Design of Concrete Structures

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To Hwa Soon

Preface

Design of Concrete Structures is the result of the continuous expansion and improvement of lecture notes for a course on reinforced concrete design, which I have been teaching to seniors at Columbia University for 15 years. Its primary purpose is to fulfill the conventional role of a textbook, namely, to assist students in absorbing the material presented in class. This means it should free students from the traditional chore of dutifully copying each word and number from the blackboard, so that they can concentrate on understanding the difficult material instead. The conscientious student will attend class well prepared by having read in advance the material to be covered.

In addition, this book includes a few topics that we never were able to cover within a 14-week, 3-point semester course. These are, for example, torsion, slab design, footings, and retaining walls. But, with a solid knowledge of the basic principles of reinforced concrete design, there is good reason to believe that the average student can master these subjects through self-study.

This book does not claim to revolutionize the way in which design is taught, but it does advance a few new ideas and it does have several noteworthy features:

1. Appendix A contains a Concrete ABC, a comprehensive glossary of terms common in concrete engineering and the construction industry, which should be of value to students new to the field. The Cement and Concrete Terminology Report of ACI Committee 116 was a valuable source.
2. Much effort went into the design of problem sets, which draw on homework assignments and exams given over the years. Rather than simply asking students to

apply formulas or procedures by rote (as is all too common), many of the problems are designed to help the students think critically and appreciate the various physical aspects of theoretical concepts.

3. The incorporation of the computer into design courses is a controversial topic among educators. The approach reflected in this book is to proceed at this point without such incorporation as much as possible. Once students have mastered the basic design principles, they should be encouraged to automate some of the procedures as a fail-safe test to see whether they have in fact understood them. The consistent step-by-step layout of the various design procedures paves the way for such programming assignments. Alternatively, students familiar with spreadsheet programs should be encouraged to use them to solve some of the problem sets. This is prudent incorporation of the computer into the classroom. I am strictly opposed to the use of ready-made design software at the early stages of an engineer's career. Students who have mastered the basic principles of design will quickly and easily learn to intelligently use such CAD systems in an engineering office—after graduation.

Chapter 1 gives a comprehensive overview of modern design philosophies and discusses the role of the structural engineer in the construction industry. An amply illustrated tour of the world of concrete is meant to expose students to the large range of possibilities and to whet their appetite for entering a career with fascinating design experiences. Even though most students are likely to have already had a first design course, typically in structural steel, they will appreciate another opportunity to be exposed to the larger picture before being consumed by a sea of technical details.

Chapter 2 is more than the traditional description of materials. First, many schools no longer offer a basic materials course with adequate coverage of concrete. Next, the field of concrete technology has made impressive advances in recent years. Much of the up-to-date technological information is rather shortlived and therefore not particularly suitable material for a design course. Yet, its importance is well-recognized and therefore some of it is included in this chapter, primarily as a source of reference information and for self-study. A third point is the fact that most students, after graduation, will find themselves occupied with the repair, rehabilitation, and strengthening of existing structures rather than with the design of new structures. Many of the problems related to our country's crumbling infrastructure are really problems of materials and their durability (or lack thereof). Therefore, a thorough knowledge of material properties is a prerequisite for solving these problems.

In Chapter 3, a foundation is laid for a basic understanding of reinforced concrete in bending. Building on this foundation, Chapter 4 presents logical design procedures for reinforced concrete flexural members.

Chapter 5 covers the three diverse topics of shear, bond, and torsion design. Emphasis is again placed on the basic concepts, on which current design practice is based, rather than on all the details. Although these details are very important in practice, they are likely to change with the next edition of the ACI Code, whereas the basic concepts will not.

The interrelationship between design and analysis is a source of confusion for students confronted with statically indeterminate structures. Even though structural analysis is taught as a separate course, it has been my experience that students generally have a hard time absorbing and applying its rather difficult concepts. Repeated exposure is often a great help. For this reason, Chapter 6 places heavy emphasis on the review of some structural analysis concepts for continuous beams and frames, especially of those methods that designers will find useful for checking purposes. This applies primarily to moment distribution, which in my view is no longer receiving the attention in structural analysis courses that it deserves. An effort is made to explain the interplay between analysis and design and to pave the way for the rewarding experience of young engineers suddenly finding themselves "in the driver's seat," by controlling the behavior of structures through design decisions.

The design of columns is covered in Chapter 7. Starting with a review of the basic theory underlying interaction diagrams and classical column buckling, the ACI Code design procedures for short and slender columns are derived and illustrated by example.

Chapter 8 deals with the design of slabs and plates. Here, I felt it useful to include sections on basic plate theory and yield line theory as supplements to the common design procedures of the ACI Code. This material should appeal to more ambitious students as preparation for a more advanced concrete design course.

A good number of additional chapters could be included in this book—chapters covering the design of buildings, pavements, dams, bridges, etc. But this book is meant as an introductory text, dealing primarily with basic principles of concrete mechanics and design. Buildings, bridges, etc. are very specific examples of *applications*. Students who have mastered the basic principles should have no difficulty applying these to specific applications. Chapter 9 was added as just one such example, namely, foundations and retaining walls. This topic is in the truest sense of the word so *fundamental* that it is a fitting subject for the final chapter. No new design principles are introduced, except for some concepts of soil mechanics. Obviously, the material presented is far from exhaustive, as entire books are devoted to this topic alone.

I have tried to reference the ACI Code as sparingly as possible to prolong the "shelf-life" of this text. But, given today's design practice, this is a difficult task. In particular, the Code requirements for shear design are still (unfortunately) largely empirical. However, there is hope that future editions will build on new insights into shear behavior of concrete members (gained, for example, through advances in fracture mechanics) that will form a more rational foundation for shear design requirements. The most recent Code changes proposed for ACI 318–95 pertain primarily to the minimum flexural steel requirements, development length specifications, and the design of slender compression members. They have not yet been adopted by ACI at the time of this writing, but have been incorporated into the book. Students should be encouraged to have ready access to the latest edition of the Code. The commentary contains valuable explanatory material, which was omitted here to avoid unnecessary repetition.

I am greatly indebted to my wife, Hwa Soon, and to my sons, Peter and Guenter, for encouraging me over the years to continue the ambitious undertaking of writing this book and actually completing it. I also would like to thank my great teacher, Alex

Scordelis, Professor Emeritus of the University of California at Berkeley. He not only advised me during my doctoral studies, but also taught me how to think as an engineer and how to transmit this knowledge to students. Finally, I would like to express my gratitude to various staff members of Prentice-Hall and ETP/Harrison: Doug Humphrey, for active support during the early stages of the project; Bill Stenquist, for seeing the book through its production; Dena Kaufman; and especially Corleigh Stixrud, for his painstaking care and patience in editing the entire work.

New York City *Christian Meyer*

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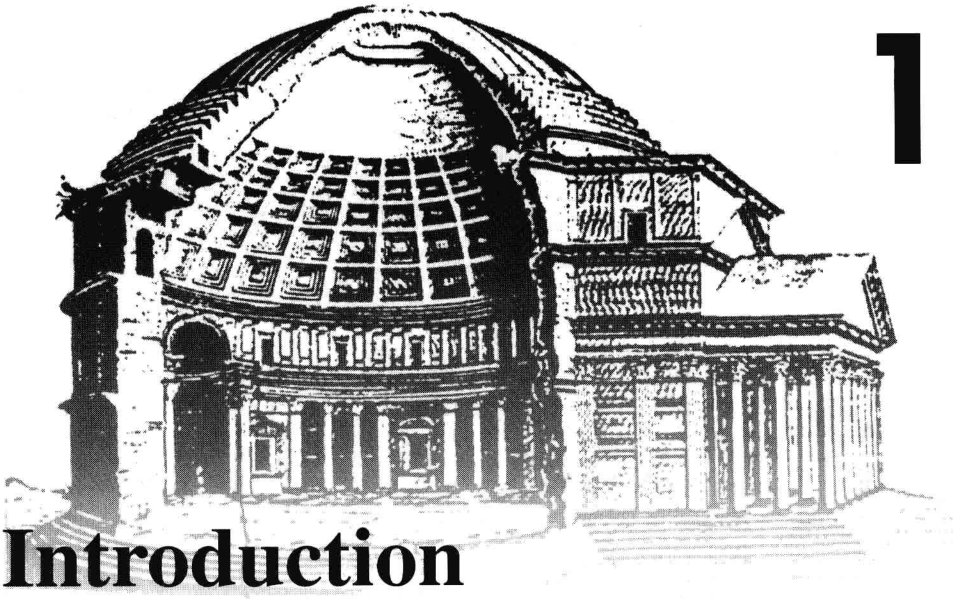

1 Introduction

1.1 HISTORICAL REMARKS

Most of us assume we can identify concrete when we see it. Yet, if we were to search for its origin or determine when it was "invented," it would soon become apparent that we would need to define concrete before we could identify it. Deferring a more elaborate definition until the next chapter, let us start with a common frame of reference, namely, the definition in Webster's New World Dictionary:

> **concrete:** a hard, compact substance made of sand, gravel, cement, and water, used in the construction of bridges, dams, buildings, etc.

Taking the gravel out of this mixture results in *mortar*, and if lime serves as the cementing or binding agent, we get lime mortar, which was most likely invented in prehistoric times. It was certainly known to the earliest civilizations, such as the Babylonians, who used it in stone masonry. The Egyptians also added gravel to mortar, that is, they knew how to make a material that by the above definition is concrete. Recently, a fascinating theory has been proposed by the French chemist, Joseph Davidovits, that the great pyramids are actually made of geopolymeric limestone concrete blocks rather than natural, quarried limestone [1, 2]. Although this theory has not been universally accepted by the scientific community, the various arguments brought forth in the current discussion lead to the certain conclusion that only very detailed scientific examinations can establish the difference between natural and synthetic stone.

Advancing a few millenia brings us to ancient Roman civilization. Even though the cement the Romans used was not the portland cement used today, there is no question that, by the above definition, they used concrete in their various constructions. The most detailed account of Roman architecture and construction in general and their building materials in particular, is found in *De architectura libri decem* (Ten Books of Architecture) by Vitruvius. On the kind of cement the Romans used for their concrete, we can read in book 2:

> There is also a kind of powder which by nature produces wonderful results. It is found in the neighborhood of Baiea and in the lands of the municipalities around Mount Vesuvius. This being mixed with lime and rubble, not only furnishes strength to other buildings, but also when piers are built in the sea, they set under water. [3]

The Roman mortar consisted of quicklime and burnt clay or natural materials, predominantly of volcanic origin, which contained reactive silica. The best known deposit of these materials was found near the village of Pozzuoli, near Naples. This is why materials that are capable of reacting with hydrated lime (due to their reactive silica content) are generally called *pozzolana*.

One of the most impressive Roman concrete structures is the Pantheon (Fig. 1.1). Completed in 126 A.D., its dome span of 43.5 m was not surpassed until the nineteenth century. Parts of the port of Ostia, built during Trajan's reign (52–117 A.D.), withstood centuries of pounding surf until the coastline shifted, and survive to this day [4].

Modern portland cement was invented in 1824 by Joseph Aspdin, a builder from Leeds in England. He patented his process of grinding limestone, mixing it with finely divided clay, burning the mixture in a kiln oven, and finely grinding the resulting clinker. He gave his invention the name portland cement because of its resemblance to the natural building stone quarried near Portland, England. The commercial success of Aspdin's cement led to the rapid spread of hydraulic cements throughout Europe. This was the beginning of the modern cement industry, which in 1990 produced 85 million tons of cement in the United States alone.

The relatively low tensile strength of concrete and the resulting susceptibility to cracking prompted builders from early on to look for proper means of reinforcement. The most successful of these pioneers, however, was not a builder but a gardener. Joseph Monier of Paris was interested in reinforcing his concrete tree planters and in 1850 patented a system of using steel wire reinforcement. Although other patents had been filed earlier, Monier's patents are generally credited with having had the most significant impact on the development of what is now called *reinforced concrete*. Some of this credit is shared by G.A. Wayss and J. Bauschinger of Germany, who purchased the German and American rights to Monier's patents and established the basic principles for the application of reinforced concrete. By the turn of the century, the behavior of reinforced concrete was relatively well understood, and together with advances in materials and structural engineering, the use of reinforced concrete spread rapidly. Another fundamental advance was made with the introduction of *prestressed concrete*, generally credited to Eugene Freyssinet of France. By precompressing the concrete, usually by means of embedded high-strength steel tendons, it is possible to subsequently subject it