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DESIGN
HANDBOOK
PRECAST and PRESTRESSED CONCRETE



Eighth Edition

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PCI DESIGN HANDBOOK

PRECAST AND PRESTRESSED CONCRETE

3RD EDITION



PCI[®] Precast/Prestressed Concrete Institute
200 West Adams Street | Suite 2100 | Chicago, IL 60606-5230
Phone: 312-786-0300 | Fax: 312-621-1114 | www.pci.org

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PCI DESIGN HANDBOOK

PRECAST AND PRESTRESSED CONCRETE

3RD EDITION

PCI Industry Handbook Committee Members

Timothy R. Salmons, PE, SE, FPCI, Chairman

Dusty Andrews, PE

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Jared E. Brewes, PhD, PE, SE

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Bradley L. Schipper, PE, SE

Perry D. Schram, PE

Larbi Sennour, PhD, PE, SE, FPCI, FACI

Irwin J. Speyer, PE, FPCI, FACI

Consulting Members

Greg Force, PE, FPCI, FASCE

S. K. Ghosh, PhD, FPCI, Hon. MACI,
FASCE, FSEI

Mohammad S. Habib, PE

Walter Korkosz, PE, SE

Karen Laptas, PE, FPCI

Peter G. Troiani, PE, SE



Dedication

The members of the PCI Industry Handbook Committee dedicate this eighth edition of the *PCI Design Handbook: Precast and Prestressed Concrete* to Irwin J. Speyer for his outstanding contributions to the handbook, as well as to the entire precast/prestressed concrete industry.

Irwin graduated from City College of New York in 1950 with a bachelor of science in civil engineering. After working as an engineer for a couple of New York engineering firms, Irwin joined Freyssinet, a French engineering firm specializing in prestressed concrete structures. We all know that Eugène Freyssinet is considered the father of prestressed concrete, so Irwin was learning from the best at that time. Irwin has said, "I wanted to be in the precast concrete business because it was new: it wasn't steel, it wasn't reinforced concrete, which was old. This was something new." It certainly was back in the late 1950s. Irwin was right there at the beginning and maintains that same enthusiasm to this day.

When Freyssinet decided to close his American office and return to France in 1961, Irwin started his own firm as a single person practitioner. He has maintained that firm ever since.

Irwin's contributions to the precast/prestressed concrete industry are extraordinary. He has served on many PCI committees since he became a professional member in 1958. He has served on every handbook committee since the third edition and was co-editor of the fourth edition.

Probably his most significant contribution to several editions of the handbook has been his ever-present questioning of material to be included. "Have you thought of this?" "Is this material recognized by the model codes?" "Are you sure that's right?" These questions always made others double check the material and often led to improvements.

Irwin is the recipient of several PCI awards, including being named a PCI Fellow in the inaugural 1994 class and a PCI Honoree in 2004, at which time 50 individuals who have made significant contributions to the Institute and the industry were honored as part of PCI's 50th anniversary. In 2008 he was honored once again as the recipient of PCI's highest award, the PCI Medal of Honor.

He served on the committees that developed the 1963, 1971, and 1995 editions of the ACI 318 building codes and was a voting member of precast-related subcommittees for the 1983, 1986, and 1989 editions. He was also a consulting member for the 1999 and 2002 codes. For these and other contributions to ACI, Irwin was made a Fellow of ACI.

On a personal note, Irwin has been married to Florence, a dedicated educator, for more than 55 years. They are deeply committed to their loving family. They have three children: David, residing in California; Deborah, residing in New York; and Seth, residing in Washington, D.C. The family, including Irwin and Florence's seven grandchildren, join us in expressing our gratitude for Irwin's commitment and accomplishments.

Saying "thank you, Irwin" does not seem to do justice to all you have done, but with all the sincerity we can muster, the members of the eighth edition PCI Industry Handbook Committee say:

THANK YOU, IRWIN!!

Foreword

PCI, the Precast/Prestressed Concrete Institute, is a not-for-profit corporation founded in 1954 to advance the design, manufacture, and use of structural precast/prestressed concrete and architectural precast concrete in the United States. To achieve this purpose, PCI continually disseminates information on the latest concepts, techniques, and design data to the engineering and architectural professions through regional and national programs and technical publications.

The first edition of the *PCI Design Handbook* was published in 1971 and focused primarily on structural products for buildings. For the design of architectural precast concrete, the *PCI Manual for Structural Design of Architectural Precast Concrete* was published in 1977. In 1978, the second edition of the *PCI Design Handbook* was published. In keeping with the tradition of continually updating information, an Industry Handbook Committee was formed in 1979 to develop the third edition, published in 1985. That edition provided, in a single source, information on the design of both architectural precast concrete and structural precast/prestressed concrete. The fourth edition, published in 1992; the fifth edition, published in 1999; the sixth edition, published in 2004; and the seventh edition, published in 2010, continued to present both architectural and structural products and systems. All past editions of the *PCI Design Handbook* present guidelines for the design of buildings. For bridge design guidelines, refer to PCI's *Bridge Design Manual* (MNL-133).

The Industry Handbook Committee continues to monitor technical advancements within the industry, with assistance from the many PCI committees responsible for a variety of specific topics. This eighth edition is the culmination of those efforts and presents current industry practice.

The members of the committee listed on the title page have made significant contributions of both their time and expertise. In addition, other PCI committees have provided reviews of specific areas and offered helpful comments. Many individuals within the industry have also provided advice and comments. PCI offers a special note of recognition and appreciation to all who were involved in this process.

It is important that the users of this handbook understand the process used by the Industry Handbook Committee in the development of the eighth edition. The process was as follows:

- The seventh edition was used as the baseline, with the understanding that the *International Building Code* (IBC) 2015 would be the model code basis for the eighth edition, along with its reference standards ASCE 7-10, including Supplement No. 1, and ACI 318-14.
- A subgroup was established for each chapter with three to seven members including a chairperson. The subgroup conducted a detailed review of the existing chapter and an exhaustive review of research and publications relevant to the subject material within that chapter. After analysis and discussion regarding improved and/or updated content, each subgroup developed a draft of their respective chapters.

- Each chapter was then edited by the technical editor and a committee ballot version was created.
- Each chapter was balloted by the committee, with resolution of all comments during meetings of the full committee. This process included 18 face-to-face meetings and 31 web-based teleconferences during the 6 years of development. There were 90 official committee ballots.
- A committee-approved version was created and sent to the PCI Technical Activities Council (TAC) for balloting and approval.
- Each chapter was balloted by TAC, with resolution of all comments by both TAC and the Industry Handbook Committee.
- Based on these approved versions, a Blue-Ribbon Review version was created. This final review was done by a Blue-Ribbon Review Committee made up of plant engineers, specialty engineers, consulting engineers, academicians, and associate members, whose names are listed on the title page. Each member of the committee is a recognized leader in the analysis and design of precast/prestressed concrete products or an expert in a closely related field. After a review period of more than eight weeks, the group met for two days with the Industry Handbook Committee and offered valuable comments. Most of their comments were accepted as improving the publication.
- A final version of each chapter was then created and thoroughly reviewed by the original chapter subgroup. This process resulted in further corrections and improvements.
- At this point in the process, PCI brought the material into conformance with its current style guide and prepared camera-ready layouts of each chapter, which were reviewed by the technical editor and the entire Industry Handbook Committee.

Updates to the seventh edition have been made throughout the document. Significant updates include the following:

- Updates were made according to the IBC 2015 model code ASCE 7-10, including Supplement No. 1, the ACI 318-14 building code, as well as other current PCI publications and publications of other technical institutions.
- Certain industry standard style items, such as the use of feet and inch marks in drawings and details and the use of the pound sign (#) to designate reinforcing bar sizes, were changed to the current conventions of PCI for the benefit of our international readers. For example: "10'-6"" is now written "10 ft 6 in." and "#6" is now written "no. 6."
- Chapter 1 includes updated photographs that illustrate more current projects, a new section on storm shelters, and an extensive update of the sustainability section.
- Chapter 2 is essentially the same as the seventh edition, updated to include new notations used in the eighth edition. It remains organized on a chapter-by-chapter basis.
- Chapter 3 load table values were all checked and verified. The 8 ft double-tee load tables were removed because those double tees are no longer used on a regular basis.

The 15 ft 0 in. × 26 in. double-tee load table was also removed because that size is only made by one PCI producer. The double-tee load tables that were retained now include 3 in. composite topping instead of 2 in. to reflect a more common construction practice. Figures and photographs were updated.

- Chapter 4 no longer includes Section 4.9 “Blast-Resistant Design” of the seventh edition. That content is now a new Appendix A developed by the PCI Blast Resistance and Structural Integrity Committee. New wind maps from ASCE 7-10 are now based on load- and resistance-factor design (LRFD). Section 4.3 “Structural Integrity” was reduced, as a more extensive discussion is included in Appendix B “Design for Structural Integrity and Disproportionate Collapse.” Example 4.5.12.1 was revised from a three-level parking structure to a five-level parking structure with more critical seismic design criteria. New figures for column base connections were added to Section 4.6.1.
- Chapter 5 includes significant revisions to ledge design and now includes dap design for thin-stemmed components, both of which are based on PCI-funded research that was reported in 2016. Section 5.14 “Design Procedure Following ACI 318-14” was added to assist the user in transitioning from ACI 318-11 to ACI 318-14. Design examples were updated to reflect current practice. A new design procedure was added for the design of slender spandrels that can result in the use of a single layer of reinforcement or the elimination of closed stirrups.
- Chapter 6 was modified in several ways. Table 6.2.1 of the seventh edition showing diaphragm overstrength factors was removed because guidelines for precast concrete diaphragm designs have been improved and new alternative provisions are discussed in Appendix C. The section on post-installed anchors was rewritten and now includes a discussion on expansion anchors, adhesive anchors, grouted anchors, and new screw anchors. Table 6.5.4 was rearranged to provide better clarity, as was Figure 6.5.5. Older triangular and rectangular stiffener design equations were replaced with a newer methodology from the latest American Institute of Steel Construction (AISC) LRFD manual. Design examples were revised accordingly. The Cazaly Hanger section (6.9.1) was modified to reflect recent research on shallow components that revealed that the seventh edition equations may be unconservative for this condition. Information on welding design aids was condensed and Grade 40 reinforcement was removed. Grade 80 reinforcement was added and E100 electrodes were included to accommodate Grade 80 reinforcement. Design Aid 6.15.7 was reorganized to better reflect ASD and LRFD values and includes additional types and grades of threaded rods and bolts. Design Aids for angle design and column base plate thickness requirements were removed.
- Chapter 7 was generally updated and Section 7.3.1, directed to the structural engineer of record, was added.
- Chapter 8 includes changes to Section 8.3.5.2 that increase the highest recommended strand lift loop capacity

from 8 kip to 10 kip. Figure 8.3.11 “Swivel Plate” was significantly revised and Fig. 8.6.1(f) is a new figure along with cautions related to rapid panel tripping. Section 8.7.2 contains significant clarifications related to erection stability.

- Chapter 9 was reorganized with an expansion and clarification of existing material. Descriptions of types and uses of various concrete mixtures were added, including high-performance concrete, self-consolidating concrete, lightweight concrete, and fiber-reinforced concrete. The discussion on aggregate durability and admixtures was expanded. A new section on fresh concrete properties was added, including slump, slump flow, air content, workability, and curing. The discussion of strand bed and the Peterman test was expanded. A description of the strand manufacturing process was added with photographs of the various stages. A discussion and caution about welding of structural bolts, anchor bolts, nuts, and washers due to chemical composition and heat treatments were added.
- Chapter 10 was generally updated. A conflict related to concrete classification remains; this is a result of concrete unit weight associated with source information that serves as a basis for much of the material contained in the chapter.
 - Chapter 10 uses the following classifications:
 - Lightweight aggregate concrete (90 to 105 lb/ft³)
 - Sand-lightweight concrete (105 to 120 lb/ft³)
 - Normalweight concrete (120 lb/ft³ and higher)

The following classifications are used elsewhere in the handbook and by American Concrete Institute (ACI):

- Lightweight aggregate concrete (90 to 115 lb/ft³)
- Sand-lightweight concrete (115 to 135 lb/ft³)
- Normalweight concrete (135 to 150 lb/ft³)

This conflict will likely remain for the foreseeable future.

- Chapter 11 was updated to include current code information.
- Chapter 12 was generally updated to improve the flow and development of the basic vibration equations. A new Section 12.11 “Damping Devices for Precast Concrete Structures” was added.
- Chapter 13 was updated with clarifications and several graphic corrections.
- Chapter 14 does not include the standard design practice for ACI 318-14 because it was still under development by the PCI Building Code Committee at the time of publication of this eighth edition. When available, it will be published in the *PCI Journal* and made available on the PCI website, www.pci.org. Code updates and organizational updates were made to improve the overall flow. Terminology updates were also made to better establish various responsible parties within a project, which set the stage for consistency throughout the handbook. The specifications for both structural and architectural precast concrete are available on the PCI website in the

- form of an editable Microsoft Word document.
- Chapter 15 was generally updated with clarifications and graphic corrections.
- Appendix A “Blast-Resistant Design of Precast, Prestressed Concrete Components” is totally new and replaces Section 4.9 of the seventh edition. It was prepared by the PCI Blast Resistance and Structural Integrity Committee and published in the *PCI Journal* as a committee report in the Winter 2014 issue.
- Appendix B “Design for Structural Integrity and Disproportionate Collapse” is new and is an expansion of Section 4.3 of the seventh edition.
- Appendix C “Precast Concrete Diaphragm Design in Accordance with Alternative Provisions of ASCE 7-16” is totally new and reflects upcoming code changes based on research sponsored by multiple organizations. Major funding was provided by the Charles Pankow Foundation, the National Science Foundation, and PCI. This research is called the DSDM (Diaphragm Seismic Design Meth-

odology) research. Current acceptance criteria, ICC-ES AC468, and evaluation report, ICC-ES ESR-3010, allow use of this methodology prior to adoption of IBC 2018.

Substantial efforts have been made to ensure that this handbook is accurate. However, PCI cannot accept responsibility for any errors or oversights in the use of material or in the preparation of engineering plans. The designer must recognize that no handbook or code can be a substitute for experience and engineering judgment. This publication is intended for use by professional personnel competent to evaluate the significance and limitations of its content and able to accept responsibility for the application of the material it contains.

PCI considers each new edition of the handbook to be a living document. The user is encouraged to submit comments and suggestions for improvements to be incorporated in the next edition. Questions concerning the source or verification of any material in the handbook should be directed to PCI at the email address ihberrata@pci.org.

Comment by Chairman Tim Salmons:

The PCI Design Handbook: Precast and Prestressed Concrete, eighth edition, is the result of the collaborative efforts of dedicated committee members, the technical editor, PCI staff, and countless industry volunteers whose devotion to the technical advancement of precast/prestressed concrete is a fitting of the Institute. It has been a humbling honor to have served alongside of each of you while stewarding this flagship publication through its eighth generation.



Members of the Blue Ribbon Committee

Sergio F. Breña, PhD, FASCE

Mark Cerminara, PE, SEI

Parisha Chandhria, PE, SCS

Matthew C. Cooper, PE

Timothy A. Cullen, PE

Sami H. Elashri

Mary Ann Griggas-Smith, PE

Jason P. Lien, PE, FPCI

Gregory Lucier, PhD

Harry A. Nash, PE

Nathan Niebauer, PE

Andrew E. N. Osborn, PE, FPCI

Christopher Pfeil, PE

Charles Pizzano, PE

James M. Sirko, PE, FPCI

Joseph H. Tuttle II, PE

Catherine Warfel, PE

Table of Contents

Chapter 1	Precast and Prestressed Concrete: Applications	1-1 to 1-28
Chapter 2	Notations	2-1 to 2-30
Chapter 3	Preliminary Design of Precast/ Prestressed Concrete Components	3-1 to 3-50
Chapter 4	Analysis and Design of Precast/ Prestressed Concrete Structures	4-1 to 4-100
Chapter 5	Design of Precast and Prestressed Concrete Components	5-1 to 5-162
Chapter 6	Design of Connections	6-1 to 6-122
Chapter 7	Structural Considerations for Architectural Precast Concrete	7-1 to 7-28
Chapter 8	Component Handling and Erection Bracing	8-1 to 8-34
Chapter 9	Precast and Prestressed Concrete: Materials	9-1 to 9-48
Chapter 10	Design for Fire Resistance of Precast and Prestressed Concrete	10-1 to 10-26
Chapter 11	Thermal and Acoustical Properties of Precast Concrete	11-1 to 11-28
Chapter 12	Vibration Design of Precast/ Prestressed Concrete Floor Systems	12-1 to 12-12
Chapter 13	Tolerances for Precast and Prestressed Concrete	13-1 to 13-36
Chapter 14	Specifications and Standard Practices	14-1 to 14-18
Chapter 15	General Design Information	15-1 to 15-58
Appendix A	Blast-Resistant Design of Precast, Prestressed Concrete Components	A-1 to A-28
Appendix B	Design for Structural Integrity and Disproportionate Collapse	B-1 to B-18
Appendix C	Precast Concrete Diaphragm Design in Accordance with Alternative Provisions of ASCE 7-16	C-1 to C-8
	Index	

CHAPTER 1

PRECAST AND PRESTRESSED CONCRETE: APPLICATIONS

1.1	Introduction.....	1-2
1.1.1	History of Precast/Prestressed Concrete in North America	1-3
1.1.2	Features and General Principles.....	1-4
1.1.3	Sustainability and High-Performance Building Code Considerations.....	1-5
1.1.3.1	Precast Concrete Industry and Sustainability.....	1-6
1.1.4	Common Products.....	1-6
1.2	Applications.....	1-10
1.2.1	Building Structures.....	1-10
1.2.1.1	Precast Concrete Structural Systems (Total-Precast Concrete System).....	1-10
1.2.1.2	Precast Concrete Enclosure Systems (Cladding).....	1-10
1.2.1.3	Residential Buildings	1-13
1.2.1.4	Justice Facilities	1-14
1.2.1.5	Office Buildings	1-15
1.2.1.6	Warehouses and Industrial Buildings.....	1-15
1.2.1.7	Educational Facilities.....	1-17
1.2.1.8	Storm Shelters.....	1-18
1.2.1.9	Other Building Structures	1-18
1.2.2	Parking Structures	1-19
1.2.3	Stadiums/Arenas	1-21
1.2.4	Bridges	1-22
1.2.5	Other Structures and Applications	1-24
1.3	Production Process.....	1-25
1.3.1	Structural Components versus Architectural Components	1-25
1.3.2	Long-Line, Multiple-Piece Forms versus Single-Piece Forms	1-26
1.3.3	Prestressed Components versus Nonprestressed Components	1-26
1.3.4	Pretensioned Components versus Post-Tensioned Components.....	1-27
1.3.5	Production Limitations.....	1-27
1.4	References and Photo Credits	1-28
1.4.1	References.....	1-28
1.4.2	Photo Credits	1-28

1.1 Introduction

1.1.1 History of Precast/Prestressed Concrete in North America

The growth of precast and prestressed concrete is a story of the vision and boldness of a few notable people. These people took a new idea and maximized its potential by modifying and improving existing methods, conceiving new methods, and inventing new devices, all with a focus on mass production. An excellent portrayal of the beginnings and the growth of precast and prestressed concrete in North America and the early pioneers is given in a series of papers¹ that were developed to commemorate the 25-year silver jubilee of the founding of the Prestressed Concrete Institute. A similar publication² was developed at the 50-year golden anniversary of the institute, now known as the Precast/Prestressed Concrete Institute (PCI). PCI was chartered on June 18, 1954.

The most important event leading to the launching of the precast/prestressed concrete industry in North America was the construction in 1950 of the famed Walnut Lane Memorial Bridge in Philadelphia, Pa. (Fig. 1.1.1a). From technical and historical perspectives, it is both surprising and fascinating that the Walnut Lane Memorial Bridge was constructed of prestressed concrete. There was very little published information on the subject and there was a total lack of experience with linear prestressing in this country at that time. Furthermore, the length of the bridge span involved (the main span of the structure was 160 ft long) would have been a daring venture in the late 1940s anywhere in the world. The bridge became a reality through a fortunate sequence of events and the vision, courage, and persistence of a few extraordinary individuals.

Forty years after the construction of the Walnut Lane Memorial Bridge, and after several of its post-tensioned girders underwent major repairs, it was decided to replace the entire superstructure. The replacement is an all-pretensioned design consisting of three simply supported spans identical to the original bridge. The new structure consists of only seven girders in each span, compared with seven in the approach spans and 13 in the main span of the original bridge. These pretensioned girders were modified hybrid standard AASHTO (American Association of State Highway and Transportation Officials) Type VI girders and were manufactured in a PCI certified plant about 100 mi from the site (Fig. 1.1.1b).

Following completion of the Walnut Lane Memorial Bridge, American engineers and the construction industry enthusiastically embraced prestressed concrete. While many of the early applications remained in bridge construction, such as the lower Tampa Bay crossing now known as the Sunshine Skyway, American engineers and contractors were simultaneously conceiving new devices, improving techniques, and developing new materials for all types of structures.

The 1950s were the years that brought into focus the seven-wire strand, long-line beds (Fig. 1.1.2), admixtures, high-strength concrete, vacuum concrete, steam curing, and many other innovations. With these developments, coupled with the technical and logistical support provided by PCI, the industry grew, and the applications of precast and prestressed concrete began to appear in an impressive variety of structures.



Figure 1.1.1(a). The original Walnut Lane Memorial Bridge was the recipient of the 1978 American Society of Civil Engineers Outstanding Civil Engineering Achievement Award.



Figure 1.1.1(b). In 1990 the Walnut Lane Memorial Bridge was rebuilt using pretensioned, prestressed girders.



Figure 1.1.2. Long-line, prestressed, double-tee casting bed is one key to both economy and quality.