
17. SBCCI, *Standard Building Code*, Southern Building Code Congress International, Birmingham, AL, 1999.
18. ICBO, *Uniform Building Code*, International Conference of Building Officials, Whittier, CA, 1997.
19. ICC, *International Building Code*, International Code Council, Falls Church, VA, 2000, 2003.
20. NFPA, *NFPA 5000 Building Construction and Safety Code*, National Fire Protection Association, Quincy, MA, 2003.
21. ACI Committee 318, "Building Code Requirements for Structural Concrete (ACI 318-95)," American Concrete Institute, Farmington Hills, MI, 1995.
22. *2001 California Building Code*, California Building Standards Commission, Sacramento, CA, 2002.
23. ACI Committee 318, "Building Code Requirements for Reinforced Concrete (ACI 318-89)," American Concrete Institute, Detroit, MI, 1989.
24. *Building Code of the City of New York*, 2001 Edition, Gould Publications, Binghamton, NY, 2001.
25. BSSC, *NEHRP (National Earthquake Hazards Reduction Program) Recommended Provisions for the Development of Seismic Regulations for New Buildings and Other Structures*, Building Seismic Safety Council, Washington, DC, 1994, 1997, 2000, 2003.
26. ACI Innovation Task Group 1 and Collaborators, "Acceptance Criteria for Moment Frames Based on Structural Testing (T1.1-01) and Commentary (T1.1R-01)," American Concrete Institute, Farmington Hills, MI, 2001.
27. Hawkins, N. M., and Ghosh, S. K., "Acceptance Criteria for Special Structural Walls Based on Validation Testing, Proposed Provisional Standard and Commentary," S. K. Ghosh Associates, Inc., Northbrook, IL, 2003.
28. ASCE, *ASCE 7 Standard Minimum Design Loads for Buildings and Other Structures*, ASCE 7-02, American Society of Civil Engineers, Reston, VA, 2002.