REINFORCED CONCRETE

A Fundamental Approach

by

Dr. Edward G. Nawy, P.E.

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Preface

Reinforced concrete is a widely used material for constructed systems. Hence graduates of every civil engineering program must have, as a minimum requirement, a basic understanding of the fundamentals of reinforced concrete. Additionally design of the members of a total structure is achieved only by trial and adjustment: assuming a section then analyzing it. Consequently design and analysis were combined to make it simpler for the student first introduced to the subject of reinforced concrete design.

The text is an outgrowth of the author's lecture notes evolved in teaching the subject at Rutgers University over the past twenty-five years and the experience accumulated over the years in teaching and research in the areas of reinforced and prestressed concrete up to the Ph.D. level. The material is presented in such a manner that the student can be familiarized with the properties of plain concrete and its components prior to embarking on the study of structural behavior. The book is uniquely different from other textbooks at this level in that most of its contents can be covered in one semester in spite of the in-depth discussions of some of its major topics.

The concise discussion presented in Chapters 1 through 4 on the historical development of concrete, the proportioning of the constituent materials, the long-term basic behavior, and the development of safety factors should give an adequate introduction to the subject of reinforced concrete. It should also aid in developing fundamental laboratory experiments and essential knowledge of mix proportioning, strength and behavioral requirements, and the concepts of reliability of performance of structures to which every engineering student should be exposed. The discussion of quality control and quality assurance should also give the reader a good introduction to the systematic approach needed to administer the development of concrete structural systems from conception to turnkey use.

Since concrete is a nonelastic material, with the nonlinearity of its behavior starting at a very early stage of loading, only the ultimate strength approach, or what is sometimes termed the "limit state at failure approach," is given in this book. Adequate coverage is given of the serviceability checks in terms of cracking and deflection behavior as well as long-term effects. In this manner, the design should satisfy all the service-load-level requirements while ensuring that the theory used in the analysis (design) truly describes the actual behavior of the designed components.

Chapters 5, 6, 7, and 8 cover the flexural, diagonal tension, and serviceability behavior of one-dimensional members: beams and one-way slabs. Full emphasis has been placed on giving the student and the engineer a feeling for the internal strain distribution in structural reinforced concrete elements and a basic understanding of the reserve strength and the safety factors inherent in the design expressions. Chapter 9, on the analysis and design of columns and other compression members, treats the subject of strain compatibility and strain distribution in a similar manner as in Chapter 5, on flexural analysis and design of beams. It includes a detailed discussion of how to construct interaction diagrams for columns as well as proportioning columns subjected to biaxial bending and buckling. With Chapter 10, on bond and development length in reinforcement, and Chapter 12, on the design of foundations and footings, the sequence of design steps of all elements except two-way floors is complete.

It is important to mention that Chapter 6, on diagonal tension, also contains detailed coverage of the behavior of deep beams, corbels, and brackets, with sufficient design examples to supplement the theory. This topic has been included in view of the increased use of precast construction, the wider understanding of the effects of induced horizontal loads on floors, and the frequent need for including shear walls and deep beams in today's multilevel structures. Additionally, Chapter 7 treats the topic of torsion in some detail considering the space constraints of the book. The discussion ranges from the basic fundamentals of pure torsion in elastic and plastic materials to the design of reinforced concrete members subjected to combined torsion, shear, and bending. The material presented and the accompanying illustrative examples should give the background necessary for pursuing more advanced studies in this area, as listed in the selected references.

Chapter 11 presents an extensive coverage of the subject of analysis and design of slab and plate floor systems. Following a discussion of fundamental behavior, it gives detailed design examples using both the ACI procedures and yield-line theory for the flexural design of reinforced concrete floors. It also includes ultimate load solutions to most floor shapes and possible gravity loading patterns. Detailed discussion of the deflection behavior and evaluation of two-way panels as well as the cracking mechanism of such panels, with appropriate analysis examples, makes this chapter another unique feature of this concise textbook.

It is important to emphasize that in this field, the use of computers prevails today. Access to transportable personal computers and handheld computers, due to their affordable cost, has made it possible for almost every student to be equipped with such a tool. Hence Chapter 13 presents programming procedures and computer programs written for both the handheld HP41C/CV/CX and in BASIC language for the Apple IIe and IIc transportable computers for the analysis (design) of sections in flexure, shear, torsion, combined loading (including compression), and members subjected to biaxial loading, as well as deep beams and corbels. As a result, the use of handbook charts was kept to a bare minimum. The inclusion of extensive flowcharts with logical steps in each relevant topic will make it possible for the reader to develop or use, without difficulty, such programs with any handheld or desktop computer.

Selected photographs of various areas of structural behavior of concrete elements at failure are included in all the chapters. They are taken from the published research work by the author with many of his M.S. and Ph.D. students at Rutgers University over the past two decades. Additionally, photographs of landmark structures, mainly in the United States, are included throughout the book to illustrate the versatility of design in reinforced concrete.

The textbook conforms to the provisions of ACI 318-83 with an eye to stressing the basics rather than tying every step to the code, which changes once every six years. Consequently, no attempt was made to tie any design or analysis step to the particular equation numbers in the code, but rather, the student is expected to gain the habit of getting familiar with the provisions and section numbers of the ACI code on a separate basis. In this manner, the student should not only master the fundamentals presented in the textbook, but should also become well versed with the ACI code as a dynamic, ever-changing document. Conversions to SI units are included in the illustrative examples throughout the book.

The various topics have been presented in as concise a manner as possible without sacrificing the need for the instructional details of an introductory course in the subject. Hence the topic of prestressed concrete has been left for more advanced works. The major portions of this book are intended for a first course at the junior or senior level of the standard college or university curriculum in civil engineering. The contents should also serve as a valuable guideline to the practicing engineer who has to keep abreast of the state of the art in concrete, as well as the designer who is interested in a concise treatment of the fundamentals.

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Introduction

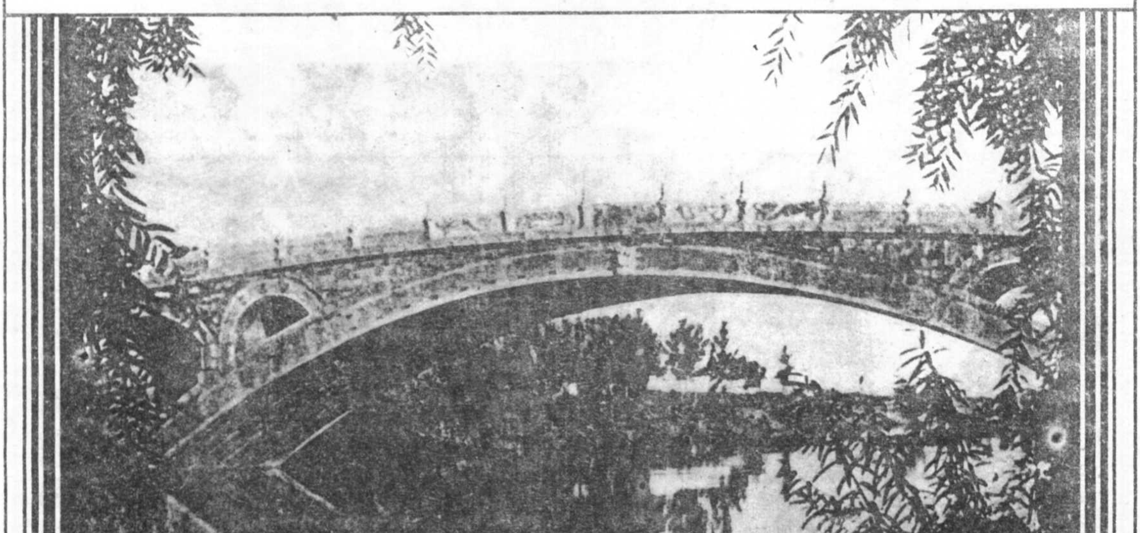

Photo 2 Chaochow Bridge on Hsiaoho River, China (A.D. 605–617). (*See* p. 1.)

1.1 HISTORICAL DEVELOPMENT OF STRUCTURAL CONCRETE

Use of concrete and its cementatious (volcanic) constituents, such as pozzolanic ash, has been made since the days of the Greeks, the Romans, and possibly earlier ancient civilizations. However, the early part of the nineteenth century marks the start of more intensive use of the material. In 1801, F. Coignet published his statement of principles of construction, recognizing the weakness of the material in tension. J. L. Lambot in 1850 constructed for the first time a small cement boat for exhibition in the 1855 World Fair in Paris. J. Monier, a French gardener, patented in 1867 metal frames as reinforcement for concrete garden plant containers, and Koenen in 1886 published the first manuscript on the theory and design of concrete structures. In 1906, C. A. P. Turner developed the first flat slab without beams.

Thereafter, considerable progress occurred in this field such that by 1910 the German Committee for Reinforced Concrete, the Austrian Concrete Committee, the American Concrete Institute, and the British Concrete Institute were already established. Many buildings, bridges, and liquid containers of reinforced concrete were already constructed by 1920 and the era of linear and circular prestressing began.

The rapid developments in the art and science of reinforced and prestressed concrete analysis, design, and construction have resulted in very unique structural

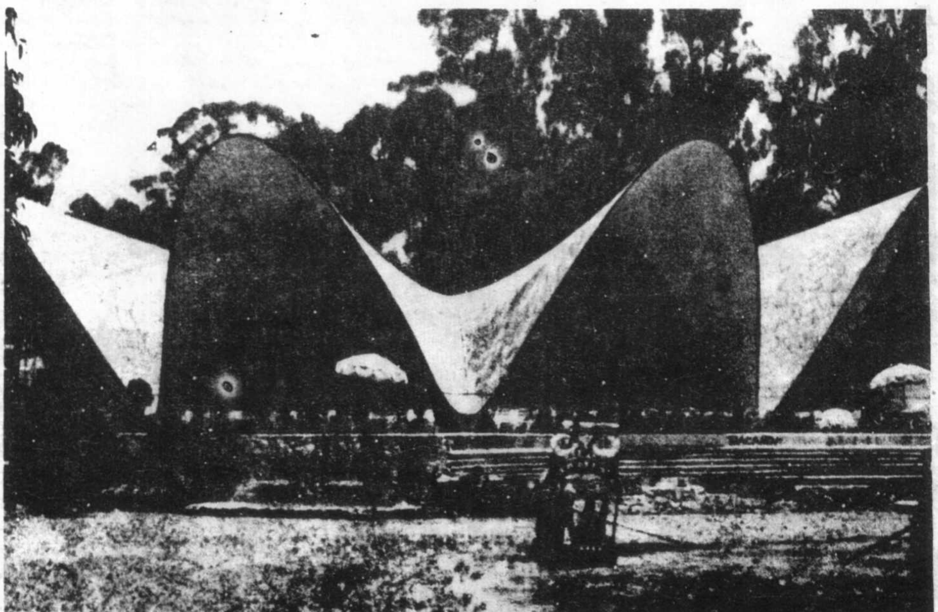

Photo 3 Felix Candela's Xochimilco Restaurant, Mexico

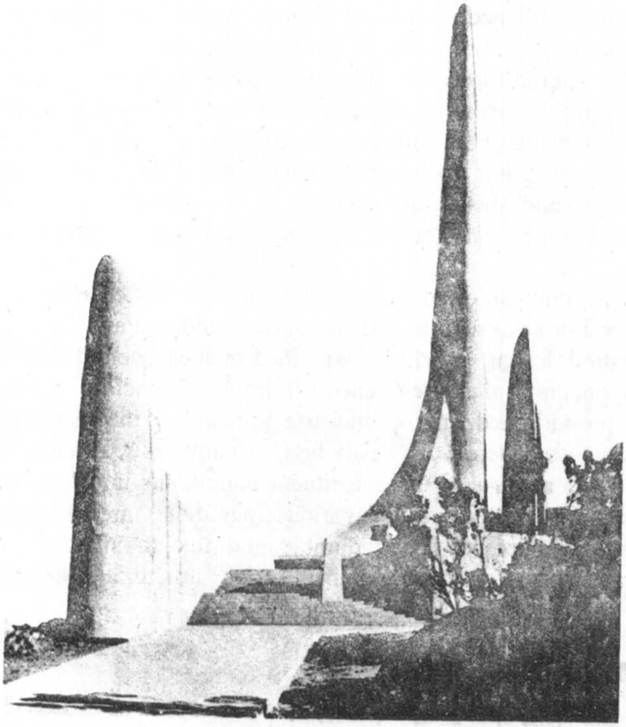

Photo 4 Afrikaans Languages Monument, Stellenbosch, South Africa (height of the main dynamically designed hollow columns, 186 ft).

systems, such as the Kresge Auditorium, Boston; the 1951 Festival of Britain Dome; Marina Towers and Lake Point Tower, Chicago; and many, many others.

Ultimate-strength theories were codified in 1938 in the USSR and in 1956 in England and the United States. Limit theories have also become a part of codes of several countries throughout the world. New constituent materials and composites of concrete have become prevalent, including the high-strength concretes of a strength in compression up to 20,000 psi (137.9 MPa) and 1800 psi (12.41 MPa) in tension. Steel reinforcing bars of strength in excess of 60,000 psi (413.7 MPa) and high-strength welded wire fabric in excess of 100,000 psi (689.5 MPa) ultimate strength are being used. Additionally, deformed bars of various forms have been produced. Such deformations help develop the maximum possible bond between the reinforcing bars and the surrounding concrete as a requisite for the viability of concrete as a structural medium. Prestressing steel of ultimate strengths in excess of 300,000 psi (2068 MPa) is available.

All these developments and the massive experimental and theoretical research that has been conducted, particularly in the last two decades, have resulted in rigorous theories and codes of practice. Consequently, a simplified approach has become necessary to an understanding of the fundamental structural behavior of reinforced concrete elements.

1.2 BASIC HYPOTHESIS OF REINFORCED CONCRETE

Plain concrete is formed from a hardened mixture of cement, water, fine aggregate, coarse aggregate (crushed stone or gravel), air, and often other admixtures. The plastic mix is placed and consolidated in the formwork, then cured to facilitate the acceleration of the chemical hydration reaction of the cement/water mix, resulting in hardened concrete. The finished product has high compressive strength, and low resistance to tension, such that its tensile strength is approximately one-tenth of its compressive strength. Consequently, tensile and shear reinforcement in the tensile regions of sections has to be provided to compensate for the weak-tension regions in the reinforced concrete element.

It is this deviation in the composition of a reinforced concrete section from the homogeneity of standard wood or steel sections that requires a modified approach to the basic principles of structural design, as will be explained in subsequent chapters of this book. The two components of the heterogeneous reinforced concrete section are to be so arranged and proportioned that optimal use is made of the materials involved. This is possible because concrete can easily be given any desired shape by placing and compacting the wet mixture of the constituent ingredients into suitable forms in which the plastic mass hardens. If the various ingredients are properly proportioned, the finished product becomes strong, durable, and, in combination with the reinforcing bars, adaptable for use as main members of any structural system.

1.3 ANALYSIS VERSUS DESIGN OF SECTIONS

From the foregoing discussion, it is clear that a large number of parameters have to be dealt with in proportioning a reinforced concrete element, such as geometrical width, depth, area of reinforcement, steel strain, concrete strain, steel stress, and so on. Consequently, trial and adjustment is necessary in the choice of concrete sections, with assumptions based on conditions at site, availability of the constituent materials, particular demands of the owners, architectural and headroom requirements, the applicable codes, and environmental conditions. Such an array of parameters has to be considered because of the fact that reinforced concrete is often a site-constructed composite, in contrast to the standard mill-fabricated beam and column sections in steel structures.

A trial section has to be chosen for each critical location in a structural system. The trial section has to be analyzed to determine if its nominal resisting strength is adequate to carry the applied factored load. Since more than one trial is often necessary to arrive at the required section, the first design input step generates into a series of trial-and-adjustment analyses.

The trial-and-adjustment procedures for the choice of a concrete section lead to the convergence of analysis and design. Hence every design is an analysis once a trial section is chosen. The availability of handbooks, charts, desktop and handheld per-